AN INVESTIGATION INTO THE POTENTIAL OF ADVANCED SENSOR TECHNOLOGY TO SUPPORT THE MAINTENANCE OF PIPELINE DISTRIBUTION SYSTEMS

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CONTENTS

DECLARATION

"I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any other degree other than that of PhD Architecture and Construction being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised another's work"

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This publication is dedicated to my parents, Mr George and Mrs Regina O. Umeadi.

ABSTRACT

The construction industry has been challenged by the UK Construction Foresight Panel to apply advanced information and communication technology to improve the performance, in terms of sustainability, of the existing built environment and infrastructure.

Traditionally, built-environment maintenance is a capital-cost-driven activity that relies either upon the subjective assessment of a built environment and infrastructure condition (i.e. a stock condition survey) to identify maintenance needs, or upon a reactive response to a component failure. The effectiveness and efficiency of the stock condition survey process to support planned maintenance has previously been questioned and a more sustainable approach, based on an objective assessment of a built environment and infrastructure performance, has been suggested. Previous attempts to develop objective-based (though not performance–based) maintenance models have largely failed, due to the limitations of technology, the daunting task of managing large amounts of data, and the inability of mathematically based models to cope with the complexity of real-life situations.

This thesis addresses this challenge by exploring the feasibility of a performance-based assessment methodology to determine the maintenance needs of a buried oil steel-pipeline system and the impact that any changes in condition may have on the performance and integrity of related components in the pipeline system. The thesis also contains an evaluation of the ability and effectiveness of piezoelectric elements in pipeline defect (crack) signature detection to predict changes in component performance with data sets derived experimentally using laboratory bench testing. Vibration sound-emission detection techniques performed on various oil steel-pipeline defects, using non-destructive testing methods, were validated using attenuation and waveform analysis.

Defect size and progression (i.e. the pattern characteristics of the defect) were monitored, measured and identified through spectrum analysis of multiple emission signals in combination with a number of frequency bands. Two series of tests were undertaken to evaluate the ability of vibration sound emission characteristics to identify steel pipeline defects, including leakage. Test Series 1 established the frequency (waveforms) of the generation of the acoustic emission signal caused by normal fluid dynamics (water flow) through the experimental steel pipe and the resulting signal propagation characteristics. Test Series 2 detected and monitored changes in the signal characteristics for incipient defects: (a) small-nail damage, (b) medium-sized nail damage, (c) large-nail damage and (d) crack to leakage source [sealed holes as a simulated corrosion to total failure]; oil was the fluid medium.

The defect sources and leakage signals were also studied, and compared with theoretical models. The results of the theoretical analysis and the laboratory experiments confirmed the ability of non-destructive testing, based on vibration sound emission techniques, to detect and distinguish between different failure modes.

The ability to carry out a basic inspection, analysis and report of a pipeline using an integrated-sensor device offers many potential benefits. The use of an integrated-sensor device is expected to provide valuable pipeline management information. Specifically the ability to detect and locate mechanical damage at the incipient stage and provide an assessment of the overall pipeline operating condition, including changes in performance profile and prediction of an estimated time to failure, has been shown to be feasible as part of a pipeline maintenance and rehabilitation programme.

LIST OF FIGURES, TABLES AND PHOTOS

contd overleaf

NOMENCLATURE

The following mathematical notation has been used throughout this thesis:

A	Attenuation
a	Contact area
c	Compression wave velocity
cj	Speed at which the leak noise propagates through the pipe
D	Transducer diameter
E	Young's modulus
E'	Apparent modulus
F	Force
K''	Specific stiffness
k	Spring stiffness
λ	Wavelength
m	Mass
ñ	Fluid density
N	Extent of near field
v	Poisson's ratio
P	Peak amplitude
P	Contact pressure
Po	Maximum contact pressure
R	Reflection coefficient
r	Radius
p	Density
Q	Quality factor & volumetric flow rate
Tf	Time between front-face reflections
TOF	Time of flight
$T w$	Maximum window length
Te	Time for response of transducer to die away
t	Layer thickness
W	Half width of sound field beam

SI units are those generally used throughout the work.

The following Glossary has been produced to avoid any ambiguity, and to assist the reader with a number of key phrases, words and abbreviation used in this thesis:

BRE	Building Research Establishment
C&D	Construction and demolition
CBM	condition-based maintenance
DETR	Department of the Environment, Transport and the Regions
DTI	Department of Trade and Industry
FEMA	Federal Emergency Management Agency
IBM	International Business Machines
JIT	just in time
NDT	non-destructive testing (evaluation method)
POSTI	Policies for Sustainable Technological Innovation in the 21st Century
RIBA	Royal Institute of British Architects
SAE	Society of Automotive Engineers

CHAPTER 1: INTRODUCTION

This chapter describes the development of the research programme detailed within this thesis. It was identified that deficiencies exist in the current built-environment maintenance process. In particular, the oil and gas pipeline system ‘process’ of maintenance needs to be more clearly identified and understood, and supported by efficient practices that integrate advanced technology into the fault detection process. The general aim of this research was to address these deficiencies by investigating whether the latest developments in sensor technology can provide the basis for an objective assessment of changes in performance of an oil steel pipeline system’s maintenance needs.

Section 1.1 details the background to the research programme; whilst in section 1.5 the research aims and objectives are considered.

1.1 Maintenance of Built Assets

This research is concerned with the development of the underlying theory and technology to support a new sustainable approach to built asset maintenance.

Achieving the goal of sustainable development continues to be one of the major global challenges of our era. The UK government has embarked on a strategy for sustainable development that has identified four aims: (1) social progress which recognises the needs of everyone; (2) effective protection of the environment; (3) prudent use of natural resources; and (4) maintenance of high and stable levels of economic growth (DETR, 1999, 2005). Taken together, this is known as the ‘triple bottom line’. The UK Construction Foresight Panel **(**DTI, 2001**)** has challenged the construction industry to apply advanced information and communication technology to improve the performance, in terms of sustainability, of the existing built assets.

With about 50% of the UK’s construction output consisting of repairs and maintenance to existing built facilities, new ways need to be found to exploit their potential and value through lateral thinking about alternative uses and the application of innovative technology to prolong asset life. The ‘process’ of maintenance needs to be more clearly identified and understood, and supported by efficient practices. Data concerning building operation, maintenance costs and better asset management will play an important part in ensuring the sustainability of existing facilities over their lifecycles. The challenge to the construction industry is to embrace sustainable thinking at every level and seek to reduce waste over the building lifecycle (DTI, 2001). This research will address this challenge by developing a new approach to maintenance planning that seeks to reduce the consumption of natural resources over the built environment and infrastructure lifecycle by designing out wasteful and unnecessary scheduled maintenance practice.

The built-asset industry, embracing construction, housing, property, infrastructure and facilities management, is a vibrant part of the UK economy and contributes almost 20% to annual GDP (Constructing Excellence, 2005). However, buildings and structures change the nature, function and appearance of both the urban and rural environment. In addition, the construction, use, repair, maintenance and demolition of built assets consume energy and resources and generate waste on a scale that dwarfs most other industrial sectors (DTI, 2001). In acknowledgment of this, the UK government identified the construction industry as a major contributor in achieving its aims to improve the collective quality of life of citizens in a sustainable manner. The report on sustainable construction (DETR, 1999) identified 10 action areas (Table 1.1) and drew attention to the need for greater research and innovation in order to develop more sustainable practices in the construction industry.

Table 1.1: Sustainable Construction Challenges (Source: DETR, 1999)

1	Re-use existing built assets.
2	Design for minimum waste.
3	Aim for lean construction.
4	Minimise energy in construction.
5	Minimise energy in use.
6	Do not pollute.
7	Preserve and enhance bio-diversity.
8	Conserve water resources.
9	Have respect for people and their local environment.
10	Set targets and monitor performance to better manage/reduce the impact of buildings on the environment.

Although the UK construction industry has begun to address the need for more sustainable practices (Egan, 1998), the vast majority of the work to date has focused on the design and construction phases of the building lifecycle. A number of initiatives (see the Egan Report Rethinking Construction (1998); DTI, 2000; Waste Strategy, 2000; Construction Foresight Report, 2002; POSTI, 1998; and the combined research project by IBM UK and BRE (1989)) have sought to contain and reduce waste in the built environment through improved processes that streamline effort and improve efficiency. Whilst the outputs from this work – for example, Building the Future (2005–6) and the construction and demolition (C&D) waste report GEWA0308BNRR-B-P/E (2006–7) – are beginning to have an effect on the sustainability of newly built assets, because of the legacy of the existing infrastructure or building stock it is unlikely that a sustainable urban environment will be produced in the short-to-medium term. Improving the sustainability of an existing building takes place through the process of asset management (maintenance or refurbishment). However, the effectiveness and efficiency of the stock-condition survey process that forms the basis of asset planning has been questioned (Jones, 2002; Machta and Moore, 1999; Papadimitriou, 1994; McCall, 1965). Specifically, it has been argued that existing maintenance/refurbishment models are difficult to understand and interpret, and are based on mathematical analysis and techniques (i.e. simulations) rather than solutions to real-world problems, such that the models are rarely used in practice.

Mathematically based solutions have, however, provided solutions in part for other service-based maintenance problems. For this reason, there is the continuing existence of mathematically based solutions today. Improved means of maintenance are being developed to better monitor built assets and other infrastructures, such as steel pipeline systems, through varying combinations of hardware and software. For example, McCall (1965), Pierskalla and Voelker (1976), Sherif and Smith (1981), Baker and Christer (1994), Dekker (1996), and Dekker and Scarf (1998) have all highlighted the pressing need for identifying and developing appropriate techniques, based on an objective assessment of a built asset’s performance, that would find greater acceptability and a more sustainable approach. Previous attempts to develop objective-based (though not performance-based) maintenance models (Brown and Burton, 1978; Shenai and Mukhopadhya 2003; Carlisle, 2003) have largely failed due to the limitations of technology, the daunting task of managing large amounts of data, and the inability of mathematically based models to cope with the complexity of real-life situations.

This thesis will suggest a new approach to built-asset maintenance that addresses these issues.

1.2 Built-Environment Key Issues

In reality only a small percentage of the UK's built environment is replaced each year. Indeed, over the next 20 years much of the built environment will comprise that which already exists or is in the planning stage (DTI, 2001). If the UK built environment is to address the changing needs of society in a more sustainable manner, then the built environment industry will have to work largely with buildings and infrastructures that already exist. One of the major recommendations for action contained in the Foresight Panel report (DTI, 2001) was to improve existing built facilities through developing innovative processes, technologies and components for the maintenance, repair and refurbishment of the built asset. The report particularly identified the potential for new technologies and 'intelligent' products to improve living and working environments and to enable information feedback to improve construction quality.

The high-profile explosion at the Buncefield oil storage complex in North London – where a depot fire raged for several days and a cloud of toxic gases covered 4,000 square kilometres of Southeast England – resulted from an undetected leak in the pipeline and storage system. This failure in service had severe social and economic consequences, and must raise doubts about the quality and reliability of the detection techniques that were being used. One potential solution would be to adopt a more robust and reliable monitoring approach to pipeline performance – one that utilises new technologies and 'intelligent' non-destructive testing of a pipeline system's in-service performance. Such new technologies and 'intelligent' non-destructive testing (NDT) methods could potentially be used to locate defects before they are sufficiently severe to cause catastrophic failure.

1.3 Current Built-Environment Maintenance Process

Traditionally built environment maintenance (Dann, et al., 1999; Umeadi and Jones, 2003) is a capital-cost-driven activity that relies upon the subjective assessment of an asset's condition (via a stock condition survey) to identify maintenance need. This thesis will investigate the appropriateness of an objective approach to infrastructure monitoring, and steel pipelines in particular, to provide a new basis for maintenance planning.

Steel is used in most of the world's infrastructure development and there are thousands of kilometres of pipeline network systems at risk of corrosion attack. Further, the inspection of a pipeline system's condition is often problematic. They are often located in harsh, inaccessible environments which make consistent and accurate data collection and processing difficult to achieve. Thus any new inspection procedures must be capable of operating across a range of environments and without the need for third-party interventions.

1.4 Traditional Pipeline Maintenance

Oil steel-pipeline system maintenance is traditionally performed in either time-based or distance-based fixed intervals, so-called 'preventive maintenance', or by corrective maintenance. When fissures or failures are discovered, they are either dealt with immediately or maintenance actions are deferred in time whilst the pipeline continues to function. Occasionally pipeline systems deteriorate prematurely, causing abrupt failure and generating severe financial, environmental and safety implications. Worldwide, repairs and maintenance of steel pipeline infrastructure generally run into many billions of pounds each year (Solarstorms.org, 2003), with the cost of repairs needing to cover not only the materials and labour costs but also the cost of disruption to users and social costs. To try to prevent this disruption, many companies carry out unnecessary repairs and replacements, which are inherently unsustainable. Inspection and monitoring of infrastructures, and of pipeline systems in particular, is a major requirement of preventive maintenance activities.

In their conclusions to a report on a major study undertaken in the early 1990s, Damon and Quah (1998) suggested that an objective, performance-based assessment approach to built-environment maintenance could be achieved by using advanced sensor technology and intelligence decision support. Although complex, it should be possible with today's technological and communication advances, to develop and embed miniaturised sensors that incorporate wireless technology into a range of built-asset and infrastructure components (Daman and Quah, 1998; DTI, 2001). Furthermore, the study suggested that if intelligent decision-support capabilities are also included in the miniaturised sensors, then it should not only be possible to monitor and report changes in state in a component's performance, but should also be possible to evaluate the impact that these changes have on its remaining lifespan and on the performance/integrity of related components in the subsystem (Davis et. al., 1998; Buychx.com, 2002). The development of such a system and the theory necessary to integrate the system into a built-asset maintenance process formed the basis of this PhD study.

1.5 Aims and Objectives of this Study

The primary aim of this research was to investigate whether the latest developments in sensor technology could provide the basis for an objective-based assessment for changes in performance of an oil steel-pipeline system's maintenance needs. In addressing this aim, the project has:

1. explored the feasibility of a performance-based assessment methodology to determine the maintenance needs of components;
2. evaluated the ability and effectiveness of piezoelectric elements in defect (crack) signatures detection (via their pattern characteristics) to predict changes in component performance using data sets derived experimentally using laboratory bench testing that modelled oil pipeline and flow characteristics;
3. validated the non-destructive (vibration sound emission) detection techniques across a range of oil steel-pipeline defect and leakage conditions; and
4. validated the natural frequency and mode shape/size (i.e. amplitude predictions) across a range of oil steel-pipeline defect and leakage conditions.

This thesis addressed these challenges by developing and testing a prototype non-destructive testing system that sought to:

- predict the location of a damaged portion of pipeline;
- monitor and report any changes in the performance of the pipeline system; and
- evaluate the impact of damage on the pipeline's integrity.

The results and data from the laboratory tests have provided the basis for the development of a new approach to real-time performance monitoring that is predominantly applied to service-based issues. The need to consider the characteristics and performance of an in-service oil steel-pipeline system is also discussed. The thesis also considers current oil steel-pipeline systems maintenance best practice and the problems that can occur.

1.6 The Research Assumptions

This research was motivated in part by the desire to improve the sustainability of existing built environment and infrastructures through the proactive use of maintenance and refurbishment. It was concerned with the development of a performance-based approach to built-environment maintenance planning that utilises real-time performance monitoring and advanced artificial intelligence techniques to predict remaining component lifespan and thus provide relevant information for a just-in-time maintenance strategy.

Implicit within the research project are a number of assumptions, which were validated at the outset of the project. These assumptions included the following:

- that it was possible to define performance measures and set performance thresholds for a steel pipeline system (measuring physical performance); and
- that, once defined, the performance profile of a pipeline system was consistent (and repeatable) over its lifespan (or part thereof).

In order to evaluate these assumptions, a research vehicle was needed that satisfied the following criteria:

- it was simple enough to allow a performance profile to be established;
- it would accommodate evaluation of the tools using live data sets;
- it was manageable within the confines of a PhD programme (i.e. performance thresholds had to be met within three years or historic data sets had to be available); and
- it was meaningful enough to allow generic conclusions to be drawn as to the appropriateness of using performance-based measures of built fabric as part of a more sustainable maintenance planning process.

The condition and performance assessment of a steel pipeline system was selected as the research vehicle. This decision was taken in light of the author’s direct experience with the current maintenance process, and as a result of discussions with potential industrial partners, which identified the need for an improved maintenance process. The considerations related to the application of advanced sensor technology incorporating intelligent wireless technology to support steel pipeline maintenance and to develop new corrosion sensing, monitoring and reporting technologies for oil pipeline maintenance. The proposed maintenance system must be:

- reliable;
- self-contained (it should be able to monitor, analyse and report performance data from remotes sites to a central maintenance facility);
- able to perform its function without manual intervention (many pipelines are located in remote and inaccessible locations); and
- economical.

Prior to the development and establishment of the performance profiles, it was essential to identify some of the primary issues and considerations pertinent to the investigation. Issues such as the identification and definition of the measures (in other words, what is steel pipeline performance profile?), although not resolving all of the key issues, may provide guidance to facilitate maintenance decision-making when implementing the measures required to prolong the life of a buried oil steel-pipeline system. The research vehicle was developed during the first six months of the research project.

1.7 Chapter Summary

This thesis presents the outcome of an investigation into the effectiveness of advanced sensor technology to monitor the performance characteristics of a transmitting pipeline system. Frequency and amplitude predictions have been validated experimentally in the laboratory using a model oil-pipeline distribution system. The accuracy of the damage (pattern) location routine and the ability of the sensors to monitor, analyse and report on changes in the performance of the pipeline system across a range of simulated pipeline situations were evaluated. The model also allowed the impact that these changes had on the pipeline systems performance to be evaluated, and this knowledge can potentially help pipeline integrity to be predicted.

The study concludes that it is possible to assess the changes in performance of a steel pipeline under induced-corrosion conditions with sufficient reliability for the process to potentially form the basis of a new objective approach to oil pipeline physical performance assessment.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews approaches to general maintenance, built-asset maintenance and steel pipeline performance assessment. Section 2.1 defines ‘maintenance’ and describes the current approaches to built-asset maintenance and maintenance theory. In section 2.2, two components of the role of any monitoring method on existing oil steel-pipeline systems are compared. Section 2.3 reviews assessment and testing techniques, focusing on those that are non-destructive in nature. section 2.4 considers types of pipeline failure, particularly corrosion beneath detached coatings; section 2.5 considers detailed oil steel-pipeline performance assessment techniques; and section 2.6 looks at possible leveraging from cardiovascular monitoring techniques.

2.1 General Review of the Approaches to Maintenance

‘Maintenance’ in the context of this thesis is concerned with service-based maintenance issues related to the built environment and infrastructures, and it is used as a generic term to describe all work undertaken to ensure the ongoing operation of the built asset. Such work includes repairs or any addition, both planned and unplanned, that is necessary to retain a built asset at an acceptable standard in order to prevent and delay its progressive deterioration due to age and usage. Although in 1964 the British Standards Institution defined (via BS3811-1993) maintenance as "work undertaken in order to keep or restore every facility, i.e. every part of a site, building and contents, to an acceptable standard", this could further be defined as a combination of any actions required for the preservation of the existing building stock and its fabric to an acceptable condition.

In principle, maintenance is recognised as the best way to look after a built asset. However, in practice little maintenance is done, simply because many built-asset owners wait for things to go wrong before acting. This results in a waste of resources and is not sustainable. As defined in the Brundtland Report (World Commission on Environment and Development, 1987): "Sustainable development is a process of change in which the exploitation of resources, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations."

It is crucial to distinguish maintenance from repairs. Maintenance can be clearly understood to mean the continual and protective care of asset fabric or of a place. Repairs, on the other hand, involve restoration or reconstruction. Nevertheless, the BS7913 (1998) definition of maintenance as routine works necessary to keep the fabric of a building in good order made it harder to see a consensus on exactly where maintenance ceases and repair starts – and this is even though BS7913 defines repair as distinct from maintenance, in that any work that goes beyond the scope of regular maintenance and is meant to remedy defects (such as decay or damage caused deliberately or by accident, neglect, normal weathering or wear and tear) could be deemed as repair. The object is often to return the built asset or artefact to good order, without alteration or restoration. However, there are considerable similarities between maintenance and repairs: both seek to extend the life of the built component or asset, and therefore include a modest degree of interrelated activities. Ironically, this ambiguous interpretation of the relationship between maintenance and repair shows there is no clear and accepted definition or demarcation.

2.1.1 Maintenance Approaches

Oil steel-pipeline systems play a very important role in everyday life: they support mobility and are the primary mode of transportation of oil from A to B. For this reason it is important that every pipeline system maintains its functionality with as little disruption as possible. To achieve this goal, regular maintenance, repair and/or rehabilitation operations must be carefully planned and executed at the proper time. However, maintenance itself can result in excessive downtime and costs to the oil industry. This is because of the requirement to take the oil pipeline system offline to carry out (possibly unnecessary and invasive) maintenance. In maintenance, a number of prefacing adjectives – such as ‘preventive’, ‘planned proactive’, ‘reactive’, ‘corrective’, ‘systematic’ and ‘regular – are often used. Furthermore, as can been seen in Figure 2.1, preventive maintenance is itself divided into two categories: predetermined maintenance and condition-based maintenance (CBM). CBM can be dynamic or done at requested intervals; predetermined maintenance is scheduled for specific points in time.

The main role of preventive maintenance is to extend the life of the steel pipeline system – that is, to take action that will reduce or obviate the need for repairs and will prevent the loss of original steel-pipeline fabric. However, there are risks that an existing pipeline system in which a damaged section of pipe has been cut out and replaced with a new section of pipe may corrode faster as a result of galvanic corrosion. This often occurs when two dissimilar metals come into contact with each other as a flow of electrons are created between the metals that eventually causes them to disintegrate. One way to prevent this corrosion is to replace one metal piece with another that is compatible with the affected piece. However, this is not often possible as oil and gas industries seek to reduce cost, and therefore tend to use the best available metal piece instead of investing extra time and cost to look for another identical metal piece (corrosionsource.com, 2003). This approach could indeed suggest that the oil companies tend to take a short-term view in which reducing costs is more important than extending lifespan, the prevention of major faults, or the adoption of a maintenance strategy that integrates and considers the long-term implication of changes in performance.

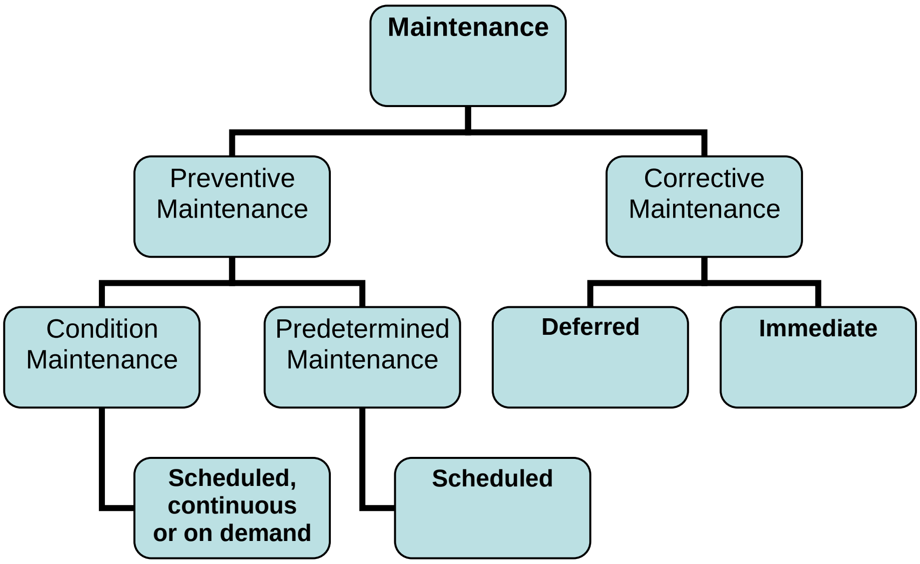


Figure 2.1: The Usual Maintenance Terms (*Source*: Lightfoot et al., 2000)

Although proactive maintenance consists of routine calibrations and programmed replacement of specific pipeline system or subsystem parts, the method and activities all consume a large amount of cost and organisational energy. Thus, the main focus of maintenance has primarily been on dealing with the known defects efficiently, more than preventing new and unknown defects from arising. Lightfoot et al. (2000) state in their paper that the term ‘predictive maintenance’ is actually somewhat misleading, and that many would prefer the term ’conditional maintenance’. Lightfoot and colleagues further state that predictive maintenance does not truly predict machine failure but detects the existence of a condition – for instance, marginally lower machine performance or a certain heat level from a bearing – that can then be used to predict when that condition will cause an unplanned failure of the machine. Therefore it is unfortunate that the use of the word ‘predictive’ has been so uniformly applied to monitoring programmes that it has since become trite and commonplace to label all maintenance programmes as predictive.

Nevertheless some detection techniques can very successfully achieve early detection of failures and indeed provide the necessary information for correct professional judgement to limit damage and plan repairs (Reliability Chat-Room, 1999). The differences between prediction and detection are clarified as follows: (1) to predict means to state in advance, forecast, foretell, portend, and prognosticate; and (2) to detect means to find out or discover the nature, existence or fact of. Given the above definitions, it is hoped that when an analysis protocol for an oil steel-pipeline condition and data acquisition monitor determine corrosion, scaling, loss of operating metal mass or other pre-existing phenomenon, analytical tools will be able to detect and predict the problem. The question when designing such a system would therefore be; do the results obtained and predicted actually foretell the pipeline’s actual condition? Are the data acquired able to indicate that the steel pipeline system will (for instance) abruptly fail shortly, and has the condition of the steel pipe really been compromised?

Where this research is so far in agreement with other authors such as Lightfoot et al. (2000) is that the key to a successful predictive maintenance programme depends on the ability to predict a future event after the detection of a condition. However, it could be argued that the continual identification and detection of a component’s condition is difficult and, as such, some conditions that could cause problems are often allowed to exist. Consequently, predictive maintenance may be perceived at times as ‘run to failure’ in order to learn for future predictions. The difference, therefore, is that predictive maintenance attempts to fix all problems (by carefully and routinely monitoring the condition of the built asset and its fabric) before they have serious economic consequences – e.g., unplanned failures (Lightfoot et al., 2000). The main benefit of this research is that it sought an effective means to extend the life of a built component and thus minimise expense associated with unanticipated downtime. It should also help to maximise productivity of the steel pipeline system in transporting oil, and should provide information that can be used for assessing whether the reliability and performance expectations are being met just in time.

Oil steel-pipeline systems fulfil various commercial needs; as an infrastructure, they are made of components and subcomponents that have a life expectancy. They require maintenance, refurbishment, renovation and repair in order to retain or extend their life expectancy. Maintenance helps to prevent and slow progressive deterioration of the horizontal infrastructure. In fact, steel pipeline systems, like other built assets and infrastructure, could deteriorate from a combination of three separate components: physical decay (i.e. rot, mould, corrosion and leak), increased functional demands and technological improvements (Jones, 2002). It could be argued that continual maintenance of an existing oil steel-pipeline system is necessary and that a comprehensive maintenance programme must be devised at each hand-over in order to combat obsolescence. Jones's (2002) view purveys the notion that a built environment and its fabric maintenance is a dynamic process in that infrastructure in general is complex in its nature and composition. It is also debatable as to whether maintenance or replacement of a failed oil steel-pipeline system is necessary at all, and also whether replacing a failed section of pipe actually constitutes refurbishment or simply maintenance aimed at extending the asset's useful life – by so doing, further neglecting the oil pipeline system's condition till it becomes critical.

Similar issues were considered by Harper (1978), who wrote that there has not been a defined maintenance programme specifically dedicated to an asset's fabric; instead, there is a continuation of "don't mend what ain't broke" attitude similar to the "run it till it fails" mentality. However, it could further be argued that pipeline systems differ in structure, composition, size and application from mechanical systems. Hence there is an insufficient understanding of their true dynamic maintenance process, and no maintenance programme has been specifically developed to continually monitor and report pipeline systems' in-service performance under varying environmental conditions. Despite recognition of such limitations, there is still no technology that is directly embedded in non-service-based components to continuously monitor, detect and report the system condition or performance, or if any do exist, they are not reported in academic literature.

In environmental and economic terms, well planned and implemented oil steel-pipeline maintenance utilising new technology and innovation that continuously monitors and reports the state of the built asset could result in a less resource-intensive measurement programme. There would be no need for unnecessary inspection and repairs; consequently, there would be a reduction of waste and energy use in the maintenance process. However, the development of such an integrated system will require a shift in philosophy; for example from cure to prevention, that truly covers planned maintenance strategies.

It is crucial that this study does not underestimate the tasks involved in the development of an effective system that can continuously monitor condition and evaluate changes in performance. This requires the development of new maintenance approaches and will undoubtedly lead to gains, not only for the built-environment industry but also the materials community and society as a whole.

2.1.2 Current Approaches to Built-Asset Maintenance

According to Jones (2002), the traditional process model for built-asset maintenance (see Figure 2.2) places a stock condition survey at the centre of the maintenance decision-making process. The stock condition survey is effectively a snapshot of the physical condition of an asset (or portfolio of assets) at any given point in time. From this information, a stock condition profile model is developed that predicts demand over a given time period (typically 5–10 years for commercial assets; 25–30 years for social assets). Demand prediction is often based on an assessment of time remaining until a given component reaches the point at which a maintenance action is required. Jones further wrote that once the demand profile has been established, budgetary constraints and minimum specification standards (e.g. legislation) are applied to the demand model, and maintenance options (along with risk assessments) are identified to ensure that the asset remains viable over the refurbishment period. Finally, prioritising algorithms are applied to the demand model to smooth cash flow and to programme interventions against alternative maintenance strategies (responsive, planned etc.). Whilst this model is widely used in practice, it does have some well documented problems.

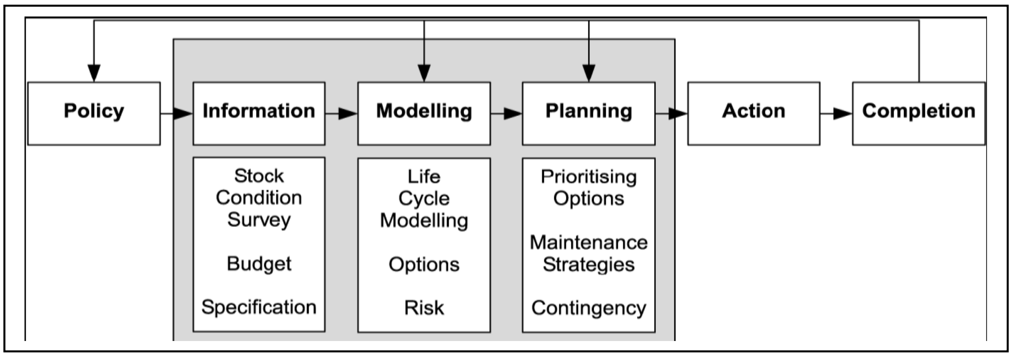


Figure 2.2: Stock Condition Survey (*Source*: Adapted from Wordsworth, 2001)

Whilst the model assumes that the maintenance planning process is driven by organisational policies, all too often policy objectives are not clear and no direct links exist between an organisation's strategic objectives and their built-asset maintenance programmes. Maintenance is viewed by many organisations as a necessary evil and cost burden (Moua and Russell, 2001), whereby in times of economic hardship budgets get cut back, and under better economic conditions the owners are reluctant to spend money to preserve the condition of buildings. Such an approach manifests itself in maintenance standards being met by the barest minimum interventions (Chew et al., 2004) and is indicative of a lack of a link between asset maintenance and organisational performance.

Indeed, Arditi and Nawakorawit (1999) argued that there is a growing recognition amongst building owners of the need to plan and manage their maintenance alongside other corporate assets, which requires building managers to effectively communicate with building users and consider their concerns (alongside physical condition) when developing maintenance programmes. Such an approach would not only improve the performance of the built asset but, through inference, also add value to the organisation.

2.1.3 Built-Asset Obsolescence and Maintenance Lifecycle

The existence of obsolescence was also recognised by the Chartered Institute of Building (1990), which proposed an alternative definition of 'maintenance and refurbishment' as "work undertaken in order to keep, restore, or improve every facility, its services and surrounds to a currently acceptable standard and to sustain the utility and value of the facility". In this definition, maintenance and refurbishment are explicitly linked to improving the value of the built asset.

According to Finch (1996), the role of maintenance is to render the property back to its prior condition, where it can fulfil basic function and is within legislative compliance. Finch further argued that the role of facilities management is to address the constantly increasing gap in existing property condition and future demands, which are directly related to:

- constant technological advancement;
- user demands; and
- market forces.

These listed factors are on a constant-increment path from the point of inception of a given built asset. This is explained further below, with the help of Jones's (2002) reinterpreted model shown in Figure 2.3.

Jones (2002) reinterpreted Finch's model to one that probably more accurately reflects what happens in practice. In Jones's model (see Figure 2.3), repeated maintenance cycles (a to d) occur until the point at which a building fails to satisfy the occupier's demands and a major refurbishment is required. Even after refurbishment, some residual obsolescence remains and this grows over repeated refurbishment cycles until the obsolescence gap is too great for an organisation to bear. At this point the organisation either relocates, the building is demolished and rebuilt, or the building is refurbished beyond its original purpose and a change of use occurs (Jones, 2002).

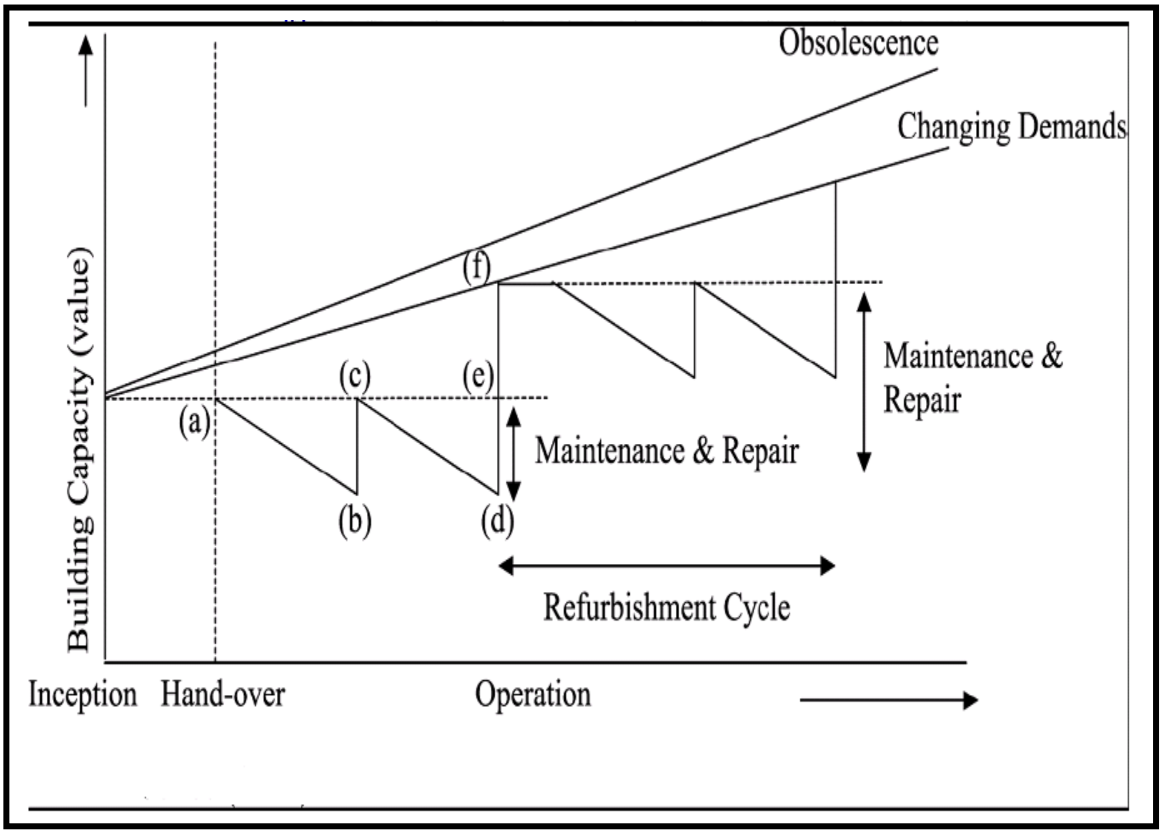


Figure 2.3: Model of the Maintenance Refurbishment Lifecycle (*Source:* Jones, 2002)

In considering these options, Jones examined the dynamics of the model and suggested that value (in the context of built-asset maintenance decision-making) went beyond merely the consideration of building technology issues, to one that acknowledged the impact of the built asset on the long-term viability of the organisation. In essence, Jones argued that ‘value’ should be explicitly linked to the ability of the built asset to support organisational performance and built-asset maintenance should be viewed as a strategic issue managed within the broader context of an organisation’s strategic planning framework.

The positioning of built-asset maintenance and refurbishment within an organisation’s management framework was considered by Quah (1998), who pointed to the changing perception of built-asset maintenance and refurbishment – from one of liability and nuisance, to one of supporting the core income-generation activities of the organisation – as the key reason for elevating its status (as a key component in operational management) alongside financial, space and user management as the top-level factors in a facilities management strategic plan. However, although Quah recognised the importance of strategic maintenance management to organisations, she didn’t explicitly consider how maintenance decisions could be linked to the wider issues surrounding organisational performance (Jones, 2002). Jones’s argument is more relevant today, considering that most of the UK’s built assets that support essential services such as energy, water, waste, transport, gas and oil pipeline infrastructure were constructed more than 50 years ago and have been ageing ever since. It is a challenge that infrastructure renewal should be relevant to current circumstances, whilst at the same time being economical to perform.

The modification to Finch and Quah’s models by Jones (2002), when implemented, will make the model more relevant to be applied in the monitoring process of the continual challenges in relation to changing infrastructure demands; the model should therefore help to improve the performance of the existing infrastructure. Most importantly, if successful, it would reduce obsolescence and increase the infrastructure’s actual and desired performance in the long run, since obsolescence has often been associated with the use of rapidly evolving technology, dangerous materials or polluting processes, especially in the oil and gas industries. It is important that any tool used in long-term maintenance planning for increasing the life of the infrastructure must also consider possible short-term changes that might affect its performance. Thus the model design should be adaptable and able to be managed in such a way that it interfaces with other tools or systems in a variety of circumstances.

2.1.4 Built-Environment Maintenance Theories

‘The built environment’, according to Sharkey (1997), is a generic term covering four main strands: architecture, surveying, building and civil engineering. It is a systematic, cyclical and holistic process.

Like most other industries the general understanding has been that there are many different ways in which various materials (especially metals) are used in the built environment today. However, corrosion problems in assets persist and cover an extensive range.

There is a notion that steel is the most common metal used in built environments (because of its low cost and many other desirable properties), and it can often be protected adequately by the application of suitable coatings. For the purposes of discussing corrosion, Sereda (1961) grouped the metal components used in the built environment into four general categories: (1) those used on the exterior as cladding, roofing and flashings; (2) those incorporated into the construction as structural and reinforcing steel, masonry ties and damp courses; (3) those used in the services/infrastructure, such as piping and storage tanks for hot water, drains and heating ducts; and (4) those buried in the ground.

According to BDM (1998), FEMA (1996) and Sereda (1961), metals in use on the exterior of built environment assets are subjected primarily to atmospheric conditions comparable with the aerospace, maritime, automobile and oil (buried utilities) industries, but the effects of these may be modified by the particular elements of design and technology. As a result, the principal atmospheric factors affecting the corrosion of metals are temperature, extent of pollution by sulphur dioxide, chlorides and the length of time during which the metal remains wet by water.

Another major factor leading to the corrosion of iron and steel in built environments is faulty design (Sereda, 1961). Accordingly, different metals are affected in different ways by changes in environmental factors, but they can be monitored and remedied through improved maintenance management processes. McCoy (2001) defined a ‘blending management process’ that applies integrated technologies to support and enrich human interaction. It could be right to infer, therefore, that the maintenance process is a means of improving maintenance efficiency and it can be divided between two different concepts, with the main focus being:

1. sustainability-related objectives and measures incorporated into innovative processes or outputs (best practice); or
2. innovation processes or outputs that aim directly at improving the present and/or future quality of the built environment. In a broader sense, such processes encompass new ideas underpinned by new technology and innovation.

These issues are not just applicable to the built environment but cut across industries. The aerospace, automobile, rail and marine industries have traditionally invested a large amount of money into research and development. Each has developed its industry best practice (DTI, 1998; RIBA.org, 2002; CONNET.org, 2003) that could be studied and adopted by the built-environment industry. Best practice is nevertheless not prescriptive (ITEBD.org, 2003; CBPP.org, 2002), especially for the built-environment industry that is so large and fragmented; principally, what may work for one built-environment organisation may not work for another.

2.1.5 The Mathematical or Statistical Approach

Kurt Gödel’s theorem (ISCID.org, 2003) suggested that within a certain mathematical system one could not construct a formal proof of certain facts. Gödel explained that this was the case since no matter what complex calculus is developed to this effect, it would still be very difficult to reduce all the complexity of certain facts to simple mathematical rules. Hilbert (1927), on the other hand, argued that it is possible to reduce all problems into simple mathematical rules.

Although this argument shows precisely how difficult the application of mathematics to built-environment maintenance could be, it is possible to argue that it has been easier to state that something is possible or impossible because in mathematics certainty is easier to achieve. One problem is that in the practical world of oil steel-pipeline maintenance there are many unknown factors. For example, volatile crude and refined fluid hosting and transportation, a corrosive environment and vandalism all pose difficulties to the operating of an in-service pipeline system; thus, the use of mathematical systems to represent regular occurrences may prove difficult. Along this line, Gödel seems to argue that one could not apply the incomplete logic in a certain situation to solve an uncertain problem like the rapid detection and interpretation of real-time changes in a steel pipeline system.

In support of these arguments Tsurui and Ishikawa (1986) recommended that the Japanese approach, namely the application of engineering uncertainty, should be used. They argued that the engineering uncertainty method provides the required data that is crucial to maintenance decisions and that the engineering uncertainties approach also integrates well with reliability theory, a philosophy that was adopted in the 1920s by Bell Laboratories (Shewhart, 1931) and is based on Statistical Quality Control. According to Comillas (2001), Statistical Quality Control involved charts that combined means and ranges that are still in use (or, rather, misuse) today.

In contrast, Lewis (1999) exploited the knowledge that all equipment components are subject to wear and tear in order to seek statistical solutions that eliminated unnecessary or unplanned downtime due to failure, which is in turn unsustainable both in the short and long run. Although the reliability of the approach itself has previously been questioned, it has developed and continues to evolve in many industries.

Statistical solutions have also played a crucial role in the probabilistic evaluation of structural safety and reliability theory. Take the Ishikawa (1982) study, comprising a survey of the ‘reliability-based design of structures’, and that of Furuta (1988) on ’fuzzy diagnosis structures’, both of which see the ability to process data from various technologies into information about the item’s current condition as adding value to continual improvement of service delivery.

Figure 2.4, a statistical timeline, shows that in the 1950s and 1960s, the use of statistical process control (SPC) and statistical sampling was widely used in Western European industries. Nonetheless, in the 1980s the process was reversed and US companies looked towards the Japanese, who were searching for their approach to be adopted. Statistics were identified as one of the reasons for the Japanese success, and the Taguchi methods were exported to the US and Europe.

1920s–30s	**Statistical Quality Control**
1940s	**Chart of means and ranges**
1950s–60s	**SPC and statistical sampling**
1980s	**SPC process (Taguchi methods) were exported to US and Europe**

Figure 2.4: Timeline of Statistical Solutions in Failure Analysis

Accordingly, Scanlan et al. (2003) argued that if rapid detection of process and equipment faults is the key to maintaining high product benefits, then identifying the root cause of such faults is the key to maintaining high productivity levels. The traditional approach to root-cause analysis is to apply statistics to this data, either as univariate statistical process control or, more recently, as multivariate statistical process control whereby possible faults are detected by monitoring deviations in performance that are outside normal limits from the statistical mean. One limitation of this approach is that the underlying sensor data does not usually have a normal distribution. Furthermore, it often results in a trade-off between low control limits (for example 3-sigma), resulting in a repetition of ‘false positive’ alarms, and high limits (for example, 6-sigma or greater), with too many missed faults. This is represented graphically in Figure 2.5. The dashed vertical line represents the control limit, chosen with respect to sensor variance. Missed faults appear in the upper-left quadrant, false positives appear in the lower-right quadrant. See statistics-based fault detection model below.

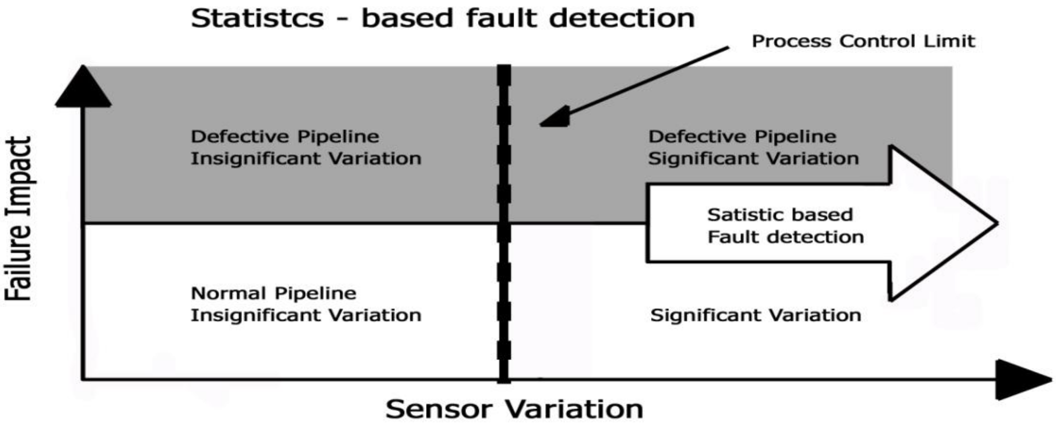


Figure 2.5: Real-Time Fault Detection (*Source*: adapted from SCM, October 2003)

Because of the aforementioned complexities in service-based issues such as steel pipeline systems, it could be argued that the interpretation process for any changing event in the steel pipeline system or subsystem would also be complex. Monitoring and detection of deviations outside the normal limits in service-based issues may require the development of a new approach to maintenance planning technology. Graham (1999) presented a more practical argument against the use of mathematically based models, in that if mathematically based solutions are to work and not place an undue burden on organisations, the technology must be standardised and be interoperable across platforms – and even, if possible, across building fabrics. In this instance, an advance sensor technology developed for a coated oil-and-gas steel pipeline system may be deployed on other subsystems.

2.1.6 Maintenance Theories in Other Industries

According to Mitchell (1998), maintenance actions based on objective evidence of need (i.e. actual condition) obtained from in-situ, non-invasive tests performed under operating conditions, are defined as comprising Condition Based Maintenance (CBM). The emphasis in this approach to maintenance is that the asset condition is assessed under operation with the intention of making a decision as to whether or not it requires maintenance, and, if that be the case, at what time the maintenance action needs to be carried out to avoid a failure. The automobile and aerospace industries could be said to have exploited a degree of automation in assessing an item’s condition, which varies from human visual inspection to fully automated systems. The approach (known as ‘reliability-centred maintenance’) requires the deployment of intelligent and smart sensors for condition monitoring, diagnosis, prognosis and data manipulation. The Society of Automotive Engineers (SAE, 1978) defines ‘reliability-centred maintenance’ as “a logical technical process to achieve design reliability, which requires the input of everyone associated with the item and its fabric to make the resulting maintenance program work".

For example, automobile manufacturers recommend scheduled oil changes to achieve optimal engine reliability and vehicle performance. For most new vehicles the recommended frequency of oil change is 3,000 miles (Vacante, 2001); although it can be argued that reliability-centred maintenance and the evolution of microchip technology have come together in a manner that is enhancing the reliability of automobile systems. According to Campbell (1999), the automobile industry has moved to built-in obsolescence; where there was a progression in the 1990s from preventive and planned maintenance to condition monitoring, computerisation and lifecycle management. There is no doubt that the evolving characteristics of systems and subsystems are dictating maintenance practices – predominantly, the automobile and the aerospace industries are each moving away from prevention towards prediction.

To remain competitive, Vacante (2001) argued, the automobile manufacturer has found it necessary to take a step beyond preventive maintenance, whereby the monitoring of oil status is just one of many innovative ways that reliability-centred maintenance is being used. Reliability-centred maintenance techniques have been implemented to enable a vehicle's owner to observe the vehicle performance during product use. The use of built-in test devices that provide system status on the vehicle dashboards empowers the customer with accurate information that can lead to substantial cost avoidance and savings, thereby making it possible to divert monies set aside for unnecessary maintenance activities to other things. This is unlike the built-environment industry, which is often slow in adopting new approaches and technologies.

In the aerospace industry it was not until World War II that the subject of built component reliability became a serious concern. For example: 60 per cent of US aircraft destined for the Far East proved unserviceable; 50 per cent of electronic devices failed while still in storage; the service life of electronic devices used in bombers was only 20 hours; and 70 per cent of naval electronics devices failed (Pačaiová and Raschman, 2001). According to Wylie et al. (1997), the condition survey process on aircraft was often carried out after each aircraft had landed and the aircraft was then taken out of service for a period of time in order to 'find-and-fix' the fault. The condition survey process usually put line maintenance at a time disadvantage because, firstly, the maintenance team had to identify the cause of the problem and then the time and resources required to fix it. Secondly, decisions had to be made as to whether corrective action could be taken, given other factors – for example, accessibility ('gate time') and availability of required resources – or whether the repair should be deferred in order to save money. Most often, the flight team had to check whether regulations would allow the aircraft to fly with the problem. According to Lewis (1999), this practice and the tendency to save money often promoted a 'fix it at the last minute' philosophy.

The main challenge of this research is to shift the focus from the current maintenance approach ('interval condition survey') towards continuous condition and in-service performance assessment with real-time reporting. Therefore, the driving force has been quality and reliability; and although the concepts of quality and reliability are related, they are not the same. Pačaiová and Raschman (2001) defined the 'quality' of a product or service as its ability to ensure complete customer satisfaction, while the technical standard SAE JA1011 defined 'reliability' as the ability of a system or component to perform its required functions under stated conditions for a specified period of time. When the concepts of quality and reliability are brought together under reliability-centered maintenance, they will help to meet the industrial improvement approach that is focused on identifying and establishing the operational, maintenance and capital improvement policies that will manage the risks of equipment failure most effectively.

2.1.7 Summary of Challenges

The built-environment maintenance process is generally linear (i.e. queue-based), and the subjective assessment of an asset's condition via a stock condition survey so as to identify maintenance need has been shown (through literature reviews) to be unreliable. Other problems highlighted with current approaches are that maintenance models have largely failed due to: the limitations of technology; the daunting task of managing large amounts of data; and the inability of traditional mathematically based models to cope with the complexity of real-life situations (Brown and Burton, 1978; Shenai and Mukhopadhyay et al., 2003; Carlisle, (2003).

In order to redress the problems in the maintenance planning process; new ways have to be developed that will eliminate problems with downtime to ensure that a pipeline system maintains functionality with as little disruption as possible. To achieve this goal, regular maintenance, repair and/or rehabilitation operations must be carefully planned and executed at the proper time. This is because of the requirement to take the oil pipeline system out of service in order to carry out possibly unnecessary and invasive maintenance that is costly to the oil and gas industry. Nevertheless, it could be very expensive when spills occur as a result of deferring maintenance and safety precautions.

Despite the many maintenance initiatives since the late 1950s, there are still issues that need to be improved in the monitoring and maintenance process. For example:

- Demand prediction is still based on an assessment of time remaining until a given component reaches the point at which a maintenance action is required.
- The performance measurement system is still based mainly on financial information, and ignores a built asset's vital in-service performance information.
- Scheduled site visits are used both for monitoring and for inspection, which often misses incipient faults that may develop in the interval between scheduled visits.

To address these shortcomings in the existing maintenance process, a new and more reliable maintenance method needs to be developed. The emphasis of the new process should be on the continuous monitoring of the asset's performance under operation, with the intention of making a decision as to whether or not it requires maintenance. The new performance monitoring solution should take into account problems that normally develop between scheduled maintenance intervals and provide a basis for reliable maintenance planning that, through continuously monitoring of an asset's performance, would help to detect and avoid catastrophic failure.

Additionally, it is important that any new maintenance approach tackles both the planned and unplanned maintenance challenges faced by the industry. In essence, the performance of a built asset can therefore no longer be defined and expressed merely in terms of meeting its operational need. It must also meet maintenance planning process needs.

The final area examined in the study was performance measurement as a subjective evaluation method and its inability to provide continuous in-service performance information instead of just current raw data. The focus has been the possible move to an objective maintenance approach (with the provision of continuous in-service changes in performance being detected and reported) rather than the current subjective approach. On this basis, reliability-centred maintenance is suggested, supported by an integrated solution that takes advantage of the latest development in sensor technology.

In order to develop such an approach to built-asset maintenance, a system that can convert raw performance data into in-service performance information must be developed. This will require not only the identification of robust and consistent performance-based metrics and the associated analysis tools, capable of delivering reliable performance information, but also a change in maintenance philosophy from cure to prevention.

2.2 Monitoring Approaches for an Existing Pipeline System

The role of any monitoring method for an existing oil steel-pipeline system must comprise two components.

Firstly, emphasis must be placed on establishing the rate of any active corrosion process at its initiation stage and secondly mitigating the corrosive process. This test consists of target investigations that determine the causes of deterioration in order to ensure that the right maintenance decisions are made at the right time. Traditionally this involves periodic, hand held, ‘pigging’ or fly-over readings being taken and logged. However, it could be argued that the periodic monitoring approach might not achieve the objectives of monitoring an oil pipeline system’s expected performance, because it neglects those defects that develop in the intervals between inspections. Therefore to monitor corroded and corroding oil steel-pipeline systems in real time for reliability, ageing status and the presence of incipient faults requires an integrated and distributed processing system involving vast amounts of data.

2.2.1 Differences between Monitoring and Diagnostics

There are differences between monitoring and diagnostics – for example, monitoring does not have the objective of detecting defects at their incipient stage. The basic function of monitoring the condition of components is to detect defects in them on time, and to classify their severity. This is assuming (1) that, at some point in time before failure, all defects are only units in a chain of defects, and (2) that at least one defect in this chain will significantly influence the oil steel-pipeline system’s integrity.

2.2.2 Fault Detection and Diagnosis Methods

What is evident so far from the literature review outlined in section 2.1 is that there are numerous studies relating to fault detection and the diagnosis of critical processes. Whilst the literature mainly relates to aircraft engines and rotating-machine fault detection, many authors – Willsky (1976), Isermann (1984), Frank (1987) and (1990), Basseville (1988) and Gertler (1988) – have argued that such fault detection and diagnostic methods could be applied to all engineering fields.

Isermann (1984) presents the application of fault detection and diagnoses techniques as a series of four steps, termed ‘process supervision’, which is a good reference model for describing many of the fault detection and diagnosis methods that have been developed for cooling equipment. Figure 2.6 shows the four-step process. It starts with fault detection, in which a fault is indicated when the performance of a monitored system has deviated from expectation. Diagnosis, the second step, determines which malfunctioning component is causing the fault. Following diagnosis, fault evaluation assesses the impact of the fault on the system performance. Finally, a decision is made on how to react to the fault. That decision usually includes a choice between tolerating the fault, repairing it as soon as possible, adapting the control, or stopping operation until the repair is complete (Comstock et al., 1999).

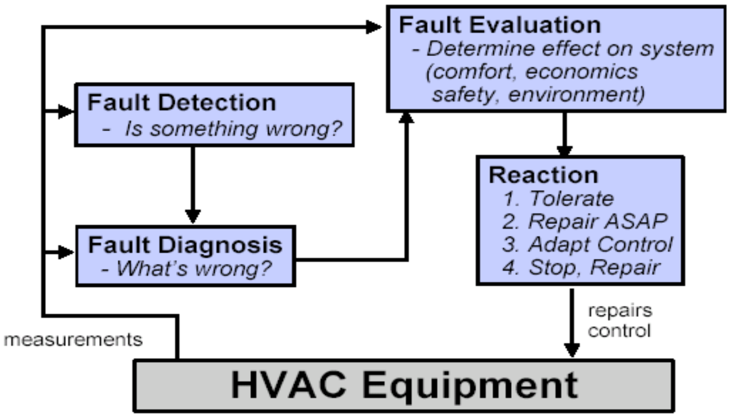


Figure 2.6: Supervision of Equipment (*Source*: Comstock et al., 1999)

In order to operationalise the model just described, it is necessary to define criteria or thresholds, in the form of appropriate outputs, for each of these steps. According to Comstock and colleagues, the outputs would be: fault or no fault for fault detection; the type of fault for diagnosis; and repair or don't repair for the fault evaluation step. In some solutions, fault detection and diagnostics are combined into one step.

2.2.3 Sequential Steps in Fault Detection

As regards fault detection, Comstock et al. (1999) wrote that this is accomplished by comparing actual performance, as determined from measurements, with some expectation of ideal performance. Hence, if the deviation exceeds a given threshold, a fault is indicated. The authors went on to explain that often this process is divided into two steps as depicted in Figure 2.7 below: pre-processing, and classification and reporting protocols. The pre-processor takes measurements from sensors and manipulates them to generate features for classification. Classifiers then operate on the features to determine whether the system contains a fault. The reporting protocol as proposed in this research relays the findings to the base station in the form of information and not raw data.

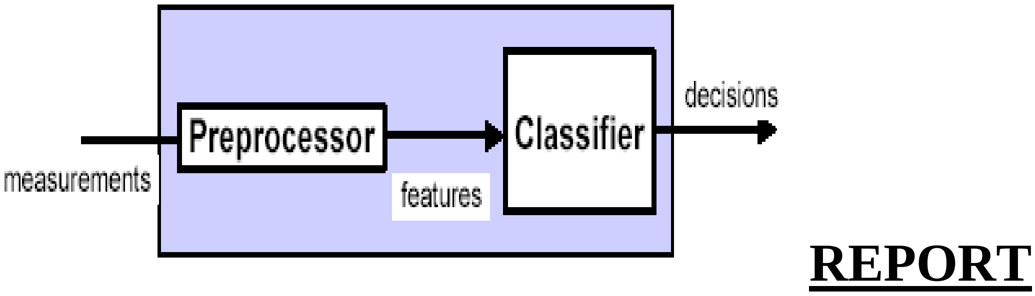


Figure 2.7: Sequential Steps in Fault Detection and Diagnosis

Furthermore, Comstock and colleagues (1999) employed three types of pre-processors: transformations, characteristic quantities, and models. ‘Characteristic quantities’ are features that are computed directly from measurements and are indicative of component performance. Examples include overall system efficiencies and heat exchanger effectiveness. Model-based pre-processors utilise mathematical models of the monitored system to generate feature model parameters that could be learned from measurements when the system is operating normally, or determined using physical models. Models can be categorised in terms of the types of performance indices; the classification can, for example, be categorised in terms of the structure, the model, and the types of dynamics.

2.2.4 Model-based Pre-processor

It has been a common practice that performance indices are often generated through model-based transformation techniques, physical parameters, innovations and characteristic quantities. A model-based pre-processor includes physical models and dynamic characteristics of an infrastructure such as the pipeline system under study. In contrast, a dynamic model includes steady-state models, linear dynamic models and non-linear dynamic models. The methods applied in order to resolve a specific processing problem would depend, firstly, upon how complex the problem is and, secondly, on the environment in which the problem exists. Comstock et al. (1999) proposed that the characteristics used by the fault detection classifier from a model-based pre-processor could differentiate between measured and modelled performance. For example, this study will apply physical parameters by modelling defect characteristics of an oil pipeline and any changes in its in-service performance as a result of simulated damage (a fissure).

Models that combine empirical parameters with some physic**s** are often regarded as ‘grey box’ models. Comstock and colleagues (1999) also pointed out that transients are often neglected in models used for fault detection and diagnosis. However, the use of steady-state models requires that the fault detection and diagnosis method has a steady-state detector to determine when the fault detection and diagnosis method is applicable.

Nonetheless, there could be other challenges, such as the stability of the model used, which could affect detection sensitivities, especially when the detection threshold is fixed. This has been empirically documented to result in greater sensitivities (detection of smaller faults), which will lead to more false alarms (an indication of a fault that doesn't exist). Heuristics are often used to determine thresholds even though more accurate predictions (a lower ratio of false alarms to correct diagnoses) have always been achieved when statistical thresholds are employed (Comstock et al., 1999).

2.2.5 Diagnosis and Classification Requirement

For many of the fault diagnosis approaches, measurements are processed in order to simplify the classification required to identify the particular component or system at fault. The overall classification problem is different for buried coated-but-corroding oil steel-pipeline fault diagnosis than general fault detection – in essence the decision is not simply binary (i.e., fault or no fault). The classifier must choose the specific defect type and size from a list of possibilities or logic. That said, the diagnostics problem could be reduced to a series of fault detection problems through fault isolation.

Fault isolation detection methods can be applied to individual components for which diagnoses are desired. For instance, the vibration signal profile from a pipeline rupture will be detected and the performance of the oil steel pipeline will be measured using its frequency spectrum. Thus the fault could be diagnosed as soon as it is detected, with no additional classification required by third-party analyses. The disadvantage of fault isolation is the large number of measurements required and the current fragmented and bulky equipment to make the measurement. Also, the diagnosis of oil steel-pipeline performance would require measurements of all relevant functions (flow/velocity/sound/vibration) related to fluid entering and leaving the pipeline section.

The general trend is that fault evaluation follows fault detection and diagnosis and requires an evaluation of the impact of a fault on the pipeline system's performance. It has long been argued that, without this step, the fault must become obvious enough to justify the expense of servicing the unit. The argument is always centred on the bottom line, i.e. profitability, and not on the causes of failures such as corrosion of the oil steel pipeline.

2.2.6 Summary

Undertaking monitoring, detection and diagnosis in order to predict a steel pipeline system's changes in performance requires assessment against specified operating conditions and failure modes. Usually, prior to construction new pipeline systems involve an analysis of the exposure environment, in order to assess potentially important deterioration mechanisms and to test the steel pipe for corrosion deterioration characteristics. For most existing oil pipeline systems it is likely to involve both automated inspection and some form of on-site non-destructive testing such as spectral vibration analysis.

The need to develop effective systems to monitor and evaluate the progression of steel pipeline deterioration characteristics can be considered crucial to addressing the built-environment industry's maintenance challenges. This, however, requires the development of new approaches that are able to deal with the limitations of the current fragmented systems in use. The new technology needs to be able to identify 'thresholds' and then interpret these thresholds as part of performance. This has not been done before for pipes, although initial testing has been carried out, and such an approach will form part of this thesis in order to develop an applicable model.

2.3 Failures and the Philosophy of Oil Pipelines

Crow (2002) writes that failure modes and effects analysis is the methodology for analysing potential reliability problems early in the failure development cycle, where it is easier to take actions to overcome these issues, thereby enhancing reliability by reducing downtime. However, failure modes and effects analysis is generally defined as a tool used to identify the potential failure modes within a process and to prioritise them based on their severity, occurrence and detection provisions.

This philosophy deals with 'fitness for service' analysis of the affected pipeline section, which is performed so as to evaluate the influence of defects on the pipeline system in order that performance degradation and structural safety are constantly evaluated, problems isolated and the cause(s) of the failure mitigated. The major causes of pipeline failures around the world are external interference and corrosion (Cosham and Hopkins, 2002), combined with the different age of the existing network and the climatic conditions in which the pipes are laid.

Defects induced by external interference and corrosion result in occasional failure and disruption of the fluid flow through the pipeline system. Cosham and Hopkins (2002) argued that there is no definitive guidance that draws together all of the assessment techniques, or assesses each method against the published test data, or recommends best practice in their application. However, the behaviour of defects in pipelines has been the subject of considerable study over the years. These studies have so far failed to establish the behaviour of corrosion defects that still remain the most common causes of damage and failure in both onshore and offshore pipelines systems. Generally, there exists a notion that pipeline failures are usually related to breakdown in the 'piping fabric' – for instance when the corrosion protection system has become faulty, as a result of a combination of ageing or failed coatings and an aggressive environment, and rapid corrosion leads to a pipeline system failure.

The main function of a steel pipeline is to host and transport oil from one location to another, and the only probable cause that is likely to stop the steel pipeline system from performing this function will therefore be some form of failure. Nowlan and Heap (1978) and Aladon (1999a) wrote that failed states are known as functional failures because they occur when an asset is unable to fulfil a function to a standard of performance that is acceptable to the user.

This definition does not, however, take into account the effect that partial failures may have on the asset, especially when the asset is performing at an unacceptable condition or level.

Based on the above understanding, failure could be said to be the inability of the steel pipeline system to meet a set of predetermined performance standards. This means that there are a set of expectations, which could be expressed both quantitatively and qualitatively.

Take a situation where a discharge pressure of a centrifugal oil pump is expected to operate within the threshold of 10 bars at 1000 litres per minute. In that instance the threshold has become the set standard as an acceptable performance for the centrifugal oil pump. In those circumstances, the discharge flow of that pump can be defined as between 999 and 1001 litres per minute at 10 bars. The expected performance threshold that the centrifugal oil pump needs to meet in order to be classed as capable is 999–1001 litres per minute at 10-bar gauge in order to transport the oil. This assumes that the condition of the oil steel-pipeline system is totally reliable in transporting the oil without loss of function and content.

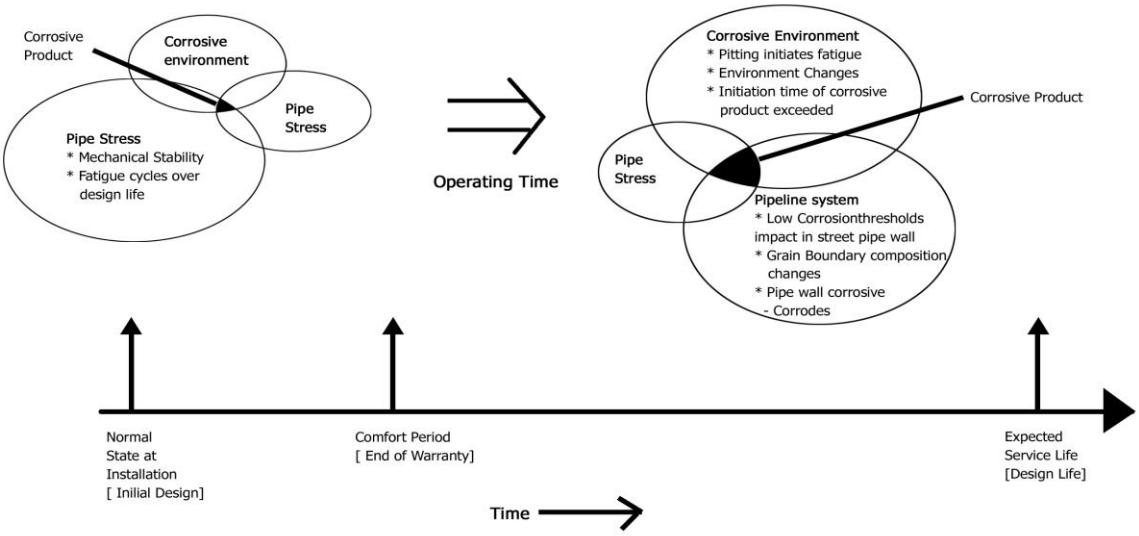


Figure 2.8: Schematic View of the Relative Importance of Corrosive Environment, Stress and Material to Determining the Life of Components over Time (*Source*: adapted and modified from Staehleconsulting.com, 2000)

In the broadest sense, a pipe has failed if it can no longer carry its intended flow from one end to the other without losses in pressure, volume or quality (Makar and Rajani, 1999). Further, Makar and Rajani argued that pipeline systems exhibit a high failure rate during their initial period of operation, that the most problematic and expensive pipe failures tend to be those associated with pipe fractures, and that most failures due to corrosion usually occur after the warranty period. See an example in Figure 2.8 above.

2.3.1 Potential Failure and Cost Arguments

There are some economic arguments against oil pipeline systems' fitness to perform that are often based on potential failure. In practice, most in the industry agree that the cost of maintenance and rehabilitating a pipeline system should be proportionate to the problems that are being addressed. Although the cost of rehabilitating a pipe may be greater than the cost of an individual repair, because repair often includes direct, indirect (insurance) and social (compensation) costs, rehabilitation or pipe replacement may often be a better long-term solution to a problematic oil pipeline than simply continuing to repair it in accordance with the maker's failure analyses. Nonetheless, the high costs of rehabilitation and replacement mean that oil industry managers need to be able to prioritise specific areas of their oil pipeline systems for renewal.

Priority setting has often been based on the past failure history of the local pipe section, with sections that reach a certain number of failures per kilometre per year being considered for replacement. However, oil pipeline failure analysis can in certain cases provide an alternative method of condition assessment that can assist in making renewal decisions more objective. Moubray (1997) used potential failure (P-F) interval to highlight two prerequisites of condition-based maintenance, namely (1) a clear indicator of decreased failure resistance, and (2) a reasonably consistent warning period prior to functional failure. Both requirements are captured in the well-known empirical graph of failure resistance versus working age (see Figure 2.9).

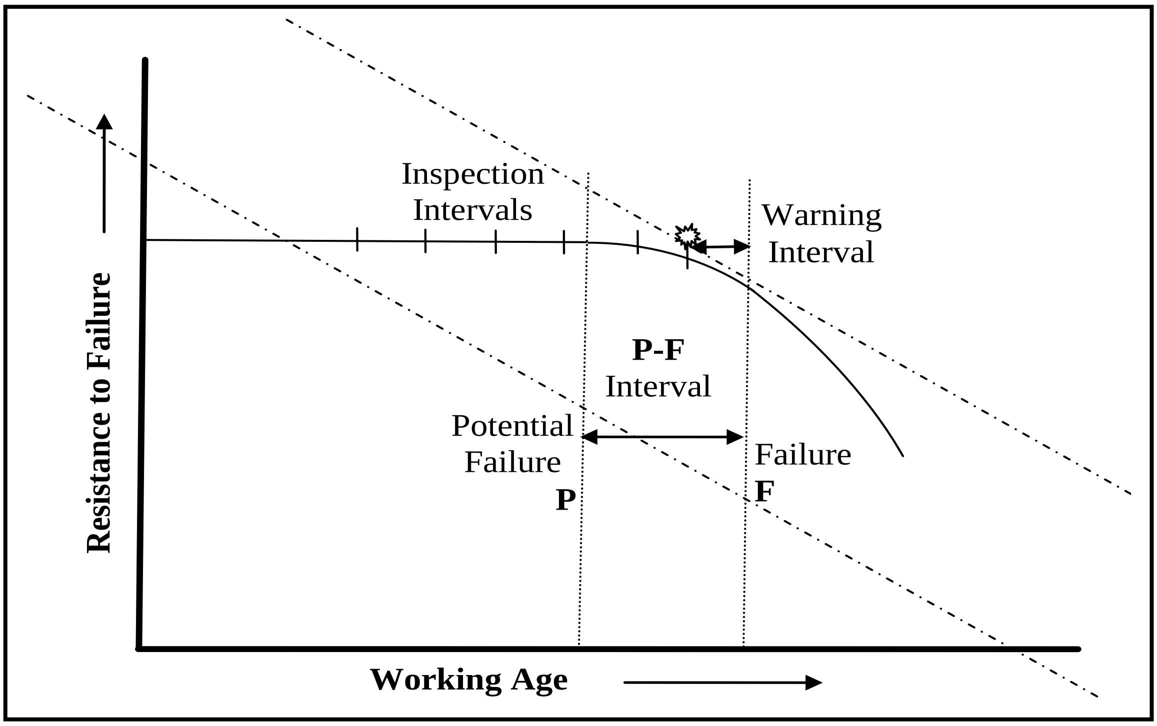


Figure 2.9: Moubray–RCM P-F Curve (*Source*: Nowlan and Heap, 1978)

However, the P-F interval technique has been widely criticised by some authors (Wiseman and RCKnowledge.com, 2002; Nowlan and Heap, 1978) as a deceptively simple idea for the fact that it takes for granted that the potential failure (P) has previously been defined. Wiseman of RCKnowledge.com argued that it is the value of P that poses the greater challenge – emphasising, therefore, that before the P-F interval is addressed, there is a need to determine when and how to declare a potential failure.

The above argument implies that Figure 2.9 could be adopted in essence to monitor a condition indicator that tracks resistance to failure, and makes the potential failure level manageable. However, that in itself gives rise to two unfortunate obstacles to implementation of the P-F interval technique; firstly, a single condition indicator that faithfully tracks the resistance-to-failure curve is rare; secondly, the resistance-to-failure curve itself is rarely available to support condition monitoring data, which are often in abundance as raw data but which in terms of performance information are valueless. However, these obstacles could be overcome if a good knowledge of the pipeline system in-service performance can be obtained.

This knowledge is very important to this thesis in that what is required is the development of a new approach to maintenance planning that provides in-service performance information instead of volumes of useless data. The fact that continuous monitoring could establish the ‘in-service performance characteristic’ from which P and F could be derived is pivotal to this research; in that an objective performance-based maintenance methodology could be used to predict the severity of faults on buried infrastructure and utilities such as the oil, gas and water pipeline subsystems.

2.3.2 Understanding Why Failures Occur

According to Staehleconsulting.com (2001), the range of environments over which materials are reliable is relatively narrow; good corrosion resistance in one domain is not a good indicator for another. Therefore, following well-established specifications, codes and standards do not prevent failures, nor does creating corrosion thresholds act as a guide to estimating fault severity. For example, it is widely documented that high-performance alloys such as stainless steel, high-strength steel, and titanium are among the most failure prone of materials. While such materials can perform well, they often fail catastrophically (Corus.com, 2001; Staehleconsulting.com, 2001). The conclusions reached are that in hazardous operations, failure modes and effects analysis does not prevent failures; moreover, unless the necessary inputs and analysis parameters are integrated into one device that could report any changes in performance continuously without third-party assistance, maintenance monitoring and assessment method will still remain static.

2.3.3 Causes and Modes of Failure

‘Causes’, according to Staehleconsulting.com (2001), are what is fixed and are usually institutional. Examples in this context include design bases, lack of failure definition, inadequate inspection, inadequate monitoring, lack of systematic approach or location for analysing prevailing conditions, ‘penny wise and pound foolish’ design choices, non-critical dependence on prior field experience, designing with only warranty objectives in mind, and basing a ‘40-year lifespan’ on fatigue analysis alone.

‘Mode’ is defined as the process by which failure occurs – for instance, chloride enters a system and the stainless steel fails. In this case, chloride is not the cause but part of the mode (Staehleconsulting.com, 2001).

It is necessary at this stage to **c**haracterise steel pipeline failure into four areas:

- **Primary Failure –** when corrosion attacks the steel pipe first and then causes secondary failures such as a leak. Primary failures can usually be detected and monitored before they fail catastrophically; however if they are neglected, eventually secondary failure may result, destroying the metallurgy components and the pipeline network.

- **Failure Investigation** is the analysis of why the condition of the steel pipe deteriorates. It is as deep into the causes of failure as root-cause failure analysis. As a result, the probability of an inaccurate diagnosis may increase and result in failure.

- **Fracture Face** is a splinter on the exposed surface of a pipeline where failure actually emanates. Most information about a failure is contained in the fractured surface, which is the area of metal exposed when the fracture takes place (Makar and Rajani, 1999). This requires thorough analysis to find out why a steel pipeline failure occurred, and the analysis may be extended to the human and management systems that allowed the failure to happen.

- **Stress Concentrations** applies to the corroded steel pipeline’s physical features that cause the apparent local stress in a part to be greater than the average across the pipeline section. They can result from changes in shape, from defects, and from changes in metallurgy, and each can increase the local stress tenfold (Sachs, 1993). Each of these defects has similar effects on a pipe, reducing the overall thickness of the pipe wall and lowering the pipe’s strength. Thus changes in performance may occur.

2.3.4 Types of Failure

Based on the above, it would be reasonable to say that the failure characteristics of a buried oil steel pipeline, or any component for that matter, could be described in several ways. One way (Alfredsson and Wååk, 2000) is to use a continuous random variable and the time to failure of the component. The time to failure for the pipeline system can be approximated by exponential distribution with parameters set out according to the deterioration stages (e.g. incipient/small, medium, large and total failure/leak). The time to failure relates to the theory of interval probabilities (Weichselberger, 2001), which can be applied as it allows the upper and lower limits to be modelled in a very wide variety of rules (such as uncertainty, partial information, and ignorance). The rules used in the theory are based on a general procedure called ‘natural extension’ (or optimisation) and can be applied to various measures. The arguments relating to a continuous random variable and the time to failure of the component are only valid if identical failure characteristics are assumed for all individuals of a given component type; however, this may not always be the case. Therefore, the properties of the random variable could be described in several equivalent ways.

Alfredsson and Wååk (2000) went on to state that it is unrealistic to assume that the component failure process is known. At best, the intrinsic failure properties of oil pipelines, or any component within them, could be evaluated under certain operating conditions. As indicated above, the true failure process depends mainly on other factors – for example, preventive maintenance. It is generally accepted that preventive maintenance affects the failure properties of components, although it is debatable whether this is in a positive or negative direction.

In this vein, therefore, different analysts have always used different systems. However, the most practical way for maintenance operations to categorise buried oil steel-pipeline failures has always been by overload, fatigue, corrosion-influenced fatigue, and wear. Take, for instance, the argument by Sachs (1993) that the application of a single load will cause the affected section of buried steel pipeline to deform or fracture as that load is applied. Sachs argued that the deformed section of a buried steel pipeline may abruptly fail over time, resulting in expensive maintenance/refurbishment action being taken (see Photo 2.1). The facts are that simply knowing that deformations exist along a pipeline section is not enough to justify a maintenance intervention. Load fluctuation in essence is under-performance, which in itself is a symptom and not the cause of an abrupt failure.

As with other failure contexts, it has always been assumed that a pipeline system has a constant instantaneous failure rate (as it is commonly referred to) on the underlying assumption that the distribution for time to failure is an exponential distribution. However, this is not always the case; Alfredsson and Wååk (2000) argued that such an assumption is rather unfortunate because it might lead to confusion. They further explained that by ‘a rate’ is meant the number of occurrences per time unit, which has a straightforward physical meaning, while the function is defined as a conditional probability per time set and this is clearly a more theoretical quantity. Therefore, although a constant failure rate could mean that the number of occurrences per time unit does not vary over time, it normally means that the conditional probability of failure per time unit is constant**.** This is not surprising as the technique is a mathematically based model that does not often agree with reality. It should be mentioned that corrosion and wear mechanisms and processes are complicated subjects and beyond the scope of this research, where the performance assessment of corroded or corroding oil steel-pipeline sections is the main focus.

Photo 2.1: Repair and Rehabilitation of Pipeline Facilities (*Source*: ACT-COSMI)

2.3.5 Failure Modes and Effects Analysis

Failure modes and effects analysis has been a requirement in aerospace and military projects for many years. Its aims are to predict the consequences of failures in complex systems by identifying the failure characteristic of an individual item in a system, and determining failure effects on the rest of the system.

Generally, in a given pipeline, failure may occur due to several apparent causes and may be initiated only in a very small section of the piping system. As a consequence it has not been practical to determine an actual probability of a failure event at a specific location in real time with currently available technologies. Indeed, the literature review has shown that the currently available technologies are not capable, and are third-party dependent, which also has limitations in itself.

Sachs (1993) wrote that fatigue is the primary failure mode for more than 90 per cent of mechanical failures. The term ‘fatigue’ originated during the 1800s when it was thought that metal parts failed because, like our muscles, they grew tired after long use. Sachs intimates that fatigue failures are caused by repeated stress cycles, further asserting that there are four stress fluctuation points (or wear mechanisms) that need to be understood**:**

- Without stress fluctuations fatigue cannot happen.
- Fatigue happens at stress levels well below the tensile strength of the material.
- Where corrosion is present, the fatigue strength of metals continuously decreases.
- A fatigue-induced crack takes measurable time to progress across the fracture face.

Based on these understandings, Sachs (1993) argues that interpretation of the failure face can disclose the forces that caused the defect and crack, and also the amount of time it takes from defect initiation to final failure, making it possible to evaluate the relative size and the severity of stress concentrations. If this argument is true, then one could say the defect evaluation on coated buried oil steel-pipe failures is particularly complicated.

The precise ratio of the failure modes in a given buried oil steel-pipeline system is dependent on the local soil conditions, external loading and pipe diameter. Circumferential breaks are the most common failure modes in small-diameter pipes, with longitudinal splitting and corrosion ‘through holes’ the most common in larger diameter pipes (Makar and Rajani, 1999). In view of the facts that pipe systems comprise sub-components that can also wear out during use, it will be vital to define pipeline failure within specific bounds and within specific tolerance limits, as early failures may come from poor design, improper manufacturing, or inadequate protection and use.

The forces that produce oil steel-pipeline failures include; corrosion, internal pressure, frost loading in northern climates, clogged pipes, truck loading, thermal stresses due to differences in ground and water temperature, the compositions of the crude oil, bending due to poor bedding, and the forces produced by expansive clays (ASTPM, 2001). The connection between these forces and the failure modes is well established in the oil facility maintenance industry, notwithstanding that they are still of research interest. In order to apply this knowledge, it is useful to understand the nature of failure mode by first examining the following:

- the failure in relation to the required performance standards, i.e. critical, degraded and incipient failures;
- the significance of the operating context;
- the use of failures as a method of control of the pipeline system process;
- the role of maintenance in restoration of desired performance;
- incipiency and its use in condition-based maintenance; and
- pipeline system-level failures.

Evidence shows that failure modes and effects analysis could provide the maintenance engineer with a tool that can assist in providing safe and reliable maintenance processes. Crow (2002) suggests that failure modes and effects analysis helps to identify potential component/built-asset fabric or process failures and it could also be used to:

- develop product or process requirements that minimise the likelihood of those failures;
- evaluate the requirements obtained from the customer or other participants in the design process to ensure that those requirements do not introduce potential failures;
- identify design characteristics that contribute to failures and design them out of the system or at least minimise the resulting effects;
- develop methods and procedures and test the product/process to ensure that the failures have been successfully eliminated;
- track and manage potential risks in design, as new build contributes to the development of corporate memory and the success of future products; and
- ensure that any failures that could occur will not injure or seriously impact the customer or the product/process.

A failure mode in one component can serve as the cause of a failure mode in another component (Crow, 2002). Crow further argues that each failure should be listed in technical terms and for functions of each component or process step, in that the failure mode should be identified whether or not the failure is likely to occur. Crow notes also that lessons should be learned from similar components, subsystems or processes and the failures that have been documented about them is an excellent starting point.

In this thesis it is argued that these steps may describe the effects in terms of physical condition but do not in any way describe the effects of those failure modes in terms of current performance – nor does the simple notion that each failure mode identified should be used to determine what the ultimate effect on in-service performance will be on the built asset or its fabric.

Drawing from the definition of failure effect and failure mode, the issues highlighted below could be described as a tool to develop performance standards or practice:

- break and leakage (causing environmental disaster and injury to wider life);
- inoperability of the pipeline system;
- improper appearance of the pipe or valve (corroding/scale formation);
- fumes and odours;
- degraded performance of the pipeline system; and
- noise.

2.3.6 Potential Failure Modes

An initial step in this process would require the creation and development of a model, and devices for monitoring the corrosion process. The model should describe a buried oil steel pipeline's physical condition as blocks connected together by lines that indicate how the pipeline system's performance is related. Any deviation could be deemed as a change in performance. Sections 2.3.3 to 2.3.5 above have highlighted the required logical relationships of a pipe system's process of corrosion and the need to establish a structure around which the failure modes and effects analysis could be developed. These relationships will be used to further establish a coding system to identify system failures. The model also usually gives scope for listing the different ways a pipeline system might fail to meet the transportation requirements or design intent in light of the assessment of its physical condition.

The potential effect(s) of failure then documents how the failure could be perceived. Each of the failure modes and effects is assigned a Severity Value (SEV), and Classification (CLASS) which is a non-mathematical value comparable with elements in neural-fuzzy logic.

According to Crow (2002), how the failure could occur should be described in terms of something that can be corrected or controlled and listed under potential causes and mechanisms of failures. In that way the probability that a given failure model might occur can easily be assigned a numeric value. However, statistical techniques for state and parameter estimation often face convergence and accuracy problems when dealing with models that have strong non-linearities (Rosenberg and Karnopp, 1983; Narasimhan et al., 2000). So it would be preferable to apply an artificial-intelligence-based non-mathematical model comparable with self-learning and execution.

2.3.7 Summary of Challenges

A literature review suggests that steel pipeline corrosion is a normal and natural process that can seldom be totally prevented. The review has indicated that various types of techniques are regularly used to monitor, control and protect a steel pipeline from corrosion. However, there are inherent obstacles to be overcome in applying the existing condition-based maintenance approach – not least, the accessibility to information and physical site as a result of fragmented technology. Thus the key challenges are the development of signal processing techniques (incorporating artificial intelligence with communication protocols) to monitor, analyse and report on a steel pipeline's condition and its associated changes in performance. This is a complex task combining many challenges, some of which are still subject to further research (e.g. hardware- and software-related issues). However, many such complex tasks can be resolved by integration of the P-F interval and curves with Jones's (2002) re-interpretation of Finch's modified obsolescence model in an intelligent device capable of self-learning.

The P-F interval technique has been criticised in that it is a deceptively simple idea and for the fact that it takes for granted that the potential failure point (P) has to be defined before application, hence posing the greatest challenge. It is important to realise, therefore, that before addressing the P-F interval, there is a need to determine when and how to declare a potential failure. In declaring a failure, account must be taken to predict the consequences of failures in complex systems by identifying the failure characteristic of an individual item in a system, and determining the failure effects on the rest of the system.

2.4 Types of Pipeline Failure

Pipeline systems can fail as a result of many causes. Some of the most common failure modes are corrosion, pitting, stress corrosion cracks, seam weld cracks, dents, and other flaws induced by external impact from earth-moving equipment. Ideally, it would be desirable to detect all the defect types with a single inspection method; in essence there are currently no such inspection methods capable of doing this. Therefore there is a great need for a way to identify cracks, corrosion and other defects that can potentially cause problems for pipeline systems.

2.4.1 Steel Corrosion Can Occur Beneath Detached Coatings

Generally there well-established knowledge about what ‘condition assessment’ of a steel pipe and its coating involves – from simple observations of flakes, scaling or cracks, to ultimate failure. In this view, condition assessment of an in-service buried coated oil steel-pipeline system must take into account problems such as corrosion that can occur beneath detached coatings; which can impose a serious threat to the pipeline even with the application of cathodic protection.

What is not apparent is what performance measures of the steel pipe could be attributed to poor condition. One key question is how the maintenance process is trying to stop the deposition of corrosive products on the steel pipeline from getting through the protective layers (see Photo 2.2). Crack growth that is covered by a thick layer of corrosion deposit could result in the crack reaching the critical depth for unstable propagation.

Again, one might ask how many of the techniques in use today can detect damage at the incipient stage, since most industrial applications are only retrospective and where the detection work is often carried out after surface fracturing has occurred. However, because preventing failures is vital, it requires that an objective maintenance process be developed, (Fuhr et al., 1995) because most cracks often have depths that consist of more than six cycles of growth events that can be seen, and well-defined visible surface markings that produce acoustic emissions during growth that makes them easy to detect with technology. Nevertheless, it is acknowledged that the presence of corrosion products is one of the symptoms of the deterioration process.

Photo 2.2: Corrosion is Shown Beneath Detached Steel Pipe Coatings

Corrosion of steel pipes results in cracks and leakages, and therefore a reduction in the pipe's ability to transport oil during the useful lifetime of the pipeline system. It has also been established (Fuhr et al., 1995; Hudachek and Dodd, 2002) that, in general, corrosion is time-related whereas fatigue and crack growth are cycle-related. However, both produce the same result, namely a loss of physical strength of the oil steel-pipeline system and consequently a change in performance.

Chajes et al. (2002) contend in their studies that the current methods for steel corrosion detection suffer from several significant drawbacks of fragmented efforts and that incessant detection, sensing and reporting of corroding steel status is required to identify a corrosion attack in its early stages. Hudachek and Dodd (2002) wrote that steel corrosion performance-related studies must be classified into three main categories: performance concepts; setting performance requirements; and performance specifications and criteria. Consequently, an appropriate maintenance strategy (e.g. responsive or preventive) can be identified and developed that considers the consequences of steel pipe failure (measured against performance criteria) in real time.

In summary, detection of a buried oil steel-pipeline deterioration process relies heavily upon techniques that can accurately and reliably sense, analyse and report these effects without third-party intervention. It is crucial that non-destructive examination techniques should have sufficient sensitivity to distinguish defects resulting from steel corrosion at an early stage. Performing a broad range of pipeline integrity analysis and testing generally requires the application of different techniques, such as modelling and analysis software, inspection tools, and a wide array of full-scale and laboratory testing facilities. Developing a new and comprehensive approach to maintenance planning that can continuously monitor, analyse and report any changes in performance of buried steel pipelines is necessary.

2.4.2 Monitoring of Oil Pipelines

It is evident today that crude oil extraction is increasingly located in remote areas, and transmission pipeline installations are getting longer and often pass through extremely inhospitable terrain. However, the economic viability of such an operation requires considerable reductions to be achieved in the capital and operational costs of these long-distance pipelines. Therefore an integrated-device-on-microchip solution that detects, analyses and reports on pipeline performance without third-party assistance is suggested to assist in meeting these cost reduction needs.

Sherwin (2000) and Tsang (2002) have written that built-asset maintenance is viewed by most organisations as a cost burden in which demand for action, identified via an assessment of the condition of the asset, invariably exceeds the funds available (see also Pitt (1997) and Shen (1997)). It was argued that in order to track and monitor defects within a system even in good times, organisations demonstrate a reluctance to spend money in order to preserve the condition of their assets (Chew et al., 2004). Hence, assets fail to be kept to their optimum operating capacity and functional performance, which ultimately leads to a spiral of decline and disrepair (Arditi and Nawakorawit, 1999). As such, an obsolescence gap develops in which the asset is unable to meet all the demands placed upon it.

Since the late 1800s, steel has been the material of choice for virtually all pipelines and tanks. However, pipelines are also inherently vulnerable because of their number, inaccessible operational environment and dispersion. Generally, pipeline operations have long been concerned with maintenance access and administrative barriers; often, landowners deny rights of access for pipeline restoration to locations where an oil leak is suspected, yet a lack of access for an integrity survey could result is crucial risks to the pipeline, environment and humans. Indeed, the fact is that higher operating pressures associated with oil steel-pipeline systems ensure that once a leak occurs, it will continue to leak until it is detected and repaired. These problems have both operational readiness and environmental implications, so technology that would allow for continuous evaluation of a pipeline’s condition is urgently needed.

The oil industry, like other pipeline operating companies, faces increasing public pressure and scrutiny to proactively maintain assets so as to ensure safe and environmentally responsible operations. Usually, the oil industry response has been to assign more resources and conduct costly direct assessment (such as inline inspection, corrosion surveys and investigative digs) across their asset base.

Apart from physical access to pipe location, there are other complications. Predictive maintenance models require current, accurate data that are not often readily available. However, as stated above, pipelines are operated across vast geographic areas and this often complicates work processes and delays the transfer of information between workers and the central database and vice versa. Moreover, the information required for maintenance decisions is often kept in several separate locations (or systems), and this could undermine and impede timely access to maintenance information and the ability to make effective decisions (Moss, 1985). Pipeline deterioration and repair actions could be performed more effectively and efficiently if maintenance technicians were provided with a system that could monitor changes of performance continuously and relay this information prior to failure. Such a system would provide information to cross-reference and review if possible how previous failures were diagnosed and repaired. The maintenance industry has been under pressure to reduce downtime. Pipeline downtime affects oil industry productivity by reducing output and increasing operating costs. However, no techniques or philosophies are capable of preventing all failures, and unexpected failures do occur, which leads to corrective maintenance and in some cases to high levels of downtime (Moss, 1985).

Given the diversity of environmental conditions and locations that cover millions of square kilometres, often with restricted access to the infrastructure to carry out repairs and maintenance; the application of an integrated-device-on-microchip solution on a buried pipeline system can help to continuously monitor any changes in performance – reduced downtime most importantly preventing pipeline system failures. Also, through the provision of in-service information, it should be possible to identify when changes in performance occur. It is crucial, therefore, that access to pipeline system information, operating conditions, and defect characteristics (if possible geographical location and serial numbers) should be available for repair reference, which is not always the case.

2.5 Assessment and Testing Techniques

2.5.1 Vibration and Acoustic Emission Monitoring

Vibration and acoustic emission monitoring is a real-time non-destructive testing (NDT) technique able to identify, control and characterise the changes in vibration and acoustic emissions activity as a defect increases from its initiation stage to its critical stage (ASTM, 1998). The methodologies have been successfully utilised for testing both composite and metal structures (ASNT, 1987); Pollock, 1989; Vahaviolos, 1996). The vibration and acoustic emission monitoring technique is versatile; hence it allows for the inspection of large and complicated infrastructures using only a few sensors and without the need for pigging/scanning or requiring access to the interior of the structure. However, there is a great need for technology that can identify cracks, corrosion, and other defects that can potentially cause changes in performance (Umeadi and Jones, 2003).

Some types of pipeline defects pose serious threats to human safety. Stress corrosion cracking, for example, can occur at any time in the life of the pipeline, and it occurs under a broad range of field conditions. This type of defect is usually oriented along the axial (lengthwise) direction of the pipe. If not detected early, the cracks may grow and/or coalesce, eventually resulting in a leak or rupture of the pipe. Although the literature has established that not all defects that develop in pipelines threaten the integrity of the pipeline system (e.g., internal inclusions such as linings are common and do not pose a serious threat to the integrity of the pipeline if they fail), NDT systems are urgently needed that can (1) provide early detection of the more serious defects; (2) differentiate between serious defects and benign inclusions; and (3) characterise the type and size of the defects for repair or replacement management.

Acoustic sound is general accepted across the different industries to mean pressure fluctuations through an elastic medium. The acoustic signal generated by a leak will travel together through both the pipe wall and the water column in the pipeline (Howley-Chastian, 2005). According to Kinsler et al. (2000), the speed of sound in seawater is roughly 1,500 metres per second, although the speed can vary with changes in temperature, salinity and pressure (unlike speeds in a pipe). It has generally been established in physics that moving objects and waves transfer energy from one location to another. They also transfer energy to objects during interactions, e.g., sunlight transfers energy from the Sun to the Earth when it warms the ground. The basic measurement of most sonar systems is the time it takes a sound pressure wave, emitted from some source, to reach a reflector and return. In essence, sound is a form of energy that is transmitted by the interaction of air molecules (on land or sea) one against another. When it propagates from a source, it sets up pressure variations in the surrounding air. These are very small variations when compared with atmospheric pressure, which is approximately 100–105kPa (kilopascals). The audible range of sound pressure variations is wide; it ranges from 20 micropascals at the threshold of hearing to 100 pascals at the threshold of pain. It can be seen that the max/min ratios involved are large. For example, from the threshold of hearing to the threshold of pain the pressure ratio is about five million to one (Bellhouse, 2004)**.**

The NDT methods described in this chapter concern waves – both mechanical and electrical in form – propagating through a corroded buried oil steel-pipeline system. In order to ‘sense and detect’ defects to failure in the oil steel pipe, the length of the vibrating sound wave is expected to be of the same order as the dimensions of the defects (Agarwal and Bull, 1989). This means that the wavelengths used in the investigations of corroded buried oil steel pipeline must be around a few millimetres (similar to the size of corrosion defects or cracks). The types of defects can be categorised in different ways: local defects are concentrated in space within a volume of a few cubic centimetres, which may occur inside-outwards or outside-inwards; ‘global’ defects are those distributed through the corroded buried oil steel pipeline occupying larger volumes.

The literature on the propagation of mechanical waves and their application to steel infrastructures is vast, and to some authors such as Aki and Richards (1980) they are also mathematically demanding. A series of studies was conducted (Graff, 1975) on waves in steel in various forms: rods, plates, beams, shells and other engineering elements. According to Yan and Jones (2000), there are no measurement standards for estimating the absolute strength of an acoustic emission source, and the literature review conducted for this thesis did not come across any similar works that have used propagation techniques to detect changes in performance of a steel pipeline system. Moreover, the lack of standardisation for estimating the absolute strength of acoustic emission sources makes it very difficult to compare the results obtained in different laboratories or on different infrastructures, thus limiting the chances of meaningful repeatability of measurements.

Some of the typical known applications in the literature of acoustic emissions are to:

- detect and examine material and structural defects (Yan and Jones, 2000);
- monitor defect growth or micro-damage progression (Hamstad, 1986);
- detect leaks (Wadley et al., 1981);
- assess differences caused by manufacturing variations (Sypeck, 1996);
- study fundamental deformation behaviour and failure of materials; and
- monitor in real time certain manufacturing processes, including proof tests.

It has been documented (Wadley et al., 1981; Hamstad, 1986; Madhuka and Awerbuch, 1986; Sypeck, 1996) that many failure processes are accompanied by detectable acoustic emission. Early investigations of this technique include those of Baerg and Schertz (1967), Wadley, et al, (1982), Scruby, et. al., (1978); more recently, a number of investigations have reported on acoustic emission waves in pipes: Agarwal and Bull, 1989; Sypeck, 1996; and Liu et al., 2000. A number of these endeavoured to locate and/or differentiate one source type from another (Madhuka and Awerbuch, 1986; Bakuckus Jr et al., 1993). Recorded acoustic emission signals parameters, such as source rise-time, threshold counts, signal amplitude, energy, duration, frequency spectra and others, were used to ‘characterise’ the acoustic emission events by Hamstad (1986) and Sypeck (1996). These studies drew attention to the fact that many of them have relied upon ad-hoc empirical methods using instrumentation that could not faithfully reproduce important characteristics of the acoustic emission signal. The conclusions of these studies are also questionable since they did not use models. It is therefore very difficult to establish the relationship between damage micro-mechanisms and acoustic emission signals. On the other hand Sypeck (1996) also drew attention to the fact that **“**if such problems could be overcome, an acoustic emission approach based upon fundamental principles promises to reveal much new insight into damage processes.**”**

In order to use vibration sound functions to obtain natural frequencies of damaged or corroded oil steel-pipeline systems with an inbuilt processor and reporting protocol, the device has to integrate the different components and relevant theories outlined here.

2.5.2 Vibration Diagnostics Methods

Vibration noise is a natural process in pipelines and equipment. It is interesting to note that the same dynamic forces that excite different materials and components (including steel pipeline systems) are also responsible for their wear and tear. It is these dynamic forces that transform from one state into another at the point where gas and solid states converge (Barkov and Barkova, 1986).

The theories for using vibration analysis across different industries are classified under two important notions in relation to pipeline condition assessment:

1 The fundamental principles of vibration monitoring is characterised as observing the changes in the pipeline system vibration condition and making an analysis of the reasons for these changes.
2 Vibration diagnostics pinpoints when defects in the controlled objects are detected and identified; including the defect type and severity.

Like acoustic emission, it is the oscillation velocity that is responsible for the transformation of vibration into noise. When the inflationary pressure in the air is proportional to the velocity of the oscillation surface, it results in a rule that limits the oscillation velocity (of any machines or equipment, in fact) (Barkov and Barkova, 1986). The theory differentiates practical problems of vibration control and vibration diagnostics, in that with diagnostics the oscillation force that is applied to the defective zone defines the defect’s signal in relation to the oscillation measured. (Models of different data shapes exist for damage cycles: absence of defect, increasing defect and severe defect.) Decisions are taken from a measured block vibration signal; hence the diagnostic method is based on pattern recognition. With diagnostics, more often the vibration acceleration is measured, while the vibration velocity is measured additionally for machine vibration control within restricted low-frequency ranges.

As an NDT technique, piezoelectric sensors are widely used for most vibration acceleration measurements, since output of the electric charge is proportional to the force that is applied to the sensor. Microphones have different methods of converting the sound pressure into an electric signal. For example in some diagnostic environments, directional microphones are used to detect noise emission sources and directions. According to Barkov and Barkova (1986), it is possible to conduct remote vibration measurement of any object using a microphone (e.g. the value of a vibration velocity).

It is generally agreed that electrochemical noise is an essentially random phenomenon of spontaneous fluctuations of freely corroding electrodes that manifests itself as current or potential noise (or sometimes referred to as ‘background noise’). This is expected to occur even under normal laminar conditions. What is not certain at this stage is whether or not the noise produced by the spontaneous fluctuations (i.e. the corroding process) can be measured and analysed in order to establish a relationship between the noises and buried steel pipeline’s underlying performance process. According to Fuhr and Huston (1998), corrosion is, after all, an electrochemical process that occurs as ions are introduced to, or removed from, an area of material – the potential and current characteristics at that location change most often at low frequency (of the order of 1Hz is widely published). This electrochemical noise can be classified into three categories (John et al., 1992): noise originating from thermal agitation of charge carriers; noise caused by the charge being transferred in discrete amounts; and noise arising from other phenomena.

It is also noted that the charge carrier effects contribute to noise whose spectral density is the amount of noise present in a given bandwidth. This argument contends that the noise spectral density is often at a low amplitude and essentially constant over a wide range of frequencies.

It has recently become possible to measure corrosion, and the noise field associated with its formation, by two related but distinctly different approaches. These approaches provide information as to the location, rate and degree of corrosion on a substrate. The results from electrochemical noise analysis could be in good agreement with established potential mapping techniques (Fasullo, 1992). For most corrosion measurement approaches, the potential noise of a defect signal can be monitored relative to a low-noise reference electrode, thereby enabling the defect signals between a pair of identical electrodes to be measured.

Probabilistic approaches are used for estimating pipeline integrity. According to Khaleel et al. (2000), probabilistic methods attempt to predict safety using crack rate-of-growth data, inspection data and the operating parameters of the pipe. It nevertheless requires valid statistical data on defect rate occurrences and distributions to be of any real use. Therefore to a non-statistical method for collecting accurate data on the actual condition and performance of an oil steel-pipeline system in service is needed.

The two predominant methods of testing the integrity of pipelines found in the literature are destructive inspection and non-destructive testing (the latter sometimes being known as non-destructive inspection (NDI) or non-destructive evaluation (NDE)). The non-destructive testing technologies are methods for the detection and measurement of corrosion and characterisation of mechanical damage and include:

- magnetic flux leakage;
- eddy currents;
- non-linear harmonics;
- ultrasonic technology;
- magnetostrictive sensing;
- real-time digital radiography;
- data analysis and display;
- shearography.

The two most common NDT methods for testing pipelines are the magnetic flux leakage method and the ultrasonic guided-wave method. Magnetic flux leakage such as ‘pigging’ is a commonly used method for inline detection (i.e. using an area on the inside of the pipe wall) and characterisation of pipeline corrosion. ‘Smart pigging’ (using NDT technology), used for the assessment of the strength of corroded pipes, is often based on estimates of corrosion depth (based on leakage data).

Using an onboard power supply and data-acquisition system, the pig records defect data while moving with the oil flow through an operating pipeline. These traditional assessment methods consider pipeline hoop stress (from internal pressure of the flowing medium) but do not account for local pipe-wall stress components due to bending or axial loading. Like most technologies, pigging may be said to have some limitations – mainly because it requires a well-founded knowledge of how pigs perform under varying conditions, of pipeline fittings and equipment, of the time interval between inspections and of physics to successfully identify the true problem. Most importantly, pigging assessment involves non-continuous monitoring and therefore faults can be missed in the intervals between inspections.

2.5.3 Destructive Inspection

Generally, an oil steel-pipe destructive inspection procedure uses a hydrostatic technique to verify that the pipeline integrity is within the safety margin for operation. The procedure does not, however, locate defects that are just below the threshold of safety. Unfortunately, a destructive testing methodology of this kind disrupts the oil pipeline system's normal daily operation, and consequently it is probably right to say that destructive testing is not the preferred approach in the industry at large. Usually, such techniques are only used for the initial inspection of pipelines before they are commissioned.

2.5.4 Summary

In contrast with destructive testing, non-destructive testing methods can detect developing defects that could lead to steel pipeline system failures, and so such methods can provide a quantitative measure of the integrity of a steel pipeline system as well as a measure of its current condition.

The technologies used in steel pipe condition monitoring are, for the most part, equipment-centric. Tools such as vibration analysis, weight loss coupons, ultrasonic testing etc. are primarily concerned with the physical condition of the built assets and facilities being tested. Inspections also focus on the physical condition of the steel pipe, but they can be equally concerned with environmental, quality and performance issues. Detecting the entire range of defect types with a single NDT inspection technique would ideally be desirable – but regrettably there is no single technique being developed so far.

2.6 Steel Pipeline Performance Assessment

There are differences between monitoring and detection techniques in that there are compromises between absolute accuracy and degree of control over the system used. Take, for example, weight-loss coupon condition assessments; these are very accurate indicators of steel pipeline corrosion loss (IntegritySolution, 2003) but cannot provide control over the dynamics of a steel pipeline system**.** The main objective of performance assessment of a steel pipeline system would be to help identify corrosion at the incipient stage and to take the steps needed to stop further degradation of the infrastructure and from total failure. Simply knowing that the steel pipeline is flaking or changing colour is not enough without being able to assess the impact of the change on the performance of the pipeline system. This research's main questions are how to start measuring performance or condition in order to ascertain the actual status of the steel pipeline. Thus, the prevailing challenges are the development of a device that can detect and report the presence of corrosive constituents that might undermine the integrity and performance of a pipeline system.

The first step in this process is the classification of steel pipeline performance characteristics. Why is the identification of changes in performance so important? It is imperative that the material composition and physical condition of corroding steel are understood, as well as its characteristics and the functions that it serves. There is also a need to understand the possibilities for tracking its progression.

Atkinson et al. (1997) identified three roles in performance measurement, namely coordinating, monitoring, and diagnostics. Poirier and Tokarz (1996) and Neely et al. (1997) have offered suggestions on the design of good performance measures. Cameron (1986), Keegan et al. (1989), Maskell (1991), Bevan and Thompson (1991), Lockamy and Cox (1995) and Kaplan and Norton (1996) have all indicated criteria to be considered in the design of performance processes and evaluations, which can be summarised in three ways:

- Define performance measures.
- Determine the quantitative values of performance measures and analyse the system's performance with respect to pipeline condition and pipeline system workload.

- Assign qualitative values to different levels of performance measures and assess pipeline system changes in performance.

The performance measures and evaluation process used for the steel pipeline systems in these cases were well defined, as can be seen above. It is suggested here that the most accurate performance for an oil pipeline system will only be obtained when the pipeline system is measured under its real transmission conditions. Therefore the question to be asked is: What is ‘steel pipeline performance’? Is it:

- a measure of the performance of the steel?
- a measure of the performance of the pipeline?
- or both?

An assessment has universally been accepted to mean any systematic procedure for obtaining information from tests and other sources that can be used to draw inferences about characteristics of people, objects or programmes. Consequently, there must be minimum performance-based requirements that must be specified in any given performance-based assessment (Preiser et al., 1988). Although there is a large body of literature on fault detection and diagnostics for applications in critical processes – see Comstock et al. (1999), Willsky (1976), Isermann (1984), Frank (1987) and (1990), Basseville (1988), Gertler (1988), Bailey (1998) and Braun (1999) – relatively little exists for applications for a built infrastructure such as a steel pipeline system. Worse still, none exists that integrates monitoring, diagnostic and reporting protocols for steel pipeline performance failure modes.

2.6.1 Changes in Oil Steel-Pipeline Performance

For the purpose of these studies, changes in oil steel-pipeline performance will mean any deviation in the normal transmission cycle process in relation to failure of a pipeline system’s objectives of hosting/transporting oil.

As mentioned earlier, first the normal (steady-state) behaviours and performance characteristics of a transmitting oil steel pipeline need to be established, and then current operating behaviour of the pipeline can be compared against the natural behaviours in order to identify any deviations. However, currently there are no protocols to continuously monitor changes in the behaviour and performance of an oil pipeline system. It is against this backdrop that a new performance-based approach to oil pipeline maintenance needs to be developed – a tool such as one based on reliability-centred maintenance would be valuable to identify the potential failure modes.

2.6.2 Changes in Performance Parameters for Oil Pipelines

Changes in performance of an oil steel-pipeline system are measured in terms of a deviation in the ability to transport oil from one location to another, against an ability to deliver crude oil under normal operating conditions. At the same time the oil pipeline system's ability to transport oil can be characterised in this research by six basic performance measures:

- oil pipeline system availability (low downtime);
- error performance (typified by an unknown blockage due to cumulative corrosion/defect);
- lost oil transmission (due to oil pipeline system cracks or leaks);
- repairs set-up time;
- speed of detection, analysis, reporting and repair for defects, cracks or leaks; and
- availability of the oil pipeline system's current condition/performance information (not data).

In general, the common approaches to measuring an oil steel-pipeline system's performance has always been value-based performance measures; although the cost and availability of technologies have always determined pipeline system maintenance options and hence maintenance management decisions. In the light of the complexities associated with maintenance, Dwight (1995) identified shortcomings in performance measures as currently used in most industries:

- The concept of accumulation of risk is not captured.
- The focus is on the immediate rather than the overall requirement.
- The measurements made are not related to business requirements.

2.6.3 Problems and Lessons from the Medical Profession

While the assessment approach may be new to oil pipelines, similar approaches have been used in other industries and professions. For example, it has been common practice in the medical field to apply different monitoring techniques to patients' diagnoses, and the medical profession has used such methods to investigate the pulsatile flow in an artery (Tijsseling, 1996). These characteristics are relevant to the current study, and some inferences for the requirements of oil pipeline systems can be drawn from this experience.

Like the oil pipeline flow-based assessments, various ultrasound modalities have been used to measure intravascular pressures changes. There is a direct comparison between fluid oil and its pipeline system and that of human blood and the arterial structure, because both constitute an intrinsically coupled system and their dynamics have been adequately described by a set of differential equations which could be solved by a fully coupled method such as Tijsseling's (1996) fluid-structure interaction in liquid-filled pipe systems. Because of many physiological and clinical implications, several differential models of fluid-structure interaction have been developed and analysed (Nobile, 2001). However, similar techniques have been used in the past for the analysis of fluid-structure interaction problems. Consequently, such a technique has been used to describe flow pattern alteration because of the compliant structure of the liquid flow in an elastic tube. This flow characteristic is driven by a pulsatile forcing function. As a result, this study's main objective is to learn from cardiovascular monitoring techniques, where the aim is to get an insight into the complex relationship between arterial pressures, wall deformation and flow field in a large artery and relate these to heart defects. Apart from the above, other areas of interest are fluid viscosity, leakage or blockages in the arterial structure, and consideration of the harmonic response of the fluid–wall interacting system where there is defective pulsatile inflow in order to predict imminent failure.

Furthermore, Hinds and Watson (1996) wrote that patients with a low cardiac output can sometimes maintain a reasonable blood pressure by vasoconstriction, while vasodilated patients may be hypotensive despite a high cardiac output. Blood pressure must always be assessed in relation to the patient's normal value. Therefore recommending that percutaneous placement of an intra-arterial cannula allows continuous monitoring of blood pressure and repeated sampling of blood for gas and acid–base analysis. This is essential when rapid haemodynamic changes are anticipated.

Many constitutive laws for the arterial wall are available in literature (Zhou and Fung, 1997; Schulze-Bauer and Holzapfel, 2003). Though these are outside the scope of this thesis, the methods used to examine the relevant mechanics remain relevant. The main areas of interest have been the response of the fluid–wall system to a pressure pulse, using Laplace transforms and including how the solution was examined in the frequency domain. Although blood flow in arteries is pulsatile, the fundamental frequency induced by the heartbeat could be assumed to be similar to that produced by compression pumps (even though they are not exactly pulsatile).

It is evident from the foregoing that the primary task of an oil steel pipeline is to host and transport oil in a similar means to how the human artery transports blood. When, the pipeline deteriorates, the questions that should be asked are:

- What happens to oil flow?
- Does the flow pattern change?
- Does the pressure change?
- Does the pipeline vibrate (more or less)? And, more importantly,
- How can any changes be detected?

The main objective of this study is to address these questions by studying techniques that can locate defects at different stages of their lifecycle, based on attenuation and waveform analysis and to evaluate and test the potential of these techniques to predict failure mode without distracting oil flow. The knowledge gained could therefore be used to develop a new approach to pipeline system integrity capable of dealing with the complexities outlined above.

2.7 Chapter Summary

The general technique of oil pipeline inspection used industry-wide is characterised by the detailed recording and assessment of individual occurrences of corrosive damage and faults. In practice, identical occurrences of (induced corrosion) defects to an oil pipeline system are evaluated differently. Furthermore, the available evidence shows that there is no unique relationship between the evaluation of defects and condition evaluation. On the contrary, condition evaluation applies in the oil industry only to overall pipeline systems and takes months to complete, by which time new defects may have developed at other locations. Although the evaluation is derived from individual oil-pipeline system inspection results, it is based in the final analysis on a subjective opinion of an assessor.

The main challenge for this study has been to develop a new and objective-based approach to maintenance that would not only improve the performance of the pipeline system but accommodate:

- continuous monitoring;
- analysis and evaluation of performance in real time; and
- the reporting of any changes in performance of the pipeline system in use.

With the key tasks for the proposed system to be developed in the methodology section

CHAPTER 3: THEORETICAL ANALYSIS OF PERFORMANCE CONSIDERATIONS FOR OIL STEEL-PIPELINE SYSTEMS

3.1 Chapter Introduction

This chapter describes the methodology and experimental design theory used to calculate the natural frequency of the oil pipeline model used in the experimental programme. It also explains how the methodology addresses the issues articulated in Chapter 2.

After an assessment of the implications of the various possible methods for data collection and data analysis, particularly for oil pipeline natural frequencies, a laboratory-simulated oil flow pipeline-testing method was used. The oil pipeline damage detection and analysis was undertaken using Fast Fourier Transform (FFT), where the defect signal was converted between the time and frequency domains using FFT to describe the magnitude and phase of the defect signals (see section 3.3). By discarding the phase information, it was possible to simplify the information in the frequency domain representation in order to generate the frequency spectrum, which was used to assess the changes on the transmitting pipeline system's performance. The frequency spectrum of vibration and acoustic emission were then utilised to quantify the normal and defective states of the pipeline system. In section 3.3.1 the background to the data collection (cross-correlation method of defect and leak location) is outlined. The analytical procedures are determined by equations 3.9–3.12.

The primary objective of using the FFT system for these experiments was because of its ability to detect fault signals and to convert those signals between the time and frequency domains, thus allowing abnormal condition-signals to be identified and information presented in graphical format.

3.2 The Methodology and Experimental Design Theory

The principles assumed herein are that the minimum size or shape of defects that can be detected is directly determined by the degree to which the defect frequencies (time-varying low-frequency modulation) were reproduced within the band 0–60ms (see Figure 3.1). Several of the lower natural frequencies of the oil pipeline system under consideration were cross-correlated to detect defect and leak location (Figure 3.4). For hard-walled pipes it was possible to resolve the frequencies (Liu et al., 2000; Agarwal, 1985; and Agarwal and Bull, 1989) to about ±0.01%, while for composite components the resolution was of the order of ±0.05%. The steel pipeline has its lower natural frequencies in the range of 50–2,000Hz, whilst most of the key failure-modes were expected at frequencies of about 1,000Hz to 5,000Hz. The order of resolution required for experimental design to distinguish between the natural frequency signal and incipient defects was ±0.2Hz, repeatable with an accuracy of ±0.05% at 400Hz.

A principal requirement in such transmission systems is that the ratio of the agitating frequency and natural frequency should be at least 2:1 and preferably 5:1. The natural frequency for the transmitting oil pipeline system is directly related to the content rigidity. For heavy crude oil, for instance, it is inversely proportional to the fluid static deflection, meaning that the larger the static deflection the lower the resistance and the lower the natural frequency. In order to ‘sense and detect’ defects to failure in an oil steel pipeline, the lengths of the vibrating noise waves are expected to be of the same order as the dimensions of the defects (Agarwal and Bull, 1989). This means that the wavelengths used in investigations of corroded oil steel pipelines must be of the order of a few millimetres to detect a defect or crack.

The time interval was measured using the spectrum analysis method, and, for signal processing, Fourier transforms and wavelet analysis were used. A periodic or non-periodic signal oscilloscope without memory capability was used to observe how the signal varied with time; however, such an approach doesn’t give a full representation. In order to fully characterise the performance of a device or system, it is necessary to analyse the components of the signal(s) in the frequency domain. This produces a graphical representation of the signal’s amplitude as a function of frequency. As such, a spectrum analyser was used in these tests. In the time domain, all frequency components of the signal were summed together and displayed as one signal. In the frequency domain, complex signals (that is, signals composed of more than one frequency) were separated into their frequency components, and the resolution that matches its scale at each frequency was displayed. From this viewpoint of the spectrum, measurements of frequency, power, harmonic content, modulation, spurs and noise could easily be made.

According to Owens (1997), the Fourier transform is a method used to express a function (which is a point in some infinite-dimensional vector space of functions) in terms of the sum of its projections onto a set of basic functions – although there are many ways of transforming image data into alternative representations that are more appropriate for certain types of analysis. Given that an image is only defined on a closed and bounded domain (the image window), it is assumed that the image is defined as being zero outside this window. It is further assumed that the image function is capable of being integrated over a real line (i.e., a line with a fixed scale).

The most common image transform takes spatial data and transforms it into frequency data, and this is done using the Fourier transform. While a step function (or a square wave form) can, according to Owens (1997), be represented as a sum of sine waves of frequency ω, 3ω, 5ω, … where ω is the frequency of the square wave, and frequency = 1/wavelength. Normally, frequency refers to the rate of repetitions per unit of time – that is, the number of cycles per second (measured these days in hertz).

Although there are numerous types of defect associated with oil pipeline failure, only two (namely local defects and global defects) were considered in the experimental programme. Local defects were categorised as those that occurred within a volume of a few cubic centimetres (e.g. cracking); global defects were categorised as those distributed along the oil pipeline and occupying larger volumes (e.g. corrosion or pitting). Two methods that may be used to measure pipeline system natural frequencies are discussed next, namely conventional parameter-based (also sometimes referred to as steady-state) methods, and a transient test from the Fourier transform of the response of the structure to an impulse.

3.2.1 Parameter-Based, or Steady-State, Technique

The steady-state method (see Mungur and Plumblee, 1969; Doak and Vaidya, 1970; Eversman, 1972; Ko, 1972) was used for condition assessment of the natural frequencies of the experimental test equipment with regard to its fluid flow, pump and joints. Experimental evaluation of the frequency vibration excitation is usually applied to pipeline systems. It often requires data manipulation (configuration) until the necessary resonance features are achieved for the particular experimental set-up. It is possible to automate the frequency-vibration excitation process and to use a steady sweep in high resolution, even when the transmitting oil steel-pipeline system's damping was low, by simply setting the steady sweep in higher-resolution mode, which helps to adjust the sweep rate and stabilise the measurement process.

3.2.2 The Transient Method

Although there are numerous techniques associated with oil pipeline damage detection and analysis, only the most common (namely the Fast Fourier Transform (FFT)/Fourier transform) was used in the experimental programme to detect the flow-induced vibration sound. Indeed, there are still only a handful of FFT tools that are deployed in the field to continuously monitor, analyse and report any changes in the performance of oil pipeline systems.

There are two basic approaches that are of interest to this research, namely time and frequency domain, sometimes referred to as '2-D fast Fourier transform' (Alleyne and Cawley, 1991). The fast Fourier transform is also known as a form of signal processing, and this technique involves two Fourier-transformed stages.

The method takes a real-world, time-varying signal and splits it into components, each with amplitude, phase and frequency. By associating the frequencies with the oil pipeline flow characteristics, and looking at the amplitudes, it was possible to pinpoint damage very accurately. This method is attractive, because the test time is very short and because it provides measurements that are fast and reliable. White (1971) first recommended this technique.

The time domain was converted using the frequency domain – that is, by converting the frequency domain into an FFT. The FFT was then used to analyse the experiments (White, 1971). The fast Fourier method transformed the oil steel-pipeline system's natural frequency (signal) into recognisable characteristics. (It should be said that the variance of the signal relates to the power in the data, and it is more usual to use the standard deviation of the signal.) Using the depth of mean value of the envelope signal made the calculation easier. By simply multiplying the fluid dynamics and defect functions, the variance in signal value can be calculated in terms of mean percentage. The calculation was carried out by a frequency domain representation (using the excitation time history known as the spectral method – see Tijsseling (1996)).

In determining the orientation of signals associated with the defect zone and fluid flow through the pipeline system, each state in the pipeline variable coefficients was represented by planar travelling-wave solutions. For example, the fluid (water or oil) pressure may be represented by:

$$P(z,t) = [\sum_{1}^{N} P_i^1 e^{ik,z} p_i^2 e^{-ik,z}] e^{i\omega\tau}, \tag{3.1}$$

where *N* is the maximum number of wave numbers, *P*(*z*,*t*) is the fluid (water or oil) pressure and *e* is the pipe-wall thickness. Through the differential equations, all states in the pipeline variable coefficients; (e.g. V_i^1 & V_i^2) can be represented by one set of coefficients (e.g. P_i^1 and P_i^2) (Steens, 2004).

The equations are solved through boundary conditions or excitation conditions. The spacing between the frequency points produced by the Fourier transform was l/*T*, where *T* is the time record length. If the resonant frequency is taken to be that of the frequency point at which the response magnitude was at a maximum, the uncertainty in the value of the natural frequency obtained was l/2*T*. In the event that the frequency resolution generated is required to be improved, that will also require that the response recording must be extended or increased.

The spectral method does, however, suffer from one drawback (Hatfield and Wiggert, 1983). Representation of Dirac delta-like time histories in the frequency domain can result in problems due to the discrete nature of the fast Fourier transform, meaning that the time domain approach is better suited to one-off events (transients). Higher frequencies are cut off due to the practicalities of sampling rates; this means that correct representation of such transients is unattainable. Even with low-damping pipeline systems, the amplitude of the fluid motion could be considerably reduced after a few hundred cycles, so there is a limit to the time for which the response can be recorded with an acceptable degree of accuracy. These factors effectively limit the frequency resolution that can be obtained when extracting acoustic emission leakage (cracking) signals from various transmitting pipe situations, as were evaluated and tested by Liu and colleagues (2000), Zhang (1997) and Agarwal and Bull (1989). Several techniques have been used to investigate the mediums flowing in the pipeline, i.e. air, water and industrial gases.

The acoustic emission technique has been widely used as a standard for leak detection and inspection of pipeline defects. As with other methodologies, acoustic emission involves the assembly of fragmented software and hardware capabilities to enable direct monitoring, detection, diagnosis and reporting without the help of a third party.

The parameter-based and FFT techniques require that the number of data points, n, used in the computation of the Fourier transform are increased each time. The times taken for the transform were proportional to $n\log_{10}n$ and the store required was also proportional to n, so it can be seen that the computation requirements increase rapidly with n. In practice, however, high frequency resolution is usually only required in the region of the resonant peaks, whereas the standard transform gives the same resolution throughout the spectrum. Shannon’s theorem states (Shannon, 1948) that it is possible to take advantage of this fact by recording the response for a sufficiently long time as to give the required resolution at a sample rate, which is high enough to prevent aliasing.

This data was then fed through the PICO-digitised system bandpass filter centred on the region of interest, which outputs a smaller number of points on which the transform was performed. In return, FFT techniques produced the spectrum over the bandwidth of the filter with the desired frequency resolution automatically in situ. The filtering process was then repeated for other parts of the spectrum, again in situ. It saved time, given that performing the Fourier transform on the whole of the raw data would have required considerable computational capacity.

Theory indicates that when the range 0–5kHz is to be investigated, a rate of at least 6kHz would have to be used in order to prevent aliasing. The response could therefore be recorded for about one second, giving spacing between the frequency points produced by the Fourier transform of 1Hz and a resolution of ±0.5Hz if the natural frequency were to be taken as the point of maximum response.

3.3 Theoretical Background to Research Project

The basic premise of the research project was that a piezoelectric sensor mounted on the surface of an oil distribution pipeline could detect differences in the waveform (mechanical or electrical) generated by the changed flow characteristics of a fluid medium as it passed through pipes having different levels of internal damage. The sources of excitation are shown schematically in Figure 3.4. It was assumed that as the fluid flows, the pipeline system's mass and elasticity, combined with the propagation speeds of the pressure and stress waves, are all created to the same order of magnitude (Tijsseling and Lavooij, 1989). Fluid–structure interaction is unimportant, provided that the transient excitation is sufficiently rapid.

The existence of vibrations associated with liquids flowing through pipeline systems has been known for many years. The mathematical models developed by Lamb (1898) and Frizell (1898) distinguished three classes of vibrations:

- the pressure waves in the fluid, as modified by the yielding of the tube;
- the axial vibrations of the tube wall, as modified (very slightly) by the presence of the fluid; and
- the radial vibrations of the system.

The same mathematical models also derived a dispersion equation, which related pressure changes, ΔP, to velocity changes, ΔV, by the constant factor $p_f c_f$,, with p_f the mass density of the fluid and c_f the velocity of sound in the fluid. According to Tijsseling and Lavooij (1989), wavelengths and pressure waves have long been used predominantly to determine propagation speeds through pipe walls.

However, as stated previously, such approaches are unable to predict the wave patterns associated with internal cracking of oil pipeline distribution systems, which are predominantly associated with a radial vibration (acoustic emission) wave pattern. The wavelengths associated with vibrating acoustic emissions are expected to be of the same order as the dimensions of the defect (Agarwal and Bull, 1989); thus, for oil pipelines this would be in the order of a few millimetres. Furthermore, whilst there is a considerable amount of literature describing the propagation of mechanical waves and their application to steel infrastructures (Graff, 1975; Aki and Richards, 1980; Yan and Jones, 2000), there is very little published work that provides estimates of the absolute strength of the acoustic emission source. Thus, even if acoustic waveforms exist, there is no guarantee that they will be detectable by the range of piezoelectric sensors currently available.

The model for the axial motion of a fluid flowing through a steel pipeline under pressure excitation *H*(*z*,*t*) is given by equations (3.2) to (3.5) below. The (diesel oil) fluid and its pipeline system are regulated by each pair of equations respectively with some variables in the equations as subscripts. We have:

$$\frac{\partial v}{\partial r}+\frac{1}{pr}\frac{\partial p}{\partial z}=\frac{H(z,t)}{pr} \qquad (3.2)$$

$$\frac{\partial v}{\partial z}+\left(\frac{1}{K}+\frac{2R}{Ee}\right)\frac{\partial p}{\partial t}-\frac{2v}{E}\frac{\partial \sigma z}{\partial t}=0 \qquad (3.3)$$

$$\frac{\partial \bar{u} z}{\partial t}-\frac{1}{Pp}\frac{\partial \sigma z}{\partial z}=0 \qquad (3.4)$$

$$\frac{\partial \bar{u} z}{\partial z}-\frac{1}{E}\frac{\partial \sigma z}{\partial t}+\frac{vR}{Ee}\frac{\sigma p}{\partial t}=0 \qquad (3.5)$$

where u_z is the axial velocity of the fluid at the pipe wall; t is the arrival time and z is the distance along the pipe, and R is the inner radius of the pipe; σ_z is axial stresses in the pipe wall; and P is the internal fluid pressure. Friction and gravity terms are neglected in these equations as they were proposed to describe the coupled axial motion of pipe and liquid (Burmann et. al., (1979); Thielen and Burmann (1980)). The (low-frequency) pressure waves for the fluid flow are assumed here as one-dimensional, so the flow activity in the radial direction is deemed as quasi-static. The model accounts for Poisson coupling through equations (3.3) and (3.5).

Using these equations, it was possible to compute the pressure signals at any frequency due to a system of damping ratio *c* and undamped natural frequency of the pipeline system. The relative values of the response magnitude at given points around the resonant peak are dependent on the position of the peak in relation to these points. As previously stated in section 3.2, the Fourier transform algorithm was used to compute the value of the transform in hertz, whilst the single-frequency excitations were expected to be linear at the interface where the fluid interacts, or is in contact, with a damaged area of the pipe.

According to Agarwal and Bull (1989), oscillations (i.e. excitations) are expected to occur in the transmitting pipeline system because the system is perturbed from its dynamic equilibrium; and the system, using a restorative force, tries to return to that equilibrium state. The asymmetric mode ($m = 0$) may be as significant as axisymmetric modes (1, 0) (2, 0) and should be expected to occur at low frequency rather than the lowest-frequency axisymmetric (0, 1) mode.

The enveloping method has been used to solve the above problems. The premise of the methodology is that:

- the friction forces that excite the random frequency vibrations are stationary only when there are no defects; and
- in non-defective friction pipes, the random high-frequency vibration is stationary also and its power is constant in time.

However, the excitations were expected to be built around the defect zone, which, although stationary in time, may also vary periodically in time in the flow around a defect/leak as the appearance of a defect may excite high-frequency vibrations. Therefore it was assumed that partial discontinuity of flow occurred at defect zones, resulting in high peaks being observed within the low frequency bound. It was further assumed that the value of the friction forces and the power of vibration might peak, and changes in the signal were observed. Therefore the defects were detected by measuring peaks generated within the frequency band (see Figure 3.1) that was to measure the envelope spectrum of the high/low-frequency vibration in the oil steel-pipeline system (see Barkov and Barkova, 1986, 1995 and 1996).

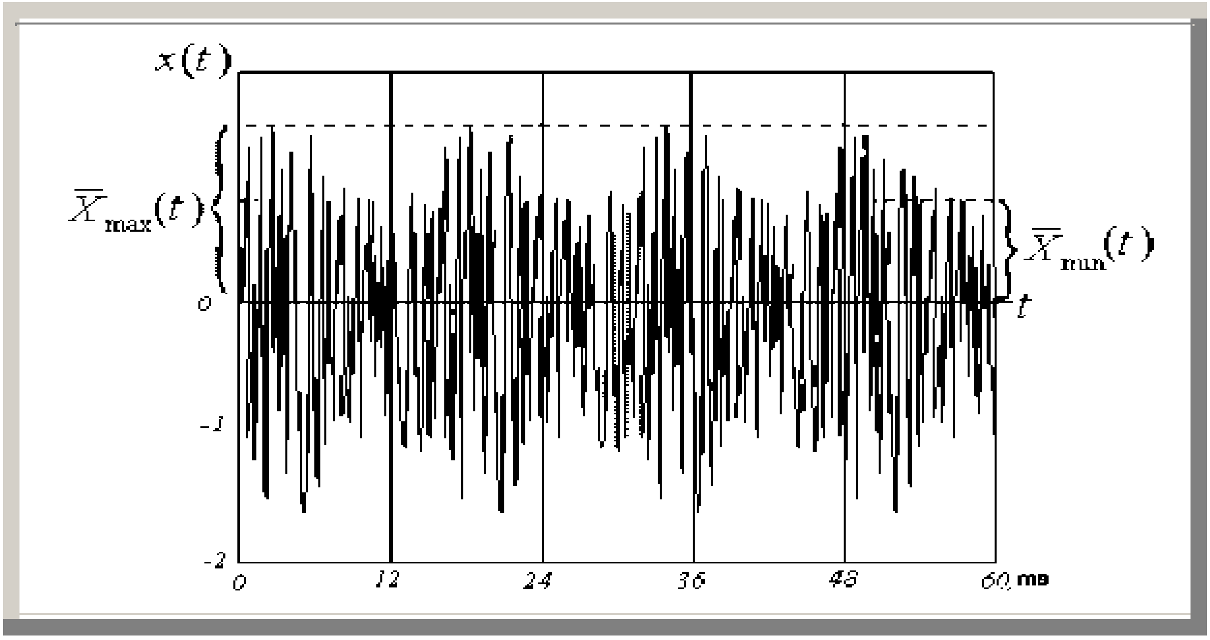


Figure 3.1: Peak Frequency Random Amplitude-Modulated Signals (*Source*: Barkov and Barkova, 1986)

The intensity of the vibration, as can be seen in Figure 3.1, varies in the time domain. The depth of modulation *m* of a random amplitude-modulated vibration signal *X(t)* can be determined in percentage terms, using the mean value of the envelope $\overline{X}(t)$:

$$m = \frac{\bar{X}\max(t) - \bar{X}\min(t)}{\bar{X}\max(t) + \bar{X}\min(t)}.100\% \qquad (3.6)$$

where $\overline{X}_{max}(t)$, $\overline{X}_{min}(t)$ are the maximum and minimum values of the enveloped signal, respectively. In contrast, Figure 3.2 indicates that when the pipeline defect type changes, the modulation frequency also changes. It can be assumed that the more the defect develops, the greater the depth of the modulation is influenced. For example, let a restoring force $F = -kx$ arise when the system is displaced through some distance *x* from the equilibrium position, and let the parameter *k* change with time because of some periodic influence: $k = k(t)$. Therefore, for such a system the differential equation of motion

$$m\ddot{x} = -k(t)x, \;\; \ddot{x} + \omega^2 x = 0$$
$$\left(\omega^2 = \frac{k}{m}\right),$$

is such that the coefficient ω^2 of *x* is not constant but explicitly depends on time. Similarly, the coefficients in the differential equation are not constant if the inertial parameter *m* depends on time. Oscillations in such systems are essentially different from both free oscillations (which occur when the coefficients in the homogeneous differential equation of motion are constant) and forced oscillations. It is also assumed, that the frequency of modulation defines the type of defect and the depth of modulation, i.e. its development.

Figure 3.2 presents, on the left-hand side in (1), an example of the time domain vibration signals of a pipeline system: (a) without faults; (b) with surface defects; and (c) with surface defects and leakage on the friction surface. The envelope spectra of the defective oil steel pipeline's vibration under conditions (a)–(c) are shown below in (2) on the right-hand side of Figure 3.2.

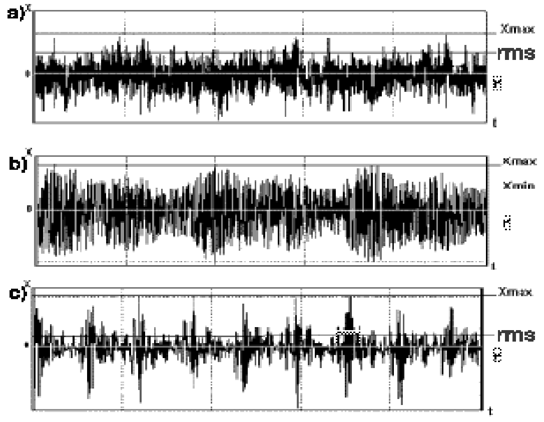
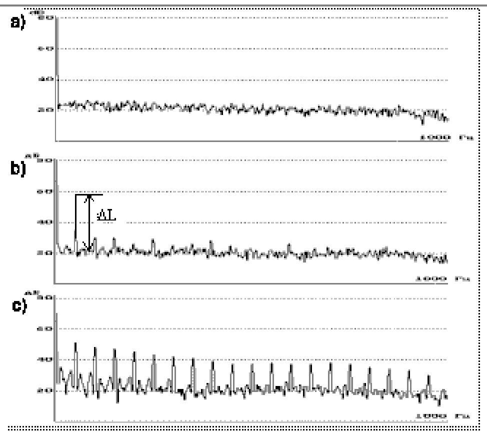
Time domain signal of high frequency vibration	**Envelope spectra of high frequency vibration**
	
(1)	(2)

Figure 3.2: Time Domain Signals of High-Frequency Defective Oil Steel-Pipeline Vibration
(*Source*: Barkov and Barkova, 1986 (modified))

It was expected that if an oil steel-pipeline system had no defects, the envelope spectra of its random vibration would not contain any harmonic components, whereas the envelope spectrum of vibration of a defective oil steel-pipeline system would contain a strong harmonic component that is indicative of a smooth and periodic variation of vibration signal power (Figure 3.2). In an oil-carrying steel-pipeline system with shock pulses, the power of low-to-high frequency vibration is expected to change abruptly, whereby a number of multiple harmonic (wavelike) components would appear in its envelope spectrum. This made it possible to simultaneously observe the development of all defects by considering the values in excess of harmonic components on certain frequencies against the background value of the random components. Consequently, it would be possible to define the partial depth of modulation, i.e. the depth of modulation for each defect mode.

According to Barkov and Barkova (1986), depth of modulation makes it possible to define the development of each defect and to identify its type. For that reason it enhances the prognosis of a diagnosed pipeline system condition, as each type of defect has its own rate of development.

In contrast to the above, a random signal (see Figure 3.3) can have any value in a certain range, so it is characterised by a particular amplitude, frequency and phase (i.e. by its peak value, root mean square value and mean value of the detected signal and peak-to-peak value).

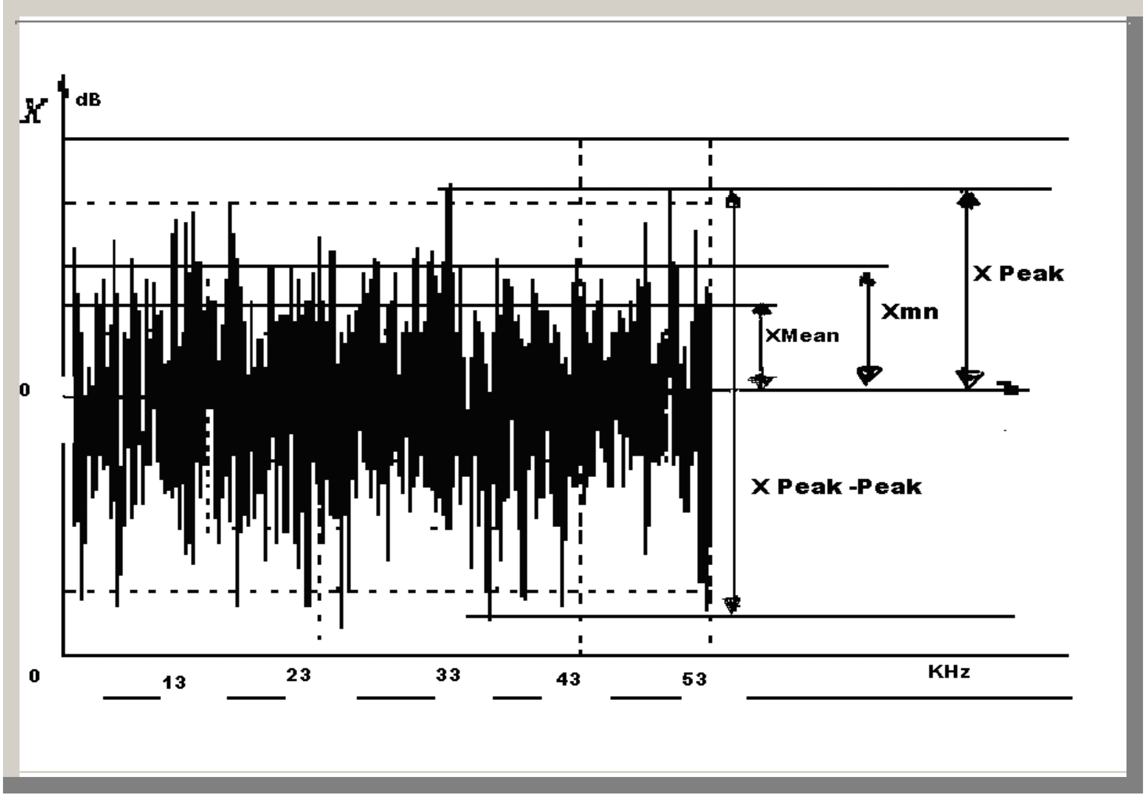


Figure 3.3: Random Vibration Signal (*Source*: Barkov and Barkova, 1986)

Smutty (1999) wrote that most real acoustic emission signals have characteristics that change over time and, further, that the individual domains of time and frequency do not often provide the means for extracting this information. Therefore an alternative method is required that can process the temporal localised signal's spectral characteristics into useable information. This alternative method can be achieved by combining time domain and frequency domain analyses, in the way recommended by Pazdera and Smutný (2000).

As mentioned in section 3.2, time-frequency representation can be divided into two groups by the nature of the transformation: linear methods (including the short-time Fourier transform and the wavelet transform), and quadratic methods (of which the Wigner-Ville transform or distribution is fundamental). In essence the differences observed in the graphical representations were generated automatically using the PICO Scope software. The frequencies (resonant peaks) were generated through Fourier transform and spectral methods as the fluid interacted with the pipeline system and the defects in real time. This has required that the hydrodynamics of the separator's aqueous part have generally been modelled using complex mathematical and numerical models, which often described the settling and coalescence of oil droplets in oil/water dispersions. In essence, such models take into account separator dimensions, flow rates, fluid physical properties, fluid quality and drop size distribution. However, these complex mathematical and numerical models are not required for this study; the main interest is the characteristics of any changes in performance of the transmitting pipeline systems.

3.4 Experimental Method of Research Project

Prior to testing, different functions were used to resolve the differences and similarities between the acoustic emission signals – for example, Fourier transforms (i.e. the spectrum analysis method) and coherence functions were applied. The logic assumed that the frequency response function of the pipeline system being tested could be expressed as the sum of a number of independent damage signals, each of which behaved like a 'single degree of freedom' system with viscous damping.

This was considered to be a reasonable approximation for a lightly damped transmission oil pipeline system whose natural damage signals may typically have damping ratings of less than 0.05. However, the assumption had to be verified in that, apart from the influence of the transmitting defective steel pipe under test, a similar pipe-defect source with a particular fluid flow rate but different transducer characteristics could result in similar acoustic emission signals. This is typically the case when a two-degrees-of-freedom system has two closely spaced natural frequencies, ω_{n1} and ω_{n2}, as vibrational kinetic energy will transfer from one degree of freedom to the other in a periodic fashion. The frequency of the transfer is known as the beat frequency, given by $(\omega_{n1} - \omega_{n2})$.

Should the above assumption be proven to be reasonable, that would mean that the accuracy of the technique may depend on a given failure mode and the damping ratio, c, as well as the accuracy of the analogue-to-digital conversion and the level of any other noise sources at the time when the signal is recorded, Δt, such as from:

- digital-to-analogue converter (DAC);
- data lines: D0, D1, D2, ...;
- analogue: continuous electrical signals;
- digital: method of representing information using solely 1s and 0s (usually 5V and 0V);
- LSB: least significant bit;
- MSB: most significant bit; and
- charge-coupled device (CCD): 'dark' noise (vibration) and 'read' noise.

For example, acoustic sound emission or photon noise is known to result from the inherent statistical variation in the arrival rate of photons on a CCD, whilst dark noise can arise from statistical variation in the number of electrons thermally generated within the silicon structure of the CCD, which according to Thomas and Davidson (2005) is independent of photon-induced signals but highly dependent on device temperature. On the other hand, read noise can result from a combination of system noise components inherent to the process of converting CCD charge carriers into a voltage signal, and the subsequent processing and analogue-to-digital conversion.

Although the proximity of other variables, such as joints and the level of the resonance in the damaged area of interest, may be masked by the other signals, the concern is that there may be an inconsistency in the readings. However, it was hoped that the inconsistencies would be sufficiently small to be ignored by comparison. Here, the distance between the two sensor locations were computed differently, since they were mounted at different time intervals, as follows:

$$d1\frac{d-cj\,\Delta t}{2}=X \qquad (3.7)$$

where d is the distance between the two sensors' positions, cj was the speed at which the leak noise propagates through the pipe, j is a subscript below and in the formula, and Δt was the difference in arrival times of the noise at the two sensors. These three variables need to be known in order to determine the location of the leak accurately. The distance between the sensors, d, was measured reasonably accurately using a tape measure but the wave speed cj was difficult to measure in this instance, although there is a reasonable understanding of the factors that can affect it (Agarwal and Bull, 1989).

The accuracy of any of the techniques used to improve the frequency resolution was also dependent on the degree to which the spectrum of the input force (i.e. the defect) was high over the range of resonance as applying to joints and noise. That made it possible to compute the force spectrum and to find the frequency response function by dividing the response by the force spectrum; but this procedure adds considerably to the computation and instrumentation required. In seeking to predict acoustic frequencies, according to Rocha (1989) it was assumed that about the order of 10Hz acoustic emission can propagate in a gas-contained pipe (in this case, diesel oil) for distances up to 160km and gives the following approximation, in that the amplitude of the wave is expected to be related to the properties of the diesel oil in question. Therefore equation (3.8) was used to work out the distance, given the pressure at which the pipeline system was operated in the laboratory. The pipeline system was operated at 3bar with the size of the leaks measured at about 0.01mm before the nail insertions. The local pressure drop due to the leakage is given by:

$$\Delta p = 0.3 P_S (D_1 / D_p)^2 \tag{3.8}$$

where Δp is the vibration sound pressure; P_s is the static pressure in the pipe at the leak site; D_1 is the diameter of the leak hole; and D_p is the local diameter of the pipe**.** Again according to Rocha (1989), the detectable vibration sound pressure from the steel pipeline leakage has been measured to be as small as 5millibars (0.073psi), even with a static pressure sometimes of up to 69bar (1000psi). However, the pressure level often requires sophisticated noise cancellation techniques to increase the signal-to-noise ratio.

The aim of these experimental tests was to detect and determine the position of a defect, and subsequent leak signals expected from the defect zone (160–161cm; *X* between A and B; see Figure 3.4 below). The defect zone was located at the midsection of the test pipe, simulated to monitor the changes in performance of the pipeline system in service. This distance was also related to other test variables (sensor mount positions I-V in Fig 3.4 and in order to estimate ΔT the cross-correlations of the signals from the sensors were used; hence the superscripts '/*V*' and '/2' take the form mean:

$$T_1 = X_1 / V \tag{3.9}$$

$$T_2 = X_2 / V \tag{3.10}$$

$$\Delta T = (X_2 - X_1) / V \tag{3.11}$$

Therefore;

$$X_2 = D - X_1 \rightarrow \Delta T = (D - X_1 - X_1) / V \rightarrow X_1 = (D - \mathrm{V}\Delta T) / 2 \tag{3.12}$$

The determination of the accuracy of the failure patterns from these equations depended upon the sensor position and the signal processing. From Figure 3.4 it can be seen that the sensors located at defect points marked between A and B (in fact at 160cm, 160.5cm, and 161cm) are approximately five millimetres apart. However, the method assumes that, within the defect region, the response may accurately be modelled as that of a single-degree-of-freedom system. This means that severe errors would be introduced if another peak was in close proximity, with the magnitude of the error depending on the damping in each mode.

The inaccuracies caused by this event were less serious with low-damping systems as, in this case, the response decreased more quickly away from the defect zones. The choice of error function was assumed to be unaffected by the defect growth, helping to minimise the peak amplitude differences originating at the defect source. The absolute value of the response function was significant, in contrast with the rate of frequency change, which was small. It was possible from equations (3.10), giving the position of the leak relative to sensors 1 and 2, and (3.11), giving the difference in arrival times, to determine which of the failure characteristics (i.e. frequencies) would occur, given sensor positions A–C (I–III) positions in Figure 3.4.] and the defect location.

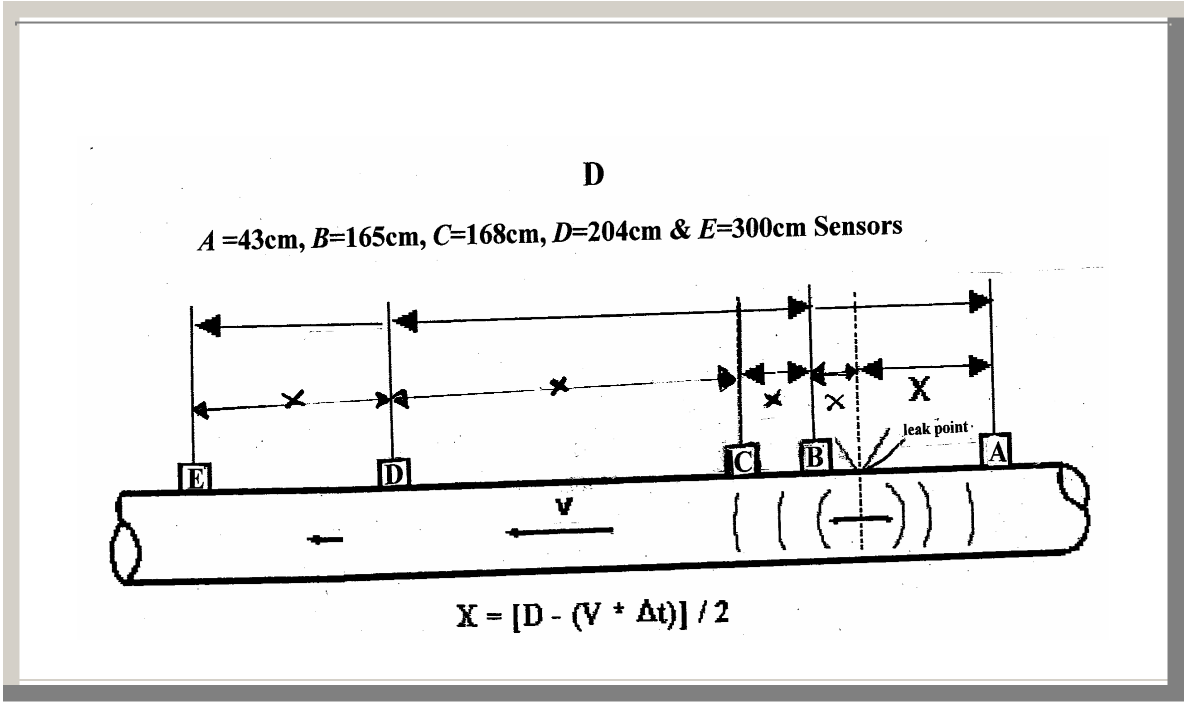


Figure 3.4: Cross-Correlation Method of Defect and Leak Location

- *X* = distance of the point [of defect and or leaks] from the reference sensing device;
- *D* = distance between the two sensing devices (for the 5 sensors was required);
- *V* = propagation wave speed;

- Δt = time delay obtained from the peak position of the cross-correlation function.

The defect source was determined using cross-correlation methods; the acoustic emission for the steady state and the defect was determined with five sensors, each mounted along the pipe and separated from each other along the length of the pipeline system at locations A to E (see Figure 3.4). The envelope of cross-correlation function for each sensor signal was calculated to determine its peak, which provided the time differential between each signal received at sensor locations A to E.

A sweep filter was used as part of PICO-Scope software that transformed the interaction between the fluid flow and the damage information into vibration and acoustic signals. This is referred to as constant Q (or constant percentage bandwidth) filtering, where a low/high pass filter combination of say 2.5 % bandwidth is swept, in real time, through a signal to produce a plot of amplitude versus frequency. The processed frequency and amplitude signals from different channels were applied to the inputs of the multiplier in order to produce the desired defect signal. The fluid passing through the defect zone excited a sound in the oil/steel pipeline system in the 120–200Hz range.

3.5 Chapter Summary

It has been shown in sections 3.3 and 3.4 that if it is assumed that the attenuation and waveform analysis were used to identify theoretical changes in the flow characteristics of a liquid medium as it passed along a damaged section of pipe, the sensors and analysers would be effective in detecting the flow characteristics around a damaged section of the pipeline.

CHAPTER 4: EXPERIMENTAL METHODOLOGY

4.1 Outline of Testing Procedures

This chapter details the design of the laboratory experimental set-up, test programme and test results (data collection and analyses). The test programme was divided into two parts: a pilot-test series (S1) of investigations to establish the natural behaviour of the pipeline system under consideration without defects and to validate the fluid and equipment used; and then a second test series (S2) to measure the effect of damage to the pipeline system. Test Series 2 was further divided into four sub-series: for a small defect (fissure), a medium-sized defect, a sealed hole and ‘failure/burst’.

The testing method is described in detail in section 4.2, and section 4.3 describes the experimental procedures and measurement made. Section 4.4 presents a summary of the results, whilst Tables C to G in Appendix A give a detailed breakdown of the results.

4.2 Experimental Set-Up

A test programme was developed in which (see Figure 4.1 below) two flow mediums, namely water and diesel oil, were pumped through a model oil distribution pipeline in which the central section of pipe (60cm) was replaceable by alternative sections having different failure characteristics.

The failure characteristics were modelled by drilling holes (0.5mm, 1.0mm and 2.0mm in diameter) through the pipe wall and inserting nails (19mm × 1.2mm (small) and 30mm × 1.15mm (medium)) into the holes from the outside into the pipe wall to simulate corrosion and cracking. The location of the nails/holes was taken as the reference point for each test. The nails were removed from the holes for the last test series (a fatigue test), although the holes remained sealed by weld solder until they failed sufficiently to produce leakage.

The acoustic emission signals associated with each test were recorded at five sensor locations A to E along the pipe (43cm, 165cm, 168cm, 204cm and 300cm respectively from the reference point). The sensor locations and characteristics were calculated by considering

Tijsseling's (1996) equations and the specific parameters associated with the test set-up. The sensors had an effective frequency range of 0.5Hz to 15,000Hz at ±3dB.

Once steady-state flow conditions were achieved (e.g. constant fluid temperature; flow pressure etc), the acoustic signals were recorded (with a sampling rate of 2KHz) over the interval: 1ms with 300 maximum number of samples for a 45-minute time period. Approximately 1,000 readings were recorded for each test; hence only summaries of the results are presented in this section (although a more detailed breakdown of the results is given in Appendix A).

The results were then converted to mean values and their standard deviations calculated using the enveloping method. The main test considerations (and thus test parameters) were; defect location, defect evolution characteristics, leakage location, results of fatigue tests using sealed holes without nails; failures analysis, changes in performance, and the effectiveness of piezoelectric sensors.

These results were obtained from a series of tests conducted using low-frequency vibration and acoustic emission sensor and fluid flow in order to measure the impact of the engineered defects (as simulated corrosion) on the performance of the steel pipeline in service. The defect size and progression characteristics were monitored, measured and identified at each stage of experiments. Spectrum and frequency analysis were used simultaneously in combination with the acoustic emission detection method to study the integrity of the oil steel pipeline's performance against the different defects and leakages models.

Tests Series 1 (S1) established the natural frequency (i.e. waveforms) of the acoustic emission signal resulting from normal fluid flow through the steel pipe without defects. Water and oil were the flow medium (see Table 5.4 in Chapter 5). The data from the water test was used for comparison (normal fluid flow) in this research since the results are very similar. Fourier transform and wavelet techniques were used to study the signals and background noise.

Test Series 2 (S2) monitored the corrosion signal sources and characteristics of the induced defects, from incipient defects (drilled holes with small nails, drilled holes with medium-sized nails, and sealed large holes) to failure (ranging from cracking to actual leakage). The signal sources from the oil steel pipeline were studied; results were obtained and were compared with S1, which comprised 20 controlled tests with oil, in order to validate the test set-up.

4.2.1 Testing Methods Used

The experimental method required that non-intrusive sensing devices (accelerometers) were connected to data acquisition and signal analysis instrumentation placed along the pipeline system, in order to detect and locate defects and leaks. The pressure signals generated from the defect and subsequent leakage location were measured. The distance between the five sensor locations that spanned the pipeline system were also accurately correlated and recorded along with the ‘controlled burst’ event that generated a low-pressure pulse propagating along the oil steel pipeline. See Figure 4.1 below for a diagrammatic layout of the rig and Photo 4.1 for a photo of what was actually constructed in the laboratory.

Finally, it was possible to measure the frequency and time interval using the spectrum analysis method; and Fourier transform and wavelet analysis were used for signal processing. In addition, the cross-correlation functions were used (see Figures 3.4 and 4.1) to establish the time intervals that the defect and leak vibration sound emission took to reach the locations of the sensors. Frequency- and time-domain measurement techniques were used (see Pazdera and Smutný, 2000).

The test definition was determined as the ability of the pipeline system, under different conditions, to transport the liquid medium. The tests sought to link changes in the condition of the pipe wall to changes in its performance characteristics – in particular, to establish whether changes in performance could be linked to known (induced) defects. Failure (corrosion) characteristics were modelled by drilling holes and inserting nails, as described above, to ascertain whether:

- a defect in the pipeline and resulting leakage had specific characteristics and influence the pipe’s ability to transport fluid; and
- wear in the pipeline required greater input of energy to move the oil.

4.2.2 Test Question

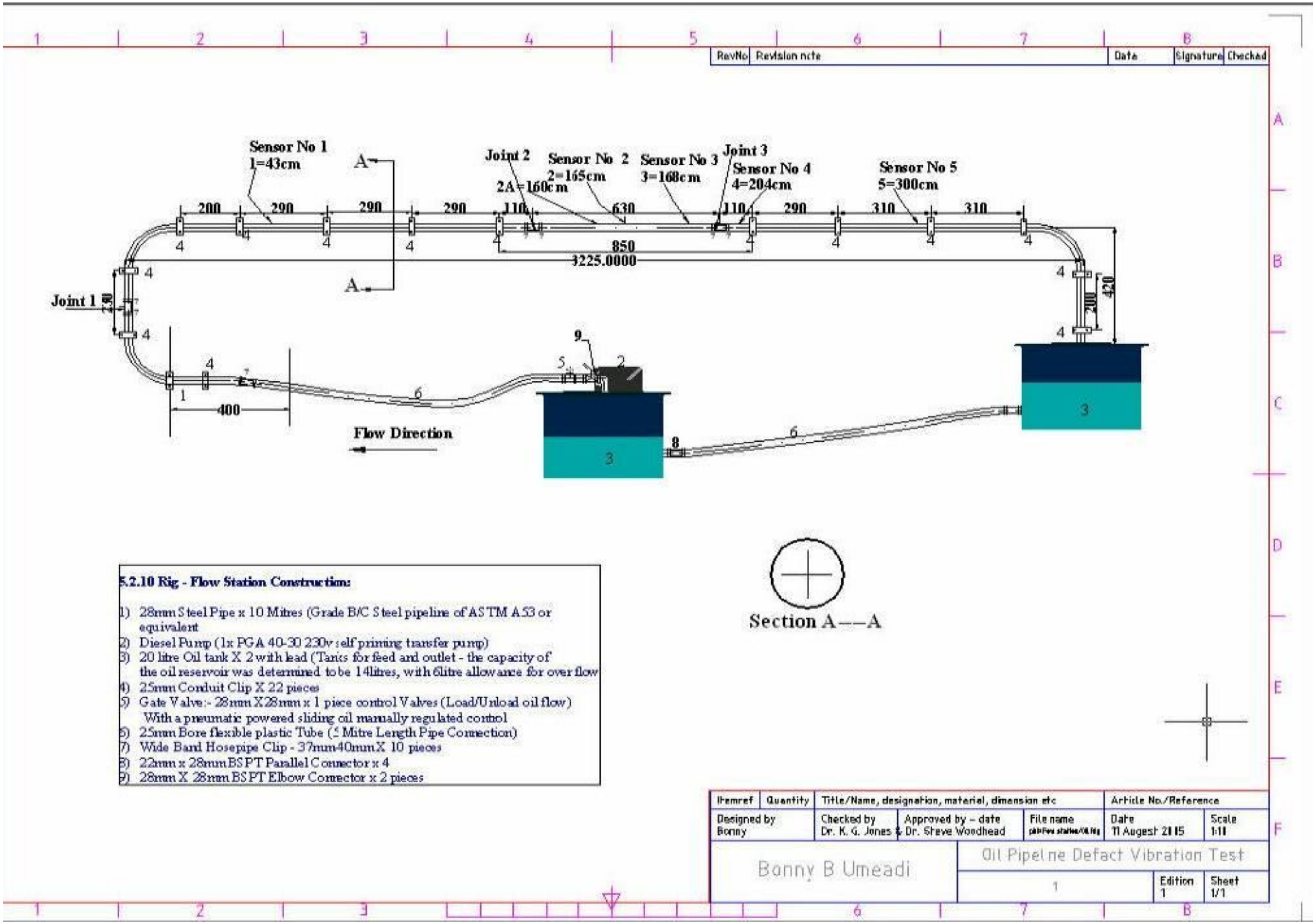
A significant question posed in this research was: Can changes in performance in a defective oil-transporting pipeline, when carrying out its primary task, be monitored in such a way as to predict failure? Can an imminent break in the pipeline (time to break, location of break) be foretold?

Time constraints meant that the failure prediction aspect of the test was not done in this phase of the experimental programme. However, it was possible to monitor the ability of the experimental defective oil-transporting pipeline to carry out its tasks using the test programmes set out on Table 4.1.

Table 4.1 Details of the Experimental Programme

Section & Test Numbers	**Flow Medium**	**Primary variable**
S1 1–100	Water and Oil	**No defect** with Water & 20 last tests with Oil
S2 1–25 S3 26–51	Diesel Oil Diesel Oil	**Nail small** 0.05mm – Defect Location, Effectiveness of Piezoelectric sensors and Evaluations
S4 52–72 S5 73–98	Diesel Oil Diesel Oil	**Nail med** 1.0 mm Defect Location Defect Evolution and Changes in Performance
S6 99–119 S7 120–145	Diesel Oil Diesel Oil	**Sealed-Hole/large 2.0** mm Defect Characteristics Failure and Defect Evolution
S8 146–171	Diesel Oil	Leakage Location
S9 172–200	Diesel Oil	Failures Analysis, Changes in Performance & Effectiveness of Piezoelectric sensors

Figure 4.1: Details of the Lab Set-up (see original diagram print as attached in the Appendices)



5.2.10 Rig - Flow Station Construction:

1) 28mm Steel Pipe x 10 Mitres (Grade B/C Steel pipeline of ASTM A53 or equivalent
2) Diesel Pump (1x PGA 40-30 230v self priming transfer pump)
3) 20 litre Oil tank X 2 with lead (Tanks for feed and outlet - the capacity of the oil reservoir was determined to be 14litres, with 6litre allowance for over flow
4) 25mm Conduit Clip X 22 pieces
5) Gate Valve:- 28mm X28mm x 1 piece control Valves (Load/Unload oil flow) With a pneumatic powered sliding oil manually regulated control
6) 25mm Bore flexible plastic Tube (5 Mitre Length Pipe Connection)
7) Wide Band Hosepipe Clip - 37mm40mm X 10 pieces
8) 22mm x 28mm BSPT Parallel Connector x 4
9) 28mm X 28mm BSPT Elbow Connector x 2 pieces

Itemref
Quantity
Title/Name, designation, material, dimension etc
Article No./Reference
Designed by Bonny
Checked by Dr. K. G. Jones & Dr. Steve Woodhead
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1
Edition 1
Sheet 1/1

Photo 4.1: Dimensional Photos of the Test Oil/Water Rig and Flow Station

4.2.3 Instrumentation

The dynamic transducers used to detect the acoustic signal in the pipelines were rigidly mounted on the pipe by a standard pipe-fitting connection fabricated in the lab (Photo 4.2).

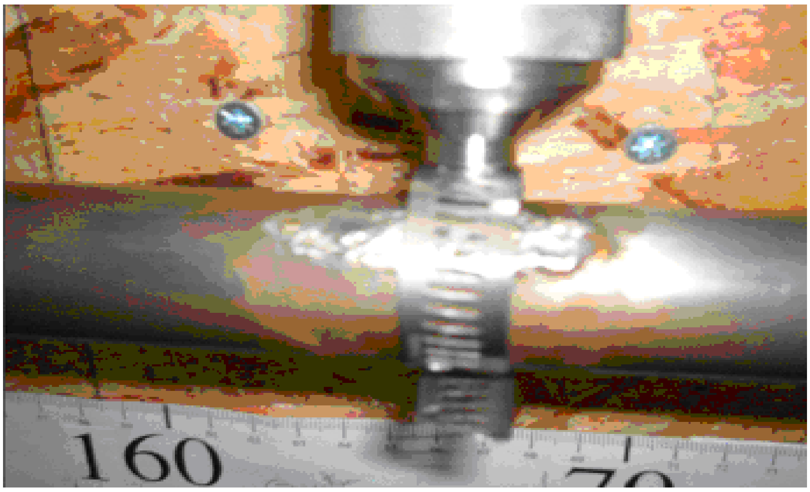


Photo 4.2: Coupled Transducers

The pressure transducers were coupled to the pipe wall and were able to pick up vibration sound signals transported by fluid flow through the pipe wall. A microphone-type sensor consisting of magnetic transducers, with input and output facilities, was connected to data acquisition equipment.

The sensor arrays were chosen for their capacities to measure signals in the order of hundreds of kilohertz. Data was collected every 15–20 seconds by both resonant and broadband sensors that were used for different applications, and the frequency ranged from 30kHz to 2MHz,

For this experiment 0–45kHz was considered ideal because it has a better frequency range and was more suitable for the entire test series. A frequency range of 0.5Hz to 15kHz at ±3dB was predicted (based on Test Series 1, S1) from the transducer's positions. It was expected that the amplitude of the vibration and acoustic signals would be affected significantly by variations in the changing condition of the steel pipeline system. The attenuation of the lower-frequency signals were less than those of the peak-frequency signals, resulting in a variation of signal strength linearly with the different defect types.

4.2.4 Data Acquisition Considerations, Software and Hardware

Vibration and acoustic emission data was collected from:

- the recording of damaged sources;
- characteristic and flow frequency (in time domain and frequency domain); and
- leak characteristic and flow frequency (in time domain and frequency domain).

The data capture and analysis software used throughout these experiments was the PICO ADC-212/3 integrated with data filter and Fourier transform. It has a 12-bit analogue-to-digital converter that was also used for digital representation of signal and vibration monitoring. The graphical representations (time record/frequency response) were created at 1,500 samples per second per channel and stored as 16 seconds of data at a preset command. The test signal was generated at 5kHz with a maximum frequency at 7kHz, making it possible to measure and record vibration signals from 0.1Hz to 250Hz. This setting represented a very adequate measurement range for the vibration signal from a damaged 1-inch pipeline.

Vibration measurements were taken using two sets of front-end piezoelectric vibration sensors (Wilcoxon Industrial Sensor, model Piezo-FET 793) and a hydrophone acoustic sensor used as a test probe (Photo 4.3). In addition, Telequipment Oscilloscope type D1011 was used as a confirmation system to the main oscilloscope CML 2105, an integrated system that comprised an liquid crystal display unit, a vibration analyser with inbuilt accelerometers, and charge amplifiers. The power source was from standard wall plugs and sockets. The filters were set at flexible high/low pass with automatically variable measurement gains. The oscilloscopes were set to measure at 0.5Hz (low-frequency limit) and 1kHz (upper-frequency limit). The measurement threshold setting was at ×1,000 to ×10,000 with 30–900,000cpm.

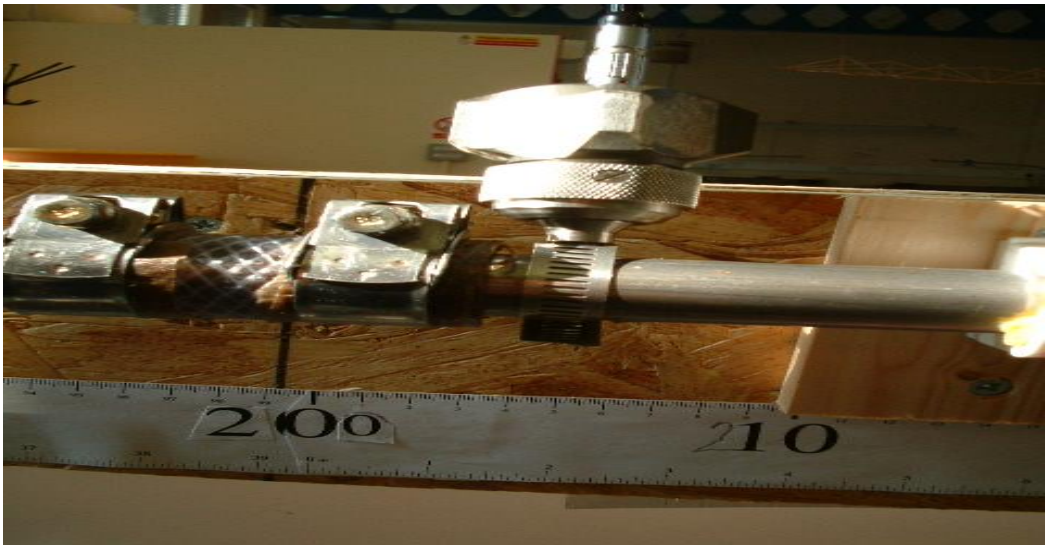


Photo 4.3: Sensor Probe Position Located at 204cm

4.2.5 Pipe Specimen

The choice of geometry for the 1-inch pipe specimen was based on practicality: ease of cutting, drilling and handling. Lateral dimensions of 10ft by 10ft (9.7m^2**)** were selected to represent the test oilfield. The configuration does not have any specific sample reference. A total of five mount point sensor positions were selected. Two coincided with the defect position on the test sample used in this experiment. The corrosion was simulated by drilling three sets of holes – measuring 0.5mm for test S2, 1mm for test S4, and 2mm for test S6 – and the holes were inserted with nails of the same size. The points on the pipeline were chosen at different distances, constituting the three defective states.

Leakage was generated by the nails being pulled out and the holes being sealed with a thin layer of solder, such that when the (pressure) flow rate increased, more force was exacted on the pipe wall and the solder join was caused to break, resulting in leaks (Photo 4.4). Diesel oil was the fluid inside the pipeline for Test Series 2. The pressure of the pipeline was generated and controlled by a pump.

Photo 4.4: The 60.2cm (2ft) Experimental Pipe Test Section (in the Centre at 160cm Mark Showing Sealed Defect)

4.2.6 Method Used to Locate Defect, Leak and Sensor Source

Figure 4.1 and Photos 4.1–4.4 give an idea of the oil/steel pipeline, the rig and the pipe test-specimen, as described above. The sensor numbers show the location of sensors, and the source is below sensors II and III. All dimensions are in centimetres, with sensors 3mm apart.

The sensor probe in position I was located at 43cm, on top of the pipe surface just before the corrosion defect propagation zone. That was after pipe-joint I and before pipe-joint II. Sensor probes II and III were positioned at 165cm and 168cm in the centre of the pipeline system. Sensor probe IV was at 204cm and sensor V at 300cm mark. Both were located past the pipe-joints and corrosion defects zone.

The defect or leak points were located at 160cm, 160.5cm and 161cm (leak point at 161cm), and the three drilled holes are within 5mm of each other. With *X* being the distance of the point of defect or leak from the reference sensing device as modified by equation (3.12), and given the schematic illustration Figure 3.4 that shows how the defect and leak point may be obtained (see section 3.4), we have:

$X_2 = D - X_1 \dashrightarrow \Delta T = (D - X_1 - X_1) / V \dashrightarrow X_1 = (D - VT\Delta) / 2$ (4.1)

e.g. X_1 = (leak point) at 161cm - A (i.e. sensor A) at 43cm, so X_1 = 118cm (4.2)

$X_{2\,=}$ = 4cm, $X_{3\,=}$ = 7cm etc.

Related information is given in Tables 4.2 and 4.3 following.

Table 4.2 Defect and leak mount position (*X*) and Sensor locations (Small, Medium, Sealed Holes without Nails, and Failure)

Sensor Mark	Sensor mount in cm	Distance to (*X*)
A-I **B**-II **C**-III **D**-IV **E**-V	-43cm 165cm 168cm 204cm 300cm	= 118cm = 4cm = 7cm = 43cm = 139cm

Table 4.3: Distance between the Two Sensing Devices

Distance between Two Sensors and Defect or Leak			cm
43cm as the sensor probe position (I),	to	165cm (sensor probe position II),	= 125cm
165cm as sensor probe position (II),	to	168cm (sensor probe position III),	= 3cm
168cm as the sensor probe position (III),	to	204cm (sensor probe position IV),	=36cm
204cm as the sensor probe position (IV),	to	300cm (sensor probe position V)	= 96cm
43cm as the sensor probe position (I),	to	300cm (sensor probe position V)	= 257cm
165m as sensor probe position (II),	to	204cm (sensor probe position IV),	=39cm
165cm as sensor probe position (II),	to	300cm (sensor probe position V)	=135
168cm as the sensor probe position (III),	to	300cm (sensor probe position V)	=132cm

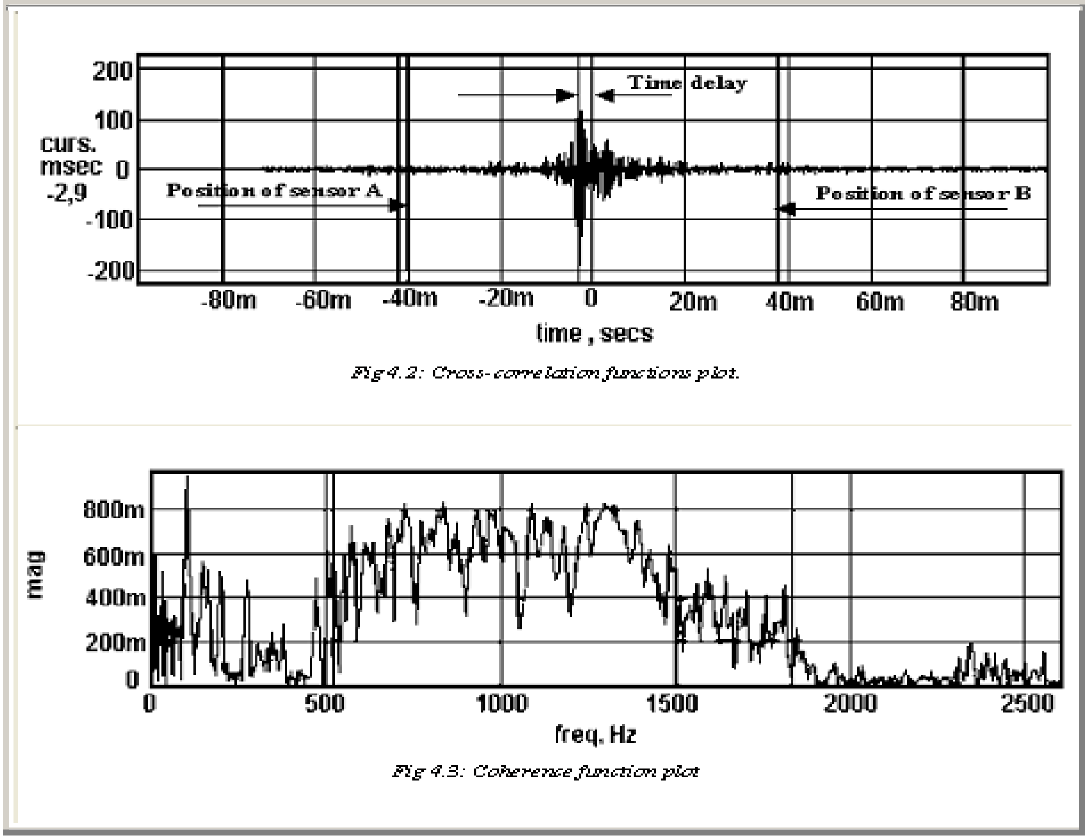


Figure 4.2: Cross-correlation Function; and Figure 4.3 Coherence Function Plot

The measurements of vibration and acoustic propagation were obtained from the steel pipeline specimen by taking an imprint of damage and leakage using a vibration sensor. Figure 4.2 shows the graphical illustration of vibration and acoustic sensor installations used to derive the vibration and acoustic signals. The respective values were then obtained by an average of the total direct measurements taken from the defect characteristic coupled to the flow dynamics.

The defect source was calculated to be located on the same plane of the pipeline system but the holes (small, medium, and sealed holes without nails) were not symmetrically located on the sample pipe. Figure 4.2 shows how the position of the defective and subsequent leak source may be obtained and further shows an example of the cross-correlation function.

The diagram in Figure 4.3 shows the position of the leak, in relation to the five sensing devices, and was determined by detecting the maximum cross-correlation function in relation to the signal's time delay. It compared two sensors' positions at a time.

The coherence function, shown in Figure 4.3, allowed the reliability rating of the measurement to be established. The dependence of the signals is defined, as those detected at any two of the five-measurement points A–E from a common defect-and-leak vibration/noise source. The coherence is normally represented between zero and unity; therefore, the nearer the coherence is to unity the closer is the link between the two or five detected signals.

4.2.7 Determining the Sample Size

The probabilistic method was used to determine the required size of sample with the following assumptions:

- $p\%$ = proportion of the target test runs;
- $q\%$ = sample proportion;
- Z = corresponding value;
- $e\%$ = margin of error;
- n = the minimum sample.

Sample size was determined using the following formula for a single proportion (Saunders et al., 2003):

$$n = p\% \times q\% \times [\frac{z}{e\%}]^2 = 25.4\% \times 74.6\% \times [\frac{1.96}{5\%}]^2 = 291 \qquad (4.3)$$

Here n is the minimum sample size required

$$p\% = \frac{2800000}{11035367} = 25.4\% \text{ (The proportion of the target test runs)} \qquad (4.4)$$

$$q\% = \frac{11035367 - 2800000}{11035367} = 74.6\% \text{ (Sample proportion; target experiments)} \quad (4.5)$$

z is the value corresponding to the level of confidence required (it is 1.96 if considered 95% certain)

$e\%$ is assumed as 5% (the margin of error required).

Then the adjusted minimum sample runs size, $n' = \frac{n}{1+\frac{n}{N}} = \frac{291}{1+\frac{291}{11035367}} = 290 \quad (4.6)$

Three hundred test runs were carried out in total: 100 for Test Series 1 and 200 for Test Series 2.

4.2.8 Measuring Flow Rate

The definition of volumetric flow rate [*Q*] is given by:

$$Q = V / t \; where \; V = volume \; and \; t = time \qquad (4.7)$$

‘Fluid’ in this context can be water or diesel oil since both are incompressible fluids that are relatively incapable of losing volume in response to pressure (and with similar flow characteristics, as noted in the lab experiments and supported by Jin et al (2003) and Vigneaux et al. (1988)). ‘Volumetric flow rate’ is defined as the flow of a volume of fluid through a pipeline system per unit of time, while ‘mass flow rate’ is related to volumetric flow rate by substituting *M* for *V* in the above equation, where *M* = mass = ρV, and ρ = density. As stated above, fluid density is assumed to be constant for incompressible fluids – but not for compressible fluids, where the volumetric flow rate must take account of information relating to temperature and pressure in order to truly represent the volume and mass flow rates.

Photo 4.5 shows the valves and out-reservoir tank, and the pump flow loop of the experimental set-up used. It takes a form similar to that of the pump suction device that is mathematically well described by the Bernoulli equation and modified by Munson (2002). Although that equation was made for a venture device, it was used to calculate the flow rate.

The key working equation was generally taken to be:

$$Q = CAT[2.p / \tilde{n}(1 - \tilde{a}4)]1/2 \qquad (4.8)$$

where *Q* is the volumetric flow rate, *p* is the measured pressure difference, *ñ* is the fluid density, *AT* the *(*pump suction) in-put cross-sectional area, *â* is a geometry factor, and *C* is the ‘output PGA 40/30t discharge coefficient’ related to discharge into the reservoir tank. This was constant and close to unity; it also accounted for vortex friction as the fluid exited into the tank. Cavitations were not a concern in this study.

Photo 4.5: Rig (Pump Suction) Input and Out-Reservoir Tank

Equation (4.8) above was appropriate for this experiment because Bernoulli's equation only applies along a single streamline and ignores the effects of viscosity. The difference between the ideal analysis and the real case was accounted for by the discharge coefficient *C*, which was a required factor. Determining *C* was part of this lab exercise; therefore the actual diesel-oil flow rate measurement was made using the same technique as used for Test Series 1 with water.

The study adopted the very crude form of measuring flow rate, because a fully enclosed channel comprising pipes and tubes does not require a sophisticated technique. Therefore a manual method was used during which a transparent 2-litre PVC measurement jar was calibrated by pasting white tape from top to bottom and graduating it with numbers 1 to 100. This jar was used to collect the oil discharge, amounting to 11 litres in 1.65 seconds, which is equivalent to *Q* being 6.6 litres per second. The flow rate was measured using a mass scale and stopwatch as described above.

4.3 Experimental Procedure and Measurement

It was noted that the sound and vibration measurement frequency range were occurring between 0.1Hz and 46.9kHz, and it occasionally extended to 100kHz. The temperature of the tap water used was 25°C with a viscosity coefficient of 1.0 cP, a density of 1.0 g/cm^3, and a vapour pressure of –733 mm Hg; (based on Lee et al. (2005)). Equally, the diesel oil temperature was between 15°C and 35°C, with a viscosity coefficient of 0.85, and a density of 1.0 g/cm$^{3.}$.

The data sets collected during these spot measurements were typically for one-minute durations. The test equipment ran for 20 minutes each time after start-up and configuration but before data was collected, to allow the system pump temperature to normalise. The characteristics of the sound and vibration analysis signal's energy level and frequency spectrum were established.

The knowledge gained in Test Series 1 (with water and oil) of the pipeline system's natural frequencies helped to better understand the diesel oil (Test Series 2) runs. The accelerometer sensors transformed the pressure (in pa) and the acceleration (in msec^{-2} or units of *g*) into a voltage (in volts) with a sensitivity of 10–100mV/g. The piezoelectric sensor was powered from an oscilloscope. Other test variables that were deemed not so relevant to the test were fluid temperature, viscosity and velocity. The least relevant of all was pipe-bend, which was assumed to have negligible effect in this study so no test was done to determine its effect.

The piezoelectric sensors used were very responsive to dynamic signals; the limitations of the dynamic response generally arise from the inertia of the pipeline system and the data acquisition equipment. To this effect, efforts have been made to identify and utilise a more effective source-identification technique for the 60cm experimental test section of pipe used.

4.3.1 Test Series 1: Test Run Setting and Procedures

Photo 4.6: Connected to CML 2105 Fourier Transform & PICO-Tec Oscilloscope ADC 212

In order to establish and compare the readings from the sensor (vibration and acoustic) and two oscilloscopes, the sensor was connected to channel 1 and set to 2ms by 10mV ×5, adjusted to zero level. Photo 4.6 shows the pc/laptop data-logger attached to a serial port, with the signal generator set at 5kHz on a time-based frequency of 7.5kHz as set out in Table 4.4.

Table 4.4: Oscilloscopes Settings for the Experimental Test

Variables	**Figures**
Time Based	= 7.50kHz
Options; *X* axis	= Linear
Y axis	+dB
Signal Generator	= 5kHz
Window	Blackman
Settings test	Recording Method: Real time, continuous.

The oscilloscopes were set to repeat scanning at the end of each signal scan-run immediately. However, the restart had a fixed delay of 1 second utilising multiple converters.

The data-sampling rate and interval were set to collect data at 1ms intervals for a maximum of 300 scans. The readings per scan were adjusted automatically to ‘as many as possible’. Setting scan time configurations at 100,000μs helped to carry out tests with a high number of scan cycles within each set time-cycle, and also to conduct a series of tests within different frequency bands.

Figure 4.4 shows results for the pipe in the experiment when it was operating in its normal state, as derived from the (averaged) details of the experimental test runs that are shown in Appendix A2 Tables C–G and Figure A3.1 - Table AH. This information helps the choice of the suitable frequency range for Test Series 2. The resulting amplitude and frequency profiles were measured at 11.70kHz, 23.95kHz and 46.90kHz; each had similar sample rates and the differences produced in each test were negligible. Figure 4.4 showed that 46.9kHz has a better frequency range and was more suitable for the entire test. Consequently, the rest of the test programmes were carried out at 46.9kHz.

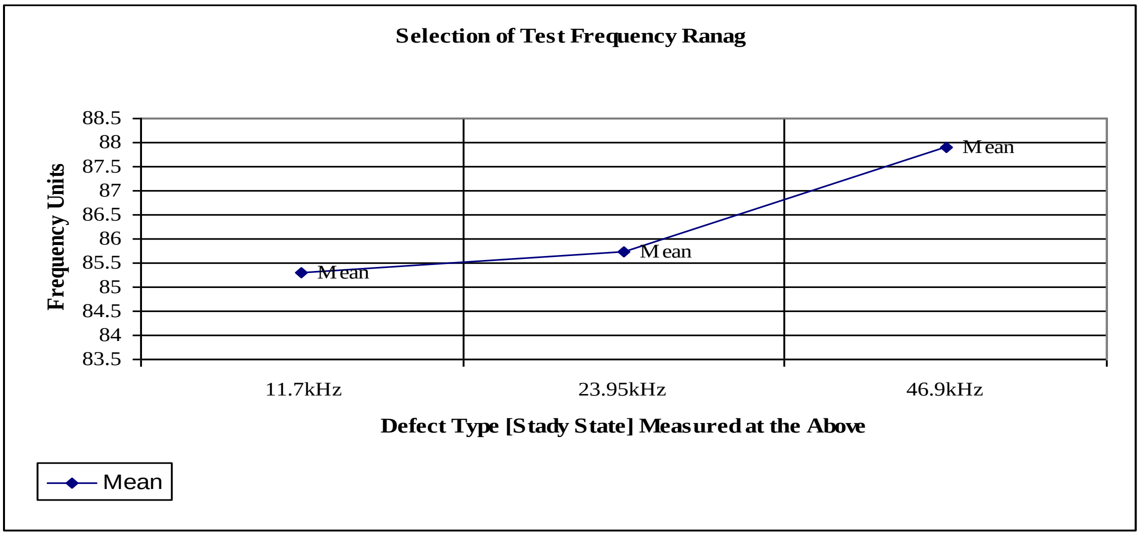


Figure 4.4: Amplitude and Frequency Selection to Determine Sample Rate for Tests Series 1 (Data taken from Table 4.4)

CHAPTER 5: EXPERIMENTAL RESULTS

5.1 Introduction

For the test configuration used in this study, the theory suggested that the results would lie in the range of 2Hz to 5kHz, or typically ±5% variations on the average; this was confirmed by Agarwal and Bull (1989). The results from this study agreed with those suggested results, with the exception of the defect burst-and-leakage tests on the average values taken from sensor location (at C in Figure 3.4). The modulated signal that was expected from the theory was -0.139, but what was recorded was +5.89, and this requires further in-depth analysis.

The results obtained in these experimental tests were encouraging; in particular, it was possible to determine the defect characteristics and location of the defect. There were nevertheless certain limitations, and one of the most significant amongst these was that the test was conducted with limited equipment. For example, five separate sensors would have been ideal but only two were available, which meant that the test had to be repeated many times. It is suggested that future tests should be conducted with more robust equipment.

The time interval measurement using the spectrum analysis method and Fourier transform and wavelet analysis utilised low- and high-frequency intelligent decomposition filters that automatically processed data without being stored first. That made it possible that when the wavelet coefficients exceeded a threshold, the most recent data samples were automatically processed *in situ*. The advantage of this approach compared with others is that the system could be integrated as a miniaturised unit with sensing, processing (cross-correlation) and reporting capabilities. Therefore it can be deployed as a continuous monitoring solution able to carry out remote analysis and reporting without third-party input. It was assumed that the characteristics of the acoustic emission propagate consistently in all directions away from the defect or leak, generated by the leaking oil flowing through the fissure in the pipeline system.

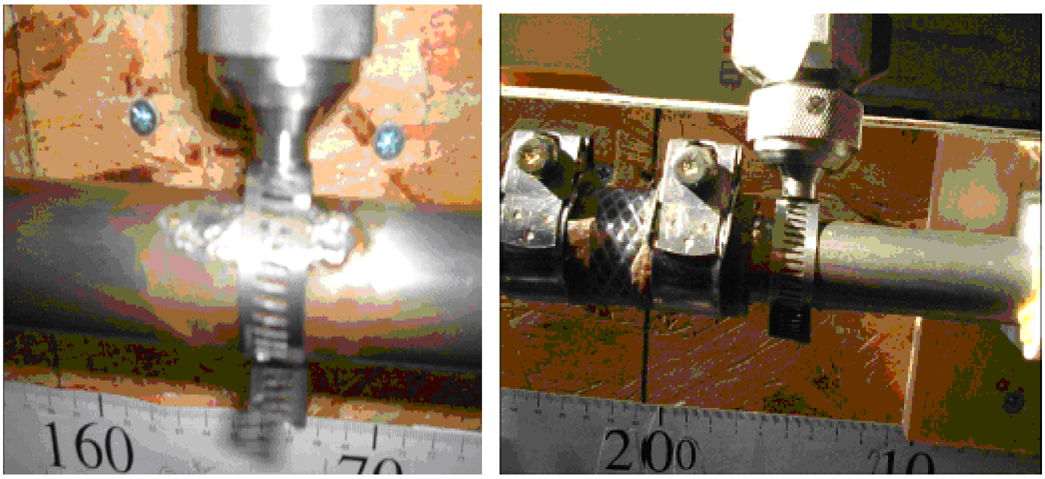
5.2 Test Series 1 Results; Determining the Natural Frequency of the Experimental Pipeline System

A detailed description of the test and analysis approach was outlined in section 4.3.1. Test Series 1 (S1, tests 1–100) was devised to determine the natural frequency of the experimental pipeline system and the flow medium, and to identify the background noise from the test apparatus. The pump, in particular, was expected to produce additional pressures and sound waves in the pipe while transmitting fluid, in addition to those associated with the failure modes being investigated.

The pipeline system consisted of three sections of pipe joined together in such a way as to allow the middle section to be replaced in each test, in order to simulate the different failure modes to be investigated. A theoretical analysis of the pipeline system suggested that sound-inducing activities would be generated in the pipeline system. A total of 300 tests were carried out at five sensor locations (labelled I–V but shown as A–E in Figure 3.4), with associated acoustic signals and pressure wave emissions recorded. The first 100 tests were performed to establish the effect of the presence of the three joints and other characteristics present in the model pipeline system, and the results are depicted in Figures.5.1a to 5.1e. Two hundred subsequent tests were conducted to identify the effect of the induced failure modes.

5.2.1 Signal Source and Characteristic Identification

When the fluid inlet valve was turned to full pressure during a test, fluid rushed through the steel pipeline. As a result of the flow, the sensors (Photo 5.1) recorded the acoustic and pressure wave emissions signals (as opposed to when the system was at rest). These recordings were effectively the natural frequency of the ‘undamaged’ pipeline system. It should be pointed out here that the inlet pressure was not recorded and as such the natural frequency readings obtained are only applicable to the two test series for the model test-rig. The impact of different inlet pressures on the natural frequency of the pipeline system will be examined in the next stage of the research.



a Sensor number **II** **b** Sensor number **III**

Photo 5.1 a & b: Sensor Numbers II and III on the 60.2cm Experimental Test Pipe Section

To locate the different defects in the pipeline system, it was necessary to find a signal characteristic at each sensor that belonged first to the natural frequency of the test apparatus, and then for the defects and leakage locations. This was accomplished in the experimental Test Series 1 and 2 by monitoring the damage location with five sensors and then searching for similarities in the signals produced by the sensors. When such similarities were found, the time difference of their arrival at each sensor was determined. Using this time difference and the sensor spacing, it was possible to determine the location of the damage or leakage. A typical plot of frequency (signal) for normal flow, small–major defects, and failure recorded at the five sensor locations are shown at Figures 5.1a to 5.1e. Similar plots were observed for all tests in Test Series 1 and 2 (including the sub-series in Test Series 2).

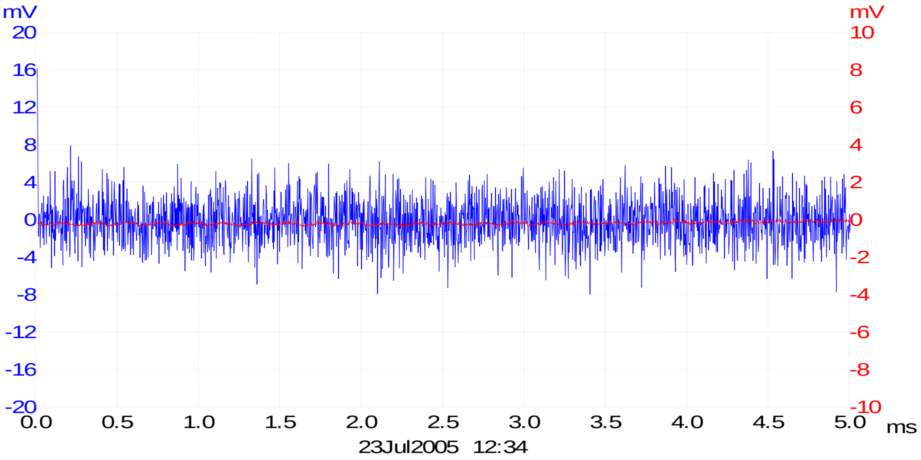


Figure 5.1a: Signal Characteristic Belonging to Defects and Leaks (Normal Flow)

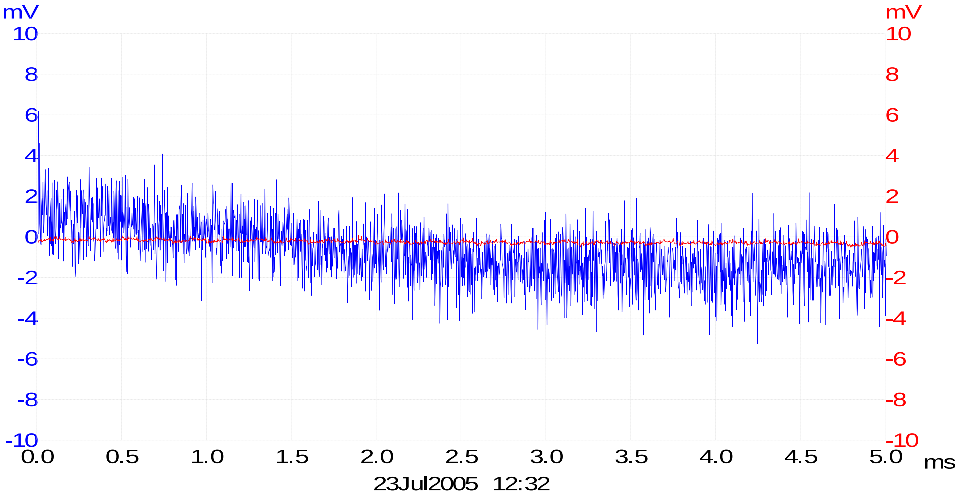


Figure 5.1b: Signal Characteristic Belonging to Defects and Leaks (Small Damage)

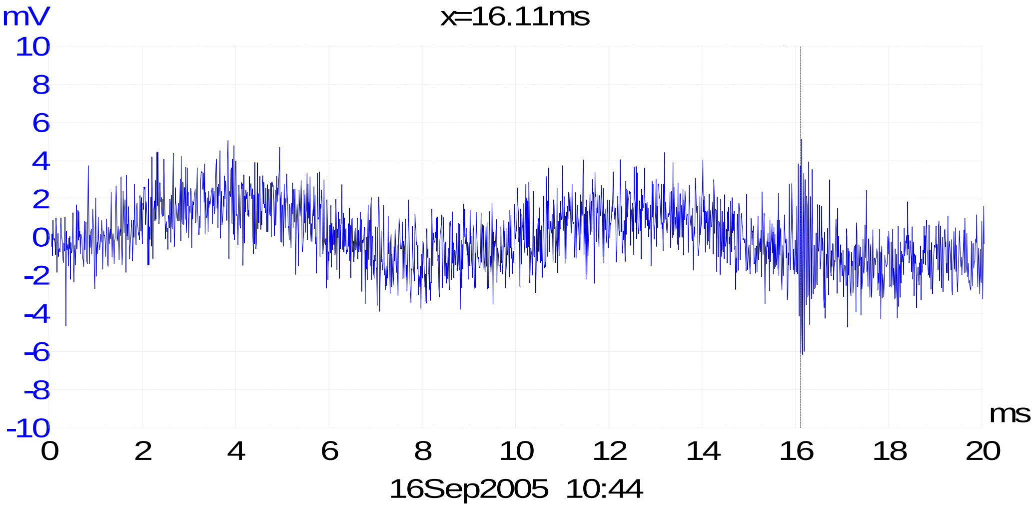


Figure 5.1c: Signal Characteristic Belonging to Defects and Leaks (Medium Damage)

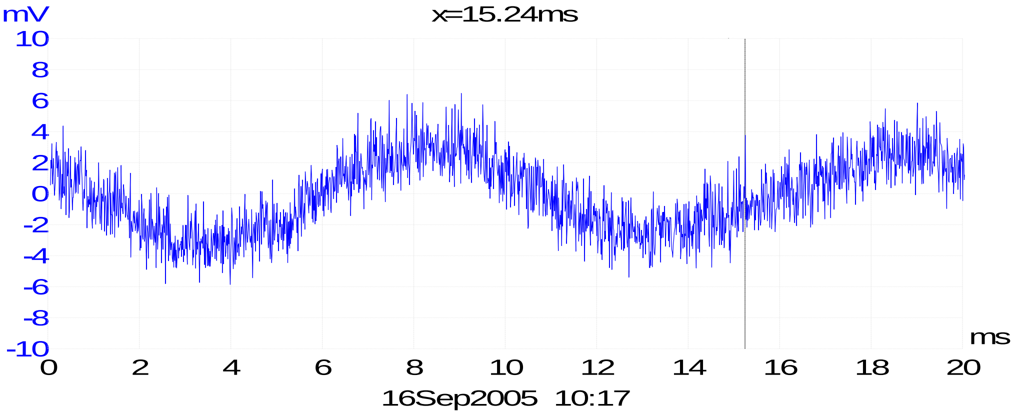


Figure 5.1d: Signal Characteristic Belonging to Defects and Leaks (Major Damage)

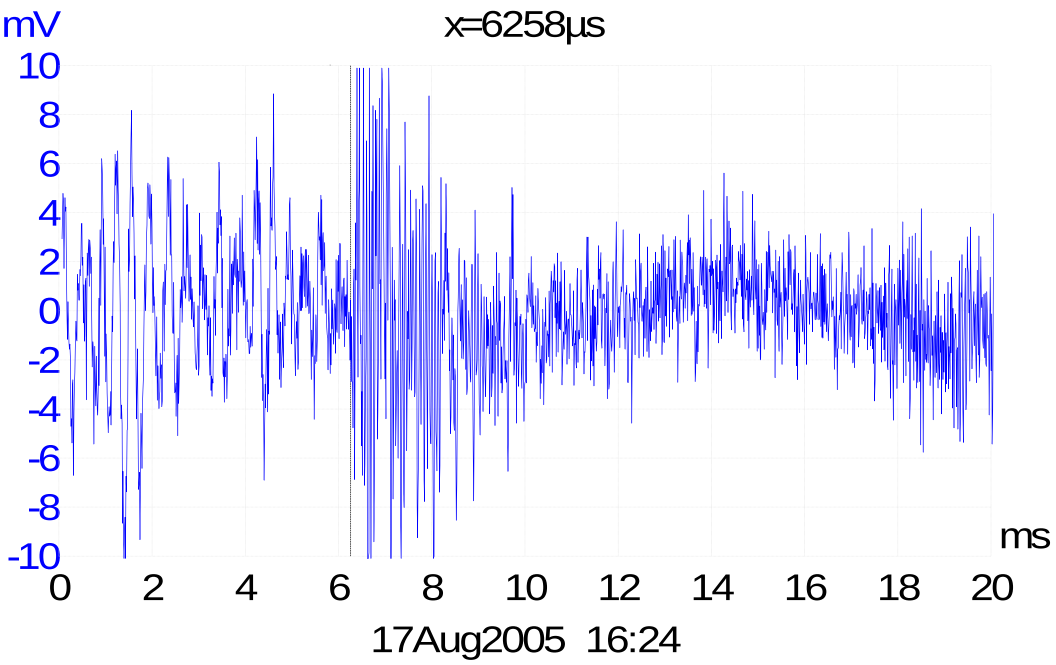


Figure 5.1e: Signal Characteristic Belonging to Defects and Leaks (Failure)

5.2.2 Graphs Showing Readings at all Sensor Locations

In addition to the results presented in Figure 5.1 above and Table 5.1 below, five more sets (one for each sensor location) displaying similar graphical representations of natural frequency are available in Appendix A. A total of 10 test runs were carried out at sensor location I (point A in Figure 3.4, 43cm from the reference point), for which Figure 5.2 (Graphs 1A and 1B) show typical natural frequencies and the corresponding spikes. The time differences between signals arriving at sensor location I and its counterpart arriving at sensor locations II, III, IV and V at later times were recorded.

The readings from the experimental apparatus were noted for a range of permutations involving six test scenarios and five sensors. Each test scenario corresponded to one of the six items of the experimental apparatus, and there are five sets of readings each corresponding to one of the five sensors (see Table 5.1).

This is how the table was populated with the data. The first test scenario corresponds to water flow, and a water flow frequency (and the corresponding spike) was measured five times, one for each of the five sensors, one by one. Thus, row 1 in each of the five sets of data in Table

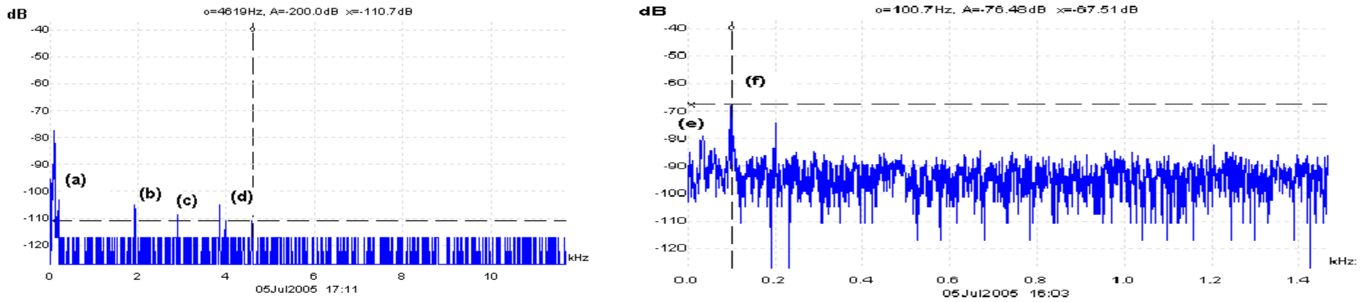
5.1 was filled. Similarly, for Test Scenario 2, readings of frequency (and corresponding spike) were noted down for Joint 1, for each of the five sensors, one at a time. Thus, row 2 of each of the five sets was completed. Similarly for the remaining rows, and this is how the whole table was populated up to the sixth item (i.e. Test Scenario 6) for each sensor at a time.

For each set of test scenarios and sensors, there are two graphs. One corresponds to frequencies of Water Flow, Joint 1, Joint 2 and Joint 3 (i.e. a, b, c and d, respectively), while the others represent the pump and oscillator (i.e. e and f, respectively). Thus, in total there are 10 graphs per test. For these 10 corresponding graphs, see Figure 5.2 for sensor location 1 (graphs A and B) to sensor location 5 (graphs A and B).

Table 5.1: Readings from the Experimental Apparatus

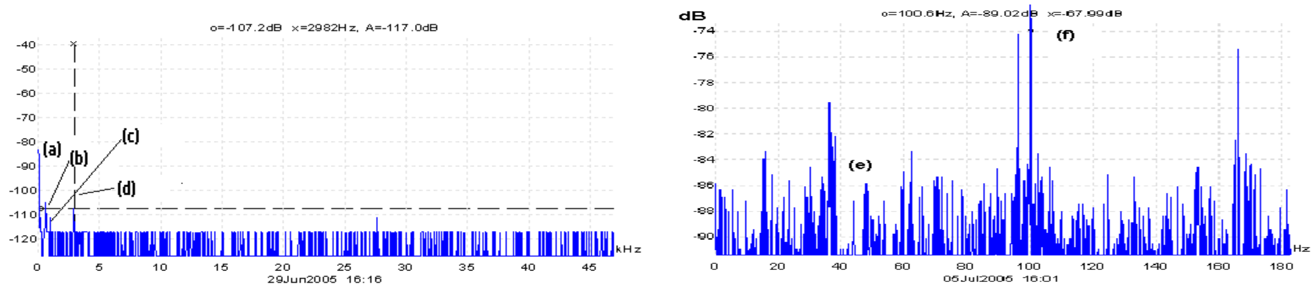
Test Scenario No.	Sensor No.	Item description	Item detonation	kHz	dB
1	1	Water flow	a	0.1 kHz	-112dB
2		Joint 1	b	1.5 kHz	-114dB
3		Joint 2	c	2.69 kHz	-110dB
4		Joint 3	d	4.7 kHz	-108dB
5		Pump	e	0.4 kHz	-110dB
6		Oscillator	f	0.5 kHz [Fig 5.2a&b]	-95dB
1	2	Water flow	a	0.16 kHz	-110dB
2		Joint 1	b	2. 81kHz	-114dB
3		Joint 2	c	3.79 kHz	-114dB
4		Joint 3	d	4.78kHz	-108dB
5		Pump	e	0.4 kHz	-110dB
6		Oscillator	f	0.5 kHz	-95dB
1	3	Water flow	a	0.12 kHz	-112dB
2		Joint 1	b	2.79 kHz	-114dB
3		Joint 2	c	3.78 kHz	-114dB
4		Joint 3	d	4.90 kHz	-108dB
5		Pump	e	0.4 kHz	-110dB
6		Oscillator	f	0.5 kHz	-95dB
1	4	Water flow	a	0.17 kHz	-115dB
2		Joint 1	b	2.75 kHz	-113dB
3		Joint 2	c	3.78 kHz	-114dB
4		Joint 3	d	4.98 kHz	-108dB
5		Pump	e	0.4 kHz	-110dB
6		Oscillator	f	0.5 kHz	-95dB
1	5	Water flow	a	0.14 kHz	-111dB
2		Joint 1	b	2.89 kHz	-114dB
3		Joint 2	c	3.78 kHz	-112dB
4		Joint 3	d	4.77 kHz	-108dB
5		Pump	e	0.4 kHz	-110dB
6		Oscillator	f	0.5 kHz	-95dB

Figure 5.2: Natural Frequencies



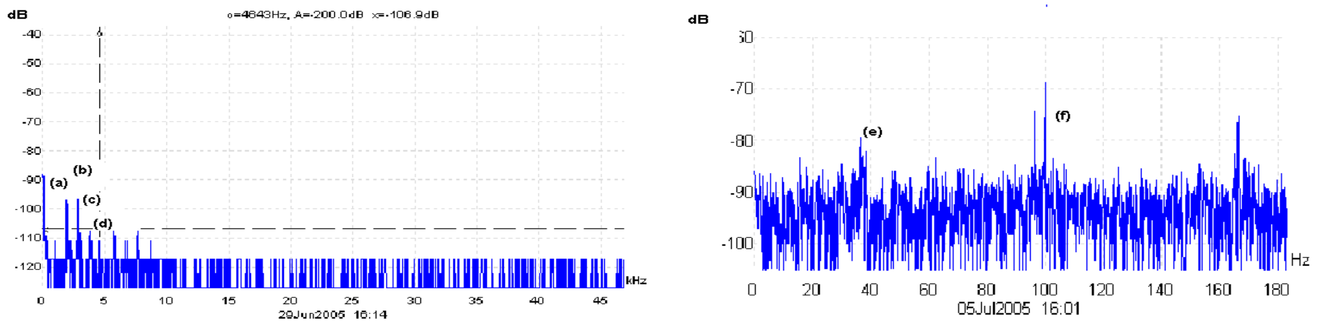
1A: Sensors Location [I] -43cm no amplification

1B: With Amplification



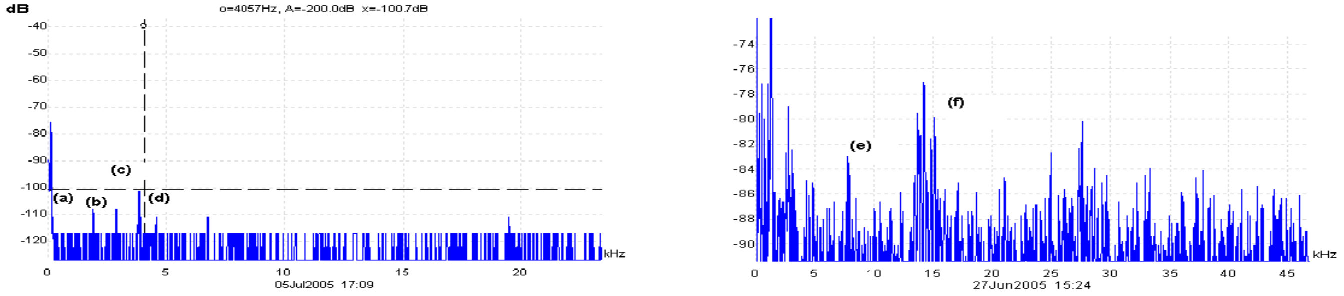
2A Sensor Location [II] 165cm no amplification

2B: With Amplification



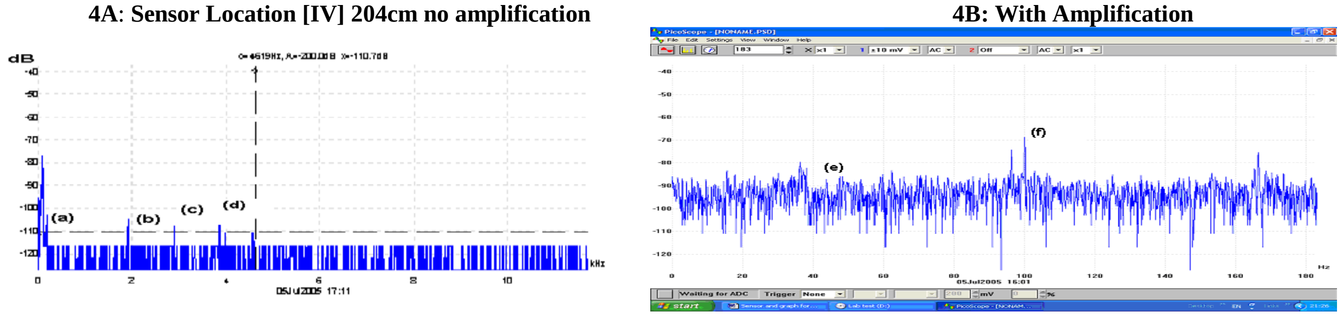
3A: Sensor Location [III] 168cm no amplification

3B: With Amplification



4A: Sensor Location [IV] 204cm no amplification

4B: With Amplification



5A: Sensor Location [V] 300cm no amplification

5B: With Amplification

5.2.3 The Signals

Table 5.2 summarises the results for all the natural frequencies of the test equipment and flow media used in Test Series 1. The data was derived from Figures 5.3a to 5.3b. The isolated spikes indicate the natural frequency response of the pipe and the system, which show profile similarities to those in Figures 5.2a and 5.2b for the oscilloscope and pump. However, it was not very clear at first whether the signals originated from the joints, the pump, the flow mechanism or other noise sources. After detailed analysis using the coherence and cross-correlation function, (see Figures 4.2 and 4.3), it was possible to establish that the vibration signals originated from (a) joint 1 nearest to the sensor at the 43cm mount before the defect source, and (b) joint 1 nearest to the sensor mounted after the 168cm position mark on the pipe surface.

Table 5.2: Measured Averaged Natural Frequencies of Test System Mounted at (II) in Test S1

System	f (kHz) Natural	Amplitude (dB)
Water flow	0.1 kHz	(-34dB)
Pump	0.4 kHz	(-110dB)
1st joints	1.5 kHz	(-114dB)
2nd joints	3.8 kHz	(-114dB)
3rd joints	4.7 kHz	(-108dB)
Oscillocope	0.5 kHz (Figure 5.2a and b)	(-95dB)

Because the readings presented in Table 5.2 are the natural frequencies of the test equipment, they can be eliminated from those recorded when the defect was introduced into the pipeline system in Test Series 2. The natural frequencies of the test equipment shown on Table 5.2 can also be seen graphically as spikes on Figures 5.3a and 5.3b.

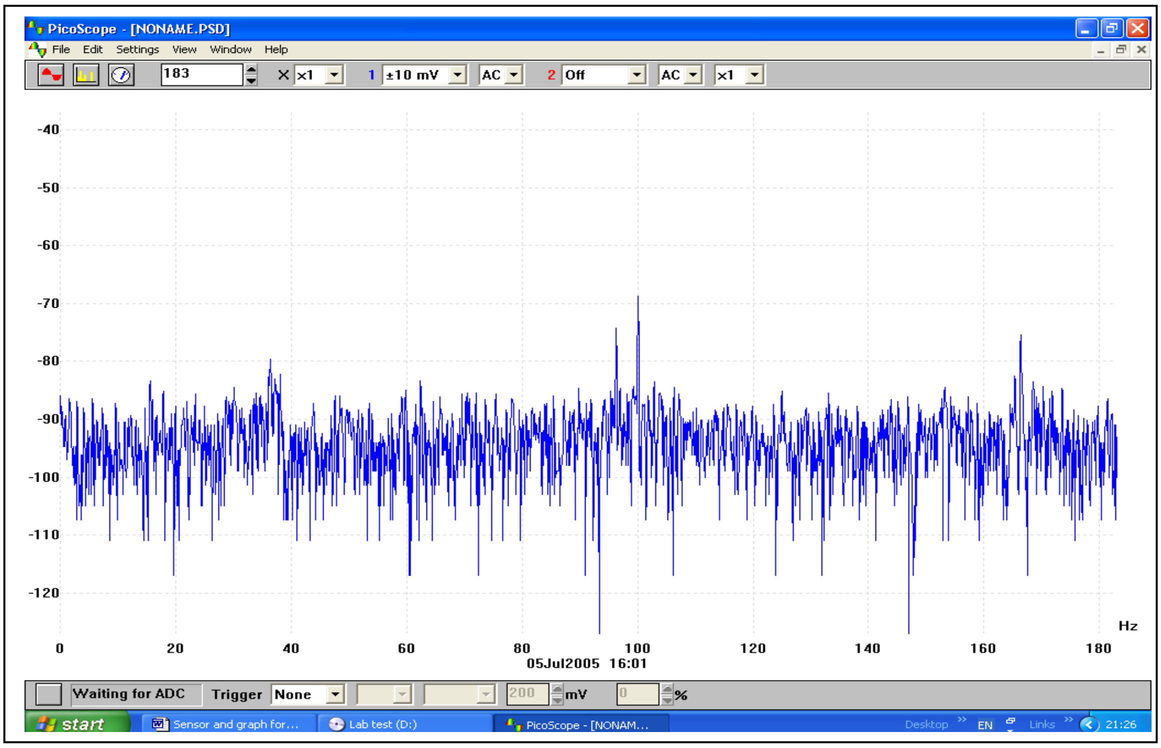


Figure 5.3a: Measured Natural frequencies (enlarged to183Hz) of Test System with Sensor Mounted at (II) in Test 1

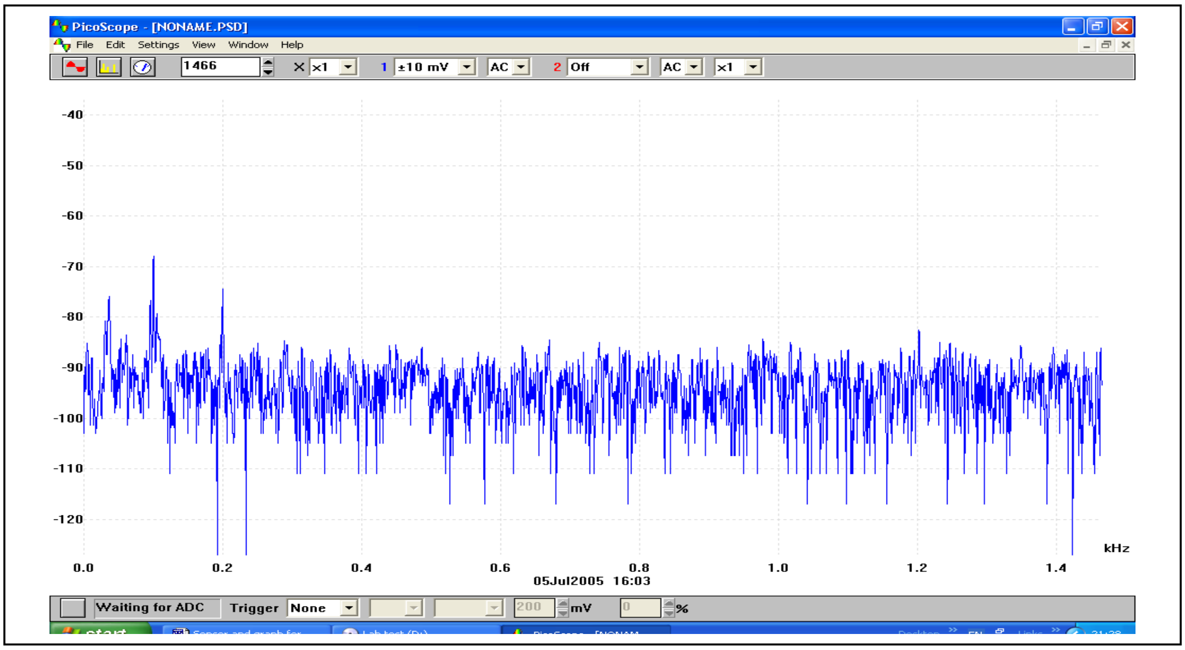


Figure 5.3b: Measured Natural Frequencies (enlarged to 1.5kHz) of Test System with Sensor Mounted at (II) in Test 1

5.2.4 Discussion

In the pilot study, Figures 5.1a to 5.1e provided a series of graphic representations showing the natural frequency readings at the sensor positions when the pump was turned on. In this state there was a resultant pressure and acoustic signal, which was recorded at the five sensor locations. Table 5.2 summarises the result of all the natural frequencies of the test equipment and the media: the average frequency was 4.7dB and the standard deviation was 1.10. This data was used to provide control values in Test Series 2 to differentiate between the damage profile and the natural frequencies. The natural frequencies and the modulation of the modelled oilrig specimens were among parameters measured in the pilot study. Thereafter the impact of the modelled defects and leaks on the oilrig were measured in Test Series 2.

The signal sources for the first set of natural frequencies are shown on Table 5.1, and Figure 5.2 shows the natural frequency measured at sensors in positions I, II and III. These results indicate that the pipeline system behaviour approximates very closely to one in which the frequencies of the pump and the water flow are indistinguishable by the vibration method due to symmetry. The presence of the joints at ± 0.3kHz reduced the degree of pipe vibration regularity. The natural frequency of water transmission was measured as 0.4kHz (volumetric flow at 6.6 litres per second – see equation (4.8) in section 4.2.8), and the frequency changes were correspondingly small, as shown in Table 5.4 and Appendix A. Tests Series 1 was conducted blind without reference data. However, small differences in the frequency changes were expected owing to the small differences in material used, i.e. wide-band hosepipe clips and vales joints.

Test procedures were repetitive and it took time to establish the natural frequencies of the pipeline system. These tests demonstrated the need for caution in interpreting measured data representing the pipe’s natural frequency and the pipeline system components and equipment. The two cases where this effect caused erroneous results were the only tests in which the oscilloscope was not correctly identified.

The frequency response shows the behaviour of the test pipeline system during a frequency change. Usually the amplitude of the input signal and the output signal amplifiers are noted, as the frequency is dynamic during measurement. In essence the frequency response contains two substantial characteristics, amplitude and phase. Generally the amplitudes were noted against frequency, as was the phase frequency. The oscilloscope display of the natural frequency is shown in Table 5.2. In this instance, the natural frequency was correctly predicted to be in one of the band's signal. In view of the approximations made in the analysis, reasonable agreement is shown between the measurements given in Figure 5.2 and Table 5.2.

To establish the respective resonances was difficult for Test Series 1 using water and oil, as is evident in Table 5.3, which shows minimal differences in amplitude and frequency. Therefore, the water's normal-state envelope signal was used as the natural frequency in this investigation. The water used had a viscosity of 1.0 at a velocity of 6.6 litres per second. It was supposed that the large waveform generated was as a result of the defect signal coupling to the liquid flow and was responsible for the vibration and acoustic resonance. This was in contrast to Test Series 2, where an increment of energy above the set voltage threshold for this test was consequently produced, resulting from the appearance of a burst and leak that generated the acoustic signal.

Table 5.3: Comparison of Amplitude vs Frequency for Oil and Water Normal-State Envelope Signals

Sensor Location	**Enveloped Signal (dB) for WATER Amplitude vs Frequency**		**Normal State Measured at 46.9kHz**	
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	Normal	kHz
I	O=65.14dB	X=89.51dB	Normal	46.9kHz
II	O=67.70dB	X=89.05dB	Normal	46.9kHz
III	O=66.914dB	X=88.69dB	Normal	46.9kHz
IV	O=64.69dB	X=88.21dB	Normal	46.9kHz
V	O=64.67dB	X=87.95dB	Normal	46.9kHz

Sensor Location	**Enveloped Signal (dB) for OIL Amplitude vs Frequency**		**Normal State Measured at 46.9kHz**	
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	Normal	kHz
I	O=64.14dB	X=89.50dB	Normal	46.9kHz
II	O=67.71dB	X=89.06dB	Normal	46.9kHz
III	O=66.89dB	X=88.70dB	Normal	46.9kHz
IV	O=64.68dB	X=88.20dB	Normal	46.9kHz
V	O=64 .68dB	X=87.96dB	Normal	46.9kHz

5.3 Test Series 1: Result Summary in the Frequency Domain

The procedure followed for the classification of the pipeline system's natural failure response in the frequency domain is given here. The effort to assess the acoustic emission and vibration activity in the frequency domain was to enrich the no-defect identification/characterisation process. A fast Fourier transform (FFT) analysis of acoustic emission and vibration waveform was also used for the identification of the pipeline failure modes. In order to find the mean values, the difference between the mean of the maximum amplitude and the mean of the frequency was then taken and divided by two to find the average amplitude of the strain for each sample segment. The mean depth of modulation, *m*, of a random-amplitude modulated vibration signal $X(t)$, measured in decibels, was determined as a percentage using the mean value of the envelope $\bar{X}(t)$, thus:

$$\boldsymbol{m} = \frac{\bar{X}\max(t) - \bar{X}\min(t)}{\bar{X}\max(t) + \bar{X}\min(t)}.100\% \qquad (5.1)$$

where $\bar{X}_{\max}(t)$ and $\bar{X}_{\min}(t)$ are the maximum and minimum values of the enveloped signal respectively. In this study the modulation *m* represents the mean percentage values in decibels, as indicated in Table 5.3 (water and oil control tests) and Table 5.4 (theoretical natural frequencies). The theoretical means indicated in the table show only the normal state at different sensor locations along the pipe. Furthermore, they show that the theoretical mean values for the enveloped signal of the normal state have a slight difference at each sensor location.

Table 5.4: Assessment of Normal-State Envelope Signal in Amplitude vs Frequency for Water

Sensor Location	**Enveloped Signal (dB) Amplitude vs. Frequency**		**Normal State Measured at 46.9kHz**		**Theoretical**
	$\bar{X}_{\max}(t)$	$\bar{X}_{\min}(t)$	Normal	kHz	
I	O=65.14dB	X=89.51dB	Normal	46.9kHz	-0.135
II	O=67.70dB	X=89.05dB	Normal	46.9kHz	-0.136
III	O=66.914dB	X=88.69dB	Normal	46.9kHz	-0.139
IV	O=64.69dB	X=88.21dB	Normal	46.9kHz	-0.153
V	O=64.67dB	X=87.95dB	Normal	46.9kHz	-0.152

5.3.1 Influences of the No-defect Test

From the findings presented in this section, it would appear that the spectral method and the analysis method have been successfully applied. It was possible to determine the natural resonant frequencies and characteristics of the different joints and relevant components that constituted the experimental pipeline system. It can be assumed that the predetermined natural frequencies will not have a significant influence on the experimental defect profiles when fully filtered out for Test Series 2. What is required to determine the defect frequencies is a straightforward and easily applicable method that takes advantage of these findings and that can allow the defect signal’s source and characteristics to be calculated.

5.4 Test Series 2: Result Summary

5.4.1 Laboratory Equipment Set-Up

The same basic test procedure was used for Test Series 1 and 2. Test Series 2 measured the frequencies and modulation of the defect parameters shown in Table 4.1. The ‘defect’ refers to: the small and medium nail insertions; the sealed hole (simulating corrosion); and failure causing bursting/leaking. Using the theoretical steady-state prediction from the pilot study, it was possible to calculate the changes in overall damage rate that had occurred. The differences between the predicted mean values and measured changes in attenuation were due to the damage profiles introduced by the insertion and removal of nails (modelled corrosion). More specifically, the relative magnitude of the flow pressure and the coupled waveform (acoustic and vibrations emission) signals were very strongly affected, as can be seen in Tables 5.5 to 5.12.

5.4.2 Details of Experimental Results in the Frequency Domain

The values measured are given in Table 5.5 for the small defect at sensor location I, showing the difference between what was expected and what was recorded. The expected mean value was 0.135 but the actual result was 0.102, a difference of 23%. At sensor location II, 0.136 was the expected result but the actual result was -0.110, which is 24% smaller. The same trend was observed at Sensors III, IV and V. The trend in the expected mean value percentage, and what was measured, can be said to be variable.

A similar pattern can be seen for the medium-nail defect, sealed holes and bursting/leaking (Table 5.5). No explanation could be found to justify the apparent difference at sensor location III for the sealed hole.

The hypothesis was that the more a defect develops, the greater the depth of the resulting modulation m**.** Therefore the frequency of modulation defines the type of defect, and the depth of modulation defines the defect size as it progresses. Following equation (3.6) and (5.1), the amplitude of the vibration signal $X(t)$ was determined in percentage terms using the mean value of the envelope. The mean percentage values that correspond to the damage transformation patterns and their failure modes are given in Table 5.9 to 5.12.

The difference between the mean values (at sensor location III) for small defects was -0.245dB, and at failure the mean value was -0.209dB (with sampling difference of ±5%). This suggests that nail insert signals (i.e. damage signals) emitted from the damaged location might have contained one or two possible defect profiles within the same frequency band.

Table 5.5: Assessment of Envelope Signal in Amplitude vs Frequency for SMALL DEFECT

Sensor Location	Enveloped Signal (dB)		Defect Type [Small]		Measured	Theoretical	Difference	% age
	Amplitude	Frequency			(M)	(T)	(T – M)	[(T – M) / T] x 100
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	**Small**	**kHz**				
I	O=72.78dB	X=89.95dB	Small	46.9kHz	-0.102	**-0.135**	-0.033	24.44
II	O=71.96dB	X=89.88dB	Small	46.9kHz	-0.110	**-0.136**	-0.026	19.12
III	O=71.85dB	X=88.89dB	Small	46.9kHz	-0.106	**-0.139**	-0.033	23.74
IV	O=71.79dB	X=88.87dB	Small	46.9kHz	-0.106	**-0.153**	-0.047	30.72
V	O=71.73dB	X=87.95dB	Small	46.9kHz	-0.101	**-0.152**	-0.051	33.55

Table 5.6: Assessment of Envelope Signal in Amplitude vs Frequency for MEDIUM DEFECT

Sensor Location	Enveloped Signal (dB)		Defect Type [Medium]		Measured	Theoretical	Difference	% age
	Amplitude	Frequency			(M)	(T)	(T – M)	[(T – M) / T] x 100
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	**Medium**	**Hz/kHz**				
I	O=88.95dB	X=82.97dB	Medium	46.9kHz	+0.035	**-0.135**	-0.17	126
II	O=81.88dB	X=85.98dB	Medium	46.9kHz	-0.024	**-0.136**	-0.112	82.35
III	O=86.89dB	X=82.89dB	Medium	46.9kHz	+0.024	**-0.139**	-0.163	11.75
IV	O=83.87dB	X=88.85dB	Medium	46.9kHz	-0.028	**-0.153**	-0.125	81.7
V	O=83.95dB	X=87.97dB	Medium	46.9kHz	-0.023	**-0.152**	-0.125	84.87

Table 5.7 shows defect concentrations and variations in the results for the sealed-hole tests of typically ±5% on the average values. Take sensor III, for instance: theoretically what was expected was -0.139, but the actual result was +5.89. These results are in contrast to the values shown in Table 5.8, where the expected result for total failure was -0.139 but the measured result was +0.024, a difference of 24%. The assumption here is that the damage causes a sudden leak and the pressure of the escaping oil generates acoustic energy via a ‘burst’ signal. The continuous sound emissions that resulted from a burst were found to generate a high-frequency spectrum.

The fatigue observed at sensor location II produced a significant amount of enveloped signal, amounting to 10mV. This enveloped signal range was above the test threshold; hence it was too high to be measured accurately at times.

The recorded percentage mean values at sensor location I was as expected and was constant, as can be seen in Tables 5.3 to 5.7. Sensor locations I was placed at the 43cm mark, just before the defect location. The logic was that this sensor location would be the most undisturbed section of the pipeline system.

Photo 5.2: The Pipeline System Showing the Sealed Holes

Table 5.7: Assessment of Envelope Signal in Amplitude vs Frequency for the Fatigue Observed at SEALED HOLES

Sensor Location	Enveloped Signal (dB)		Defect Type [Sealed Holes]		Measured (M)	Theoretical (T)	Difference (T – M)	% age [(T – M) / T] x 100
	Amplitude	Frequency						
	$\overline{X}_{max}(t)$	$\overline{X}_{min}(t)$	**Sealed Holes**	**Hz/kHz**				
I	O=89.95dB	X=84.97dB	Sealed Holes	46.9kHz	+0.012	**-0.135**	-0.147	108.89
II	O=85.87dB	X=87.98dB	Sealed Holes	46.9kHz	-0.012	**-0.136**	0.124	91.81
III	O=87.81dB	X=86.78dB	Sealed Holes	46.9kHz	+5.89	**-0.139**	-6.029	4337.41
IV	O=85.82dB	X=89.83dB	Sealed Holes	46.9kHz	-0.022	**-0.153**	-0131	85.62
V	O=84.91dB	X=88.96dB	Sealed Holes	46.9kHz	-0.029	**-0.152**	-0.123	80.92

Table 5.7 shows that, at the point of failure and with the solder-seal in, the pipeline system was operating under stress (shear cut-off). The theoretical normal state was 0.135, with the mean recorded values being +0.012, representing an averaged difference of 0.147, equating to 108.9% difference at sensor location I. The stress that the system was operating under may have been the result of increased excitation just before and during the bursting of the pipeline

seal, as the measured mean value indicated significant vibration emission signals at sensor location I.

The same could not be said of the total failure tests indicated in Table 5.8. It can be seen that the amplitude measurements are strongly affected by the dynamic and unstable conditions of the pipeline system, in contrast with the normal-state measurements (with a mean value of -0.135 at sensor I). At failure, the measured mean value recorded was +0.01, which represents a decrease of 92.6% in changes in performance of the system. This decrease in measured mean value may be the result of the overall damping of the pipeline system by the leakage, and can be translated into a measure of ultimate performance at total pipeline failure.

Table 5.8: Assessment of Ultimate Performance of the Pipeline at TOTAL FAILURE

Sensor Location	**Enveloped Signal (dB)**		**Defect Type [Failure]**		**Measured (M)**	**Theoretical (T)**	**Difference (T – M)**	**% age [(T – M) / T] x 100**
	Amplitude	**Frequency**						
	$X_{max}(t)$	$X_{min}(t)$	**Failure**	**Hz/kHz**				
I	O=88.82dB	X=86.42dB	Failure	23.4kHz	+0.01	**-0.135**	-0.125	92.60
II	O=83.01dB	X=87.98dB	Failure	46.9kHz	-0.029	**-0.136**	-0.107	79.62
III	O=74.24dB	X=85.45dB	Failure	46.9kHz	-0.070	**-0.139**	-0.069	49.64
IV	O=83.87dB	X=87.72dB	Failure	46.9kHz	-0.022	**-0.153**	-0.131	85.62
V	O=86.91dB	X=82.04dB	Failure	11.7kHz	+0.028	**-0.152**	-0.18	118.42

Table 5.9 below indicates that the frequency of sound emissions increases with defect size. It also shows frequency variations in the damage profiles at sensor locations I to V. Figure 5.4 indicates that the frequency domain was more stable for a small defect, when the data had the lowest standard deviation, and that as the defect worsened from medium to failure, the frequencies became more erratic. This raises the possibility that rapid defect transition without continuous assessment may impose problems in monitoring the pipeline system’s changes in performance. This unexpected behaviour of the pipe during abrupt failure will require more attention in the next phase of the research study.

How the percentage was calculated, at sensor location 1 with a medium defect for example, was as follows:

Normal state = -0.135 (no change)

Recorded value = +0.035 (medium defect)

% change from normal = $\frac{-0.135-0.035}{-0.135} = \frac{-0.170}{-0.135}$ = 126% (increase)

5.4.3 Discussion of Experimental Results in the Frequency Domain

There are generally notable differences between the theoretically expected and measured frequencies. This is particularly so for sensor location III in relation to sealed holes (Table 5.7) and sensor location V with regard to total failure (Table 5.8), both of which show high percentage increases in the measured defect signal. No explanation could be found to justify the 4,337.41% apparent difference at sensor location III for the sealed hole (Table 5.7). Such a significant difference could be regarded as an anomaly, and it may be that failure is better measured at sensor location III (being the most disturbed) as it was closest to the damaged location.

Table 5.9: Comparison of All Experimental Results: Normal State (Theoretical) vs Measured Defects (Small Nail, Medium Nail, Sealed Holes, and Failure)

Normal State (theory)		Defect			Defect			Defect			Defect		
Sensor	**Normal**	**Small**	**Difference**	**% age difference**	**Medium**	**Difference**	**% age difference**	**Sealed Holes**	**Difference**	**% age difference**	**Failure**	**Difference**	**% age difference**
I	**-0.135**	-0.102	-0.033	24.24	+0.035	-0.17	126	+0.012	-0.147	108.9	+0.014	-0.121	89.63
II	**-0.136**	-0.110	-0.026	19.12	-0.024	-0.112	82.35	-0.012	-0.124	91.18	-0.029	-0.107	78.68
III	**-0.139**	-0.106	-0.033	23.74	+0.024	-0.115	82.73	+5.89	-6.029	4337.41	-0.070	-0.069	49.64
IV	**-0.153**	-0.106	-6.047	30.72	-0.028	-0.125	81.7	-0.022	-0.131	85.62	-0.022	-0.131	85.69
V	**-0.152**	-0.101	-0.051	33.55	-0.023	-0.129	84.87	-0.029	-0.123	80.92	+0.028	-0.18	118.42

The results in Table 5.9 show defects with overall similar deterioration trends and characteristics, and percentage differences in test results at different frequencies. For example, the average difference obtained by mean values for a small defect at sensor location III was -0.033, which amounts to a 23.74% difference in the results from the frequency domain; while the average difference in the results from the time domain on total failure (Table 5.12) was

145.45% in voltage when fatigue and total failure were compared. These notable differences in voltages between what happened with a small defect and total failure will be useful in developing reliability-based models for monitoring any changes in performance of a pipeline system. It could be argued that the variations in the differences are probably due to variations in the defect sizes and profile, whereby (for example) a 1% change in the damage profile on the pipe wall would produce noticeable change in recorded frequency.

A 2.8% change in one of the dispersion or damage profiles could result in changes of more than 5% or more in the frequency characteristics. The degree of this variability may, however, depend on the relationship between the combinations of factors that generated the vibration emission propagation in the steel pipeline system. These include: changes in the fluid composition (contamination); changes in defect size (degradation); the fluid interface with the pipe wall; and changes in the general condition of the transmitting pipe wall resulting from operational conditions. All of these may influence the vibration and acoustic emission signals in play.

Table 5.9 also shows that the attenuation for both pipe bursting and leakage frequencies are high for the sealed holes: as the damage increases in size, the acoustic signal emitted increases too. Fluid loss resulting from the burst pipe was also noted. Early work by the Society of Automotive Engineers (SAE, 1978) was concerned with steady-state predictions where the source of energy was continuous at the time when a pipeline system transports fluid through a point of failure. It is assumed that as the pipeline system burst, the burst created the breakage (i.e. deterioration) in energy, resulting in pressure loss. At this stage there was a noticeable increase in the sound emanating from the pump. The leak thus had a marked effect on the oil transmission performance of the pipeline system, and this may have been as a result of the pumping system requiring more energy to transmit the fluid through the steel pipeline system. It is a typical manifestation of leakages to attach themselves in the acoustic signal as a relatively high-magnitude sound in frequency bands, and this sound often attaches itself to the pipeline system and its environment as distinguishable sound emissions that can propagate evenly in both directions away from the leak source. Essentially, escaping diesel oil flowing through a burst pipeline system generates an audible hissing associated to escaping liquid or gas.

Table 5.9 further shows consistent signal amplitudes coupling to different defect sizes, which may result in variations in acoustic and vibration emission signals. That could therefore readily account for the differences in the frequencies produced – although the variation in the mean frequency of the wave patterns may be ±1%, i.e. relatively small, since there may have been some interaction between the flowing diesel oil and the defective inner section of the pipe.

The results in Table 5.7 for the sealed holes demonstrate that when the pipeline system was stressed (in the form of shear cut-off), the result recorded at sensor location I differed by more than 12% from that which was expected. The stress may have resulted from the increase in excitation just before and during the pipeline seal disintegration and bursting. The differences that existed across the results for Test Series 2 showed great consistency between theory and experiment in the frequency domain: on average, the difference in the medium-defect test was about 2.6%. This suggests that the larger differences in Table 5.9 for sealed holes could be as a result of variations in the defect characteristics, which influenced the vibration emission properties.

5.4.4 Details of Experimental Results in the Time Domain

In this section of the experiment, voltage peaks were used to measure the changes in the performance of the pipeline system. The sensors detected changes in envelope signals by using voltage to differentiate between sealed holes and total failure. The primary signals of interest were from the pipeline's failure: the voltage data shown in Table 5.10 were results from sensor location I and sensor location V. The difference is inexplicably immense. In comparison, the fatigue voltage test signal shown in Table 5.11 at sensor location I displayed a gradual decay at different sensor locations. From Table 5.12 and the comparisons therein, it is clear that the signal received at each sensor location showed an offset in arrival time.

Table 5.10: Assessment of Envelope Signal in Voltage for FATIGUE Test Using Sealed Holes without Nails

Sensor Location	Envelope Signal in Voltage mV (milli-volt)		Measured voltage value		V-Peak ms (Milli-seconds)
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	XO=mV	@20ms	ms
	X	O			
I	9 mV	9 mV	XO=18mV	20ms	625.8ms
II	10 mV	10 mV	XO=20mV	20ms	14.38ms
III	9 mV	10 mV	XO=19mV	20ms	13.77ms
IV	8 mV	8 mV	XO=16mV	20ms	13.15ms
V	8 mV	7 mV	XO=15mV	20ms	12.87ms

Table 5.11: Assessment of Envelope Signal in Voltage for FAILURE Test Using Sealed Holes without Nails

Sensor Location	Enveloped Signal in Voltage mV (milli-volt)		Measured voltage value		V-Peak ms (Milli-seconds)
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	**XO=mV**	**@20ms**	**ms**
I	6 mV	6 mV	XO=12mV	20ms	16.33ms
II	6 mV	9 mV	XO=15mV	20ms	13.98ms
III	7 mV	6 mV	XO=13mV	20ms	13.75ms
IV	6 mV	5 mV	XO=11mV	20ms	13.11ms
V	5 mV	5 mV	XO=10mV	20ms	12.75ms

Table 5.12: Comparison of Difference between Experimental Results in Tables 5.10 and 5.11

Sensor Location	V-Peak (ms)		Difference Between Tables 5.10 and 5.11 (A – B)	percentage difference [(A – B) / A] × 100
	Fatigue (A)	Failures (B)		
I	16.33ms	625.8ms	-609.47	37.21
II	13.98ms	14.38ms	-0.4	2.86
III	13.75ms	13.77ms	-0.02	145.45
IV	13.11ms	13.15ms	-0.04	305.11
V	12.75ms	12.87ms	-0.12	941.18

In Table 5.11, the voltage peak measurement is seen to decrease from 13.98ms at sensor location II, to 13.75ms at sensor location III, to 13.11ms at sensor location IV, to 12.75ms at sensor location V, the furthest sensor from the defect. However, the variation of the voltage envelope's standard deviation of the lowest amplitude recorded (12.75ms at sensor location V after 15mV) may vary appreciably with distance. Although using this criterion helped to establish the vibration trend, the waveforms show decay with distance from the defect source, the most likely reason being material damping. It has also shown that it was possible to monitor the variation in signal strength and distance from the defect source. It shows that the maximum amplitude measurements are strongly affected by the proximity of the defect source. This trend is also consistent with the standard deviations indicated in Figure 5.4, which showed that vibration sound emissions increased with defect growth and decreased with distance from the defect source.

5.5 Discussion of the Main Test Considerations and Test Summary Plots

Pilot Test Series 1 revealed that, in the absence of any defect in the pipeline, dynamic forces were still active in the liquid flow itself. It was evident in Test Series 2 that the pipe generated vibration sound within the steel pipeline walls as a result of the pressure exacted by the pump and fluid flow. The dynamic forces and the pressure in the pump were the sources of acoustic and vibration emissions that were coupled to the defective pipeline system.

The voltage peaks shown in Table 5.11 were measured in milliseconds (ms) at sensor location II. They measured 13.98ms for fatigue and increased to 14.38ms for failure. In essence, different stages of the defect growth were reflected by the recorded envelope signal; the more severe the defect, the higher the acoustic emission and the standard deviation recorded.

5.5.1 Reliability of Test

The diagrams in Figures 5.4 and 5.6 show that the bigger the defect, the more variation there is between the mean values and the standard deviation for a medium-sized defect and for sealed holes. The aim of the test was to establish whether there was any real difference identified between a large and a medium-sized defect. It was supposed that there were differences when the size of the defect changed, but it could be argued that it was not because of the difference in the defect characteristic. It is important to point out here that the difference between a large and a medium-sized defect may not be noticeable from the signal, as shown in Figure 5.4. The large defect is a hole sealed with a blob of soldering – not a sharp point like those of the small and medium-sized defect tests – and therefore not 78% bigger; hence those two defect types are similar.

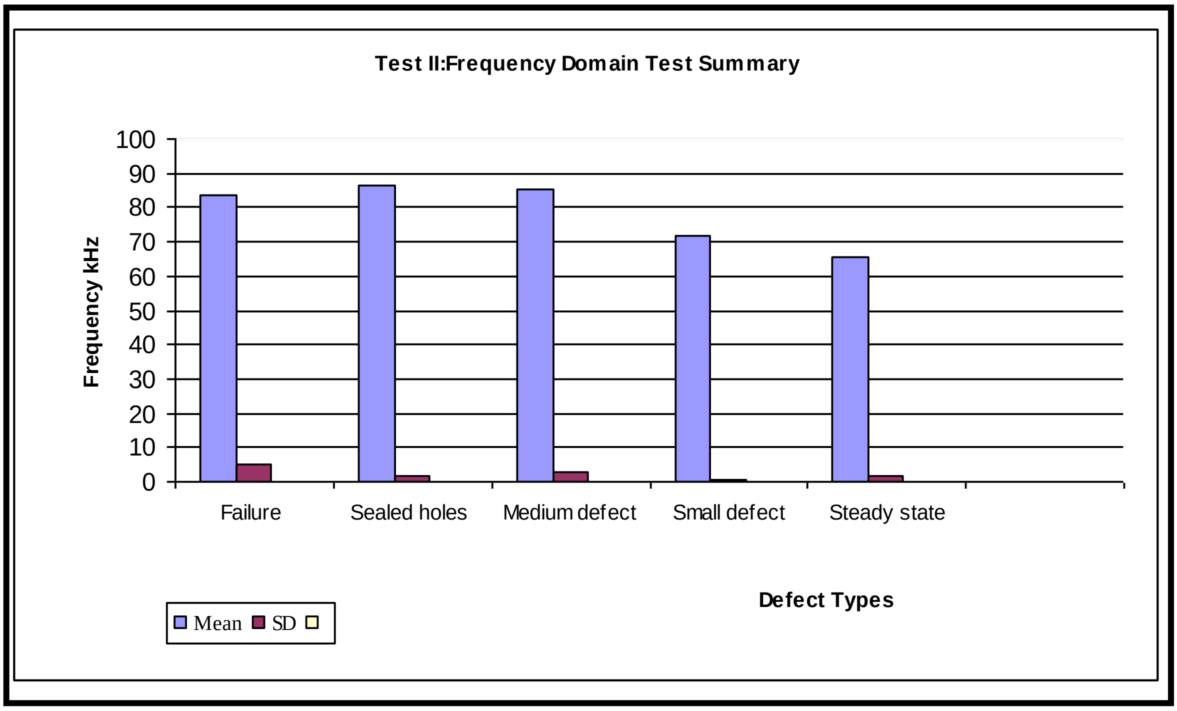


Figure 5.4: Test Summary for Test Series 1 and 2

This outcome raises other issues, particularly how to differentiate between a blob shape and a sharp point in any assessment. It was not possible to address these issues during this phase of the experimental programme. What this test programme *did* establish was that it is possible to determine defect types and sizes. Knowing that there is a defect would help a facility's manager to further investigate the condition of the pipeline system by carrying out an inspection of that particular location instead of area pipeline length of, say, a thousand kilometres.

These findings help to address the research objectives, especially the deficiencies that exist in the current built-environment maintenance process in general, where resources are often committed to catch just one per cent of the problems. The author acknowledges that a wider range of defects would need to be investigated before any proposed system could be implemented in the field.

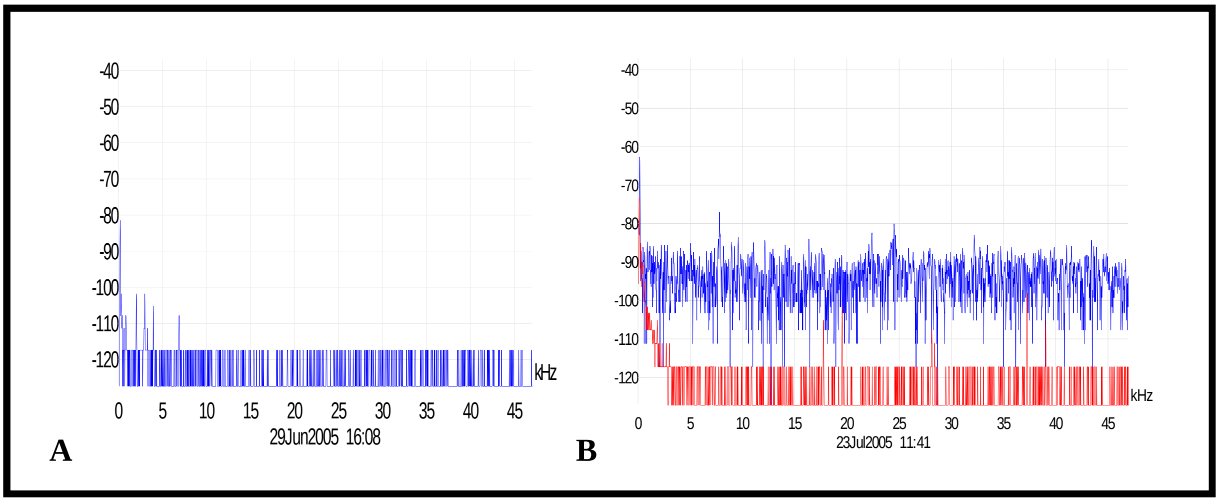


Figure 5.5: Comparison of Energy Dispensations at Different Stages of Defect. Small Defect (A) and Medium-sized Defect (B)

Figure 5.5 (elements A and B) show the frequency characteristics and comparisons of energy dispersed at different stages of the damage process. Figure 5.5 element A represents what happens with a small defect, showing the signal recorded between 0Hz (80dB) and 4.6kHz. In Figure 5.5 element B, the medium-sized defect was recorded between 0.0Hz (78dB) and 5.79kHz. These were measured with a sensor mounted at location II, while similar characteristics could be found for the other defects, with peaks at around 5.9kHz. The differences in the signals are shown in frequency bands (0 = -80dB) in Figure 5.5 element A compared with those seen in Figure 5.4 for the medium-sized defect. The signal exceeds that of the small-defect decibel threshold that was recorded at x = -62dB.

In contrast, Figure 5.5 (elements A and B) show defects in the form of peaks, from incipient to medium stages of degradation but without any leakage from the pipe. The defect signals were coupled to the fluid flow signal along the pipeline system and were correlated with the location of the defect. However, it is questionable whether this can be repeated in a wider field test, given that both the pipe length and the diameters will be scaled up.

5.5.2 Experimental Measurement of Performance using Voltage

The experimental results in this research have so far focused on the signal values that correspond to respective frequencies and time domains, the test reliability, and specifically those voltage signals that corresponded to defect locations. Damage in the pipeline system, buried or on the surface, exhibits sudden changes in voltage along the structure that could be monitored through the energy propagated in the form of vibration and acoustic signals.

These experiments compared the wave transformation activities as the waves passed the sensor locations. Figure 5.6 shows the voltage measurements at sensor location II; it measured XO-15milivolt, but dipped to XO-10milivolt at sensor location V at the time of failure. That shows correlations of propagated distance versus wave transformation, which was based on the arrival times of different damage signals at fixed frequencies. It further indicates the voltage difference and drop trend for sensor distances from the defect location and for the deteriorating conditions of the pipeline system. The percentage differences in voltage at the time of failure are indicated via a dotted line on Figure 5.6 and show an overall percentage voltage reduction on failure of -33.33% (from 15mV to 10mV).

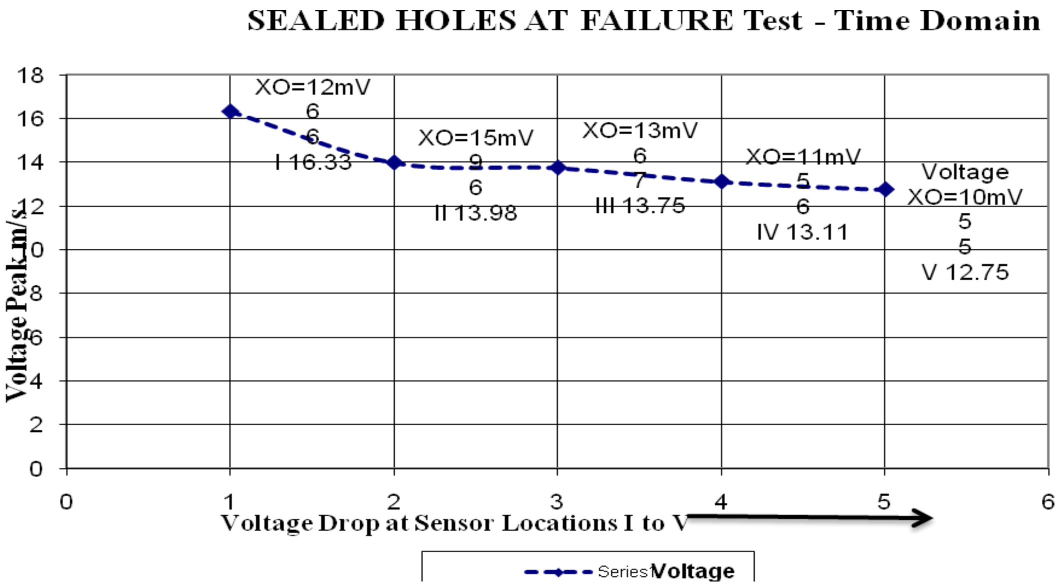


Figure 5.6: Voltage Drop, Indicating Sensor Distances from Defect Location

Although Figure 5.6 shows the voltage difference and drop trend, from both sets of figures it is evident that there is a statistical regression of about -33.33% in relation to the pipe’s performance as a result of the deteriorating conditions. The percentage difference in voltage at failure (Table 5.11) was generally negligible. For example, when comparing small-defect signals at sensor locations I to V against the normal-state signal, it was difficult at first to ascertain whether the voltage actually dropped without reference to the plots in Figure 5.6. In fact, with the envelope of the voltage signals plotted against the others, the result shows a slope downward from 16.33mV to 12.16mV. The graph shows a voltage drop from 16.33mV to just below 14mV, whilst the dotted line indicates the averaged voltage signals at different sensor locations at the pipeline system's failure. The averaged voltage percentage differences measured for the ten tests at failure was 14.9mV, which decreased to 10.8mV – that is, a drop of about 19% in mean values. It is clear that the amount of energy generated in any of these failure modes was dependent on the defect size (source intensity). Therefore it was necessary to assume that the failure mode with the dominant energy created the corresponding vibration signal. Consequently, the wave transforms were based on the arrival times of the maximum wave transforms size, as evident in Figure 5.9.

The peak amplitude method was used to identify the source of changes in performance that relate to the pipeline system. The data in Figure 5.5 and Table 5.12 show that moving the sensor from location II to location V, which is away from the defect source, typically resulted in a loss of signal amplitude. The standard deviation for the large defect shows a voltage increase from 1.25 volts to 5.45 volts, while the mean voltage value decreased at failure from 14.9 volts to 10.8 volts; these changes are significant yet tolerable.

The results demonstrate that changes in the condition generated in the form of voltage change in the pipeline system can be used to assess its in-service performances. It is right to suggest that the notable changes in the performance of the pipeline system shown in Figures 5.6 and 5.7 – namely when the holes were sealed and at total failure – would enable pipeline operators to determine leak conditions or obtain valuable information on present and past pipeline operations. The evaluations of pipeline system performance trade-offs could be said to be complicated, because functionality and maintainability are typically not captured in the analysis but can substantially affect the results.

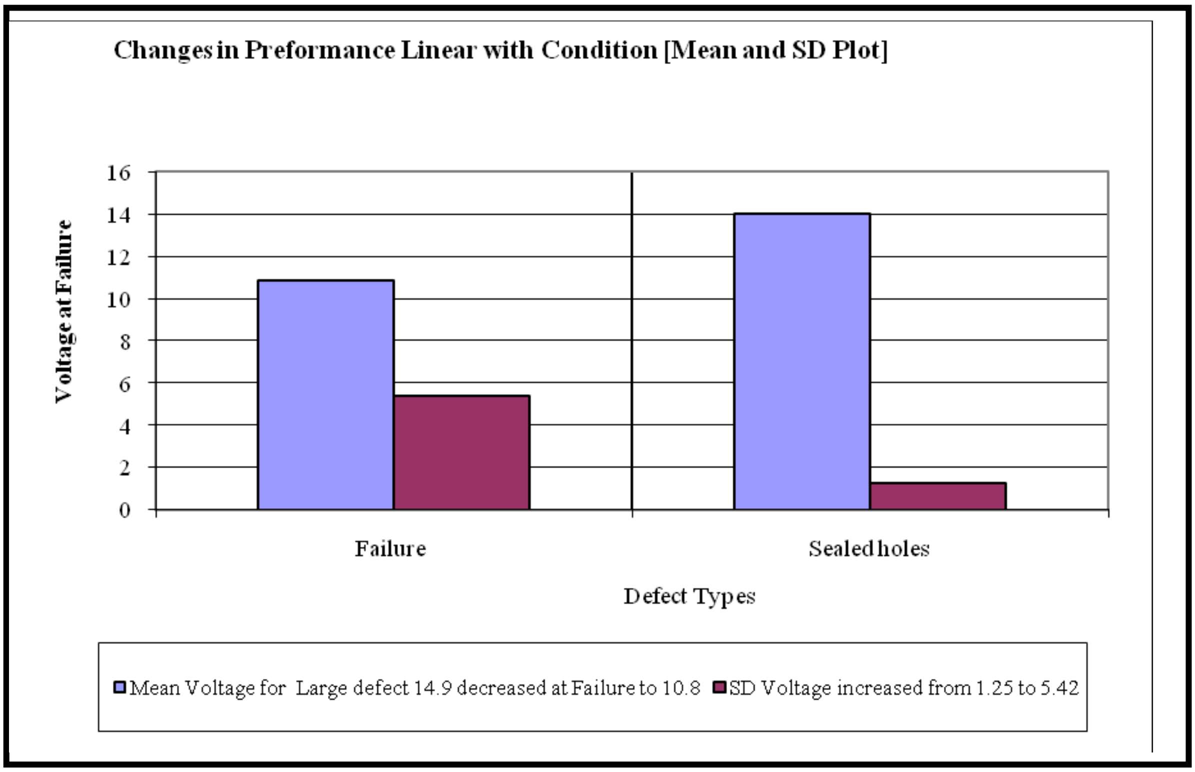
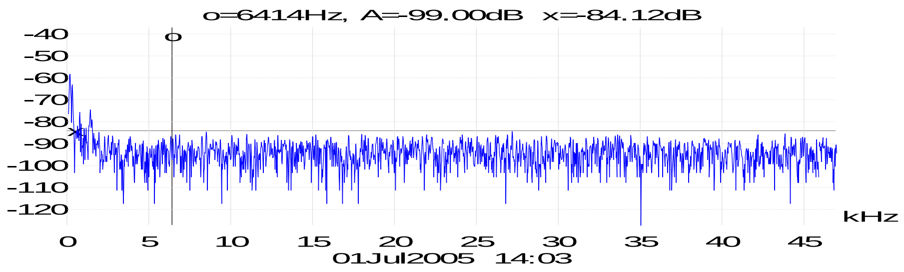


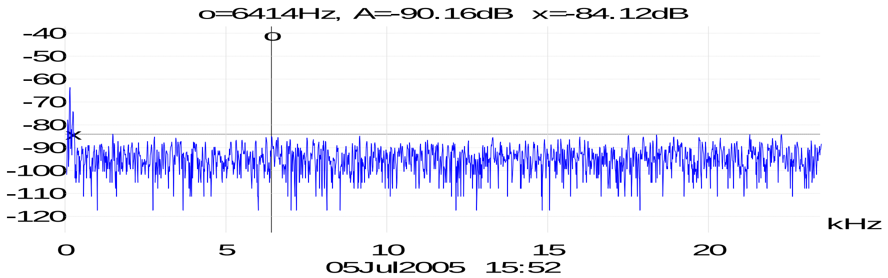
Figure 5.7: Changes in Performance: Large Defect (sealed-hole) Fatigue, and Failure Test

Figure 5.8, like Figures 5.4 and 5.7, shows the spectral analysis results. Again they represent leakage signals with some background noise. It was noticeable that both the spectrum and time domains can give the right classification of background noise and leakage signals.

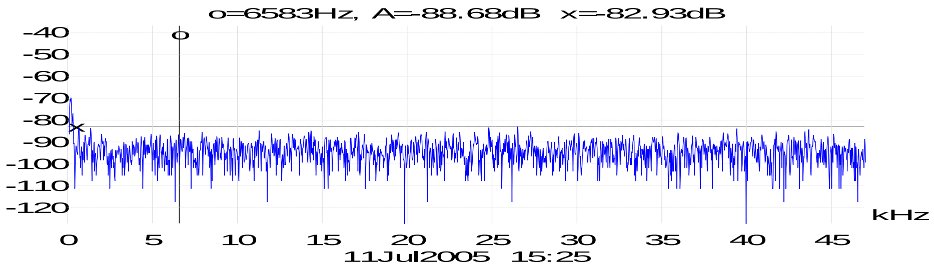
The envelope signal containing background (or what is known as ‘white’) noise could be said to be present. In essence, the smaller the defect, the higher the white noise content within the envelope signals. However, white noise is not the focus of this study.



Sensor II@46.9kHz



Sensor II@24.9kHz

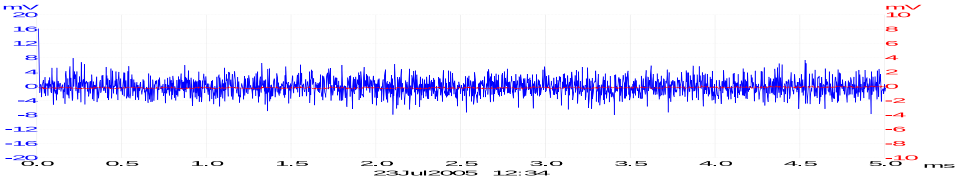


Sensor III@46.9kHz

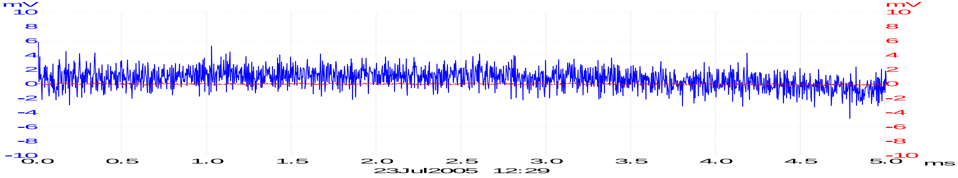
Figure 5.8: Comparison; Background Noise Signal Characteristics in Relation to Defect Size

5.5.3 Vibration and Acoustic Emission

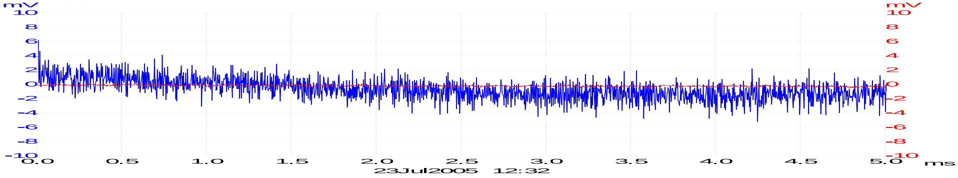
Figure 5.9 shows various domain plots: voltage on the vertical axis, against time on the horizontal axis. Both are associated with the leakage characteristics tests and show the steady-state position. Figures 5.9 elements (a) and (b) illustrate that the signal was centred on zero and the natural variation in the voltage reflects the natural variation in the pressure and acoustic signal measured. It shows a direct relationship between the voltage value and the pressure acoustic signal. When a small defect is introduced, the natural voltage variation shifts above the zero line and oscillates.



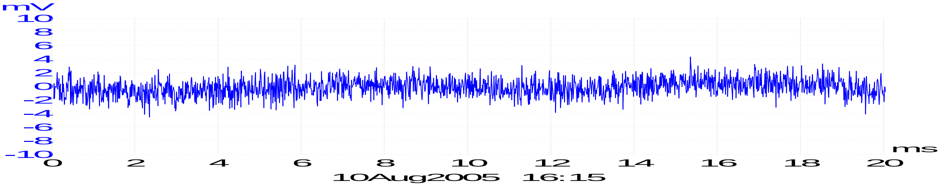
(a) Sensor placed at 168cm shows fluid flow with non-defect shape **calibration**;



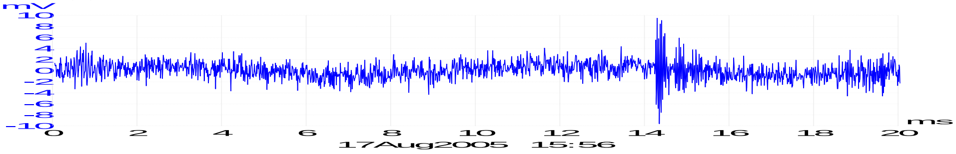
(b) Sensor placed at 165cm shows fluid flow shape with **small defect**



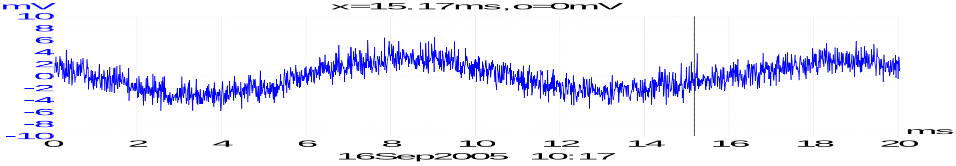
(c) Sensor at 168cm shows fluid flow shape with **small defect**



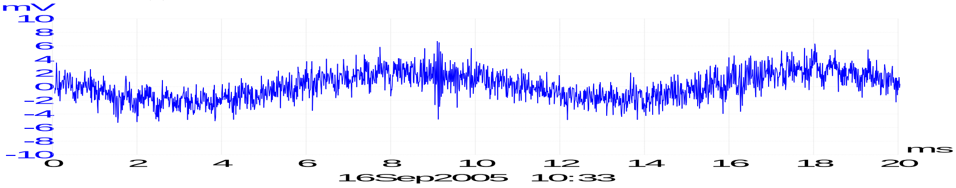
(d) Fluid flow with **Medium defect**: shape **at** 165cm (sensor II)



(e) Fluid flow **at Failure**: shape at 165cm (sensor II)



(f) **Leaks shape**: Perfect curves at **43cm** (sensor I)



(g) **Leaks** shape: Perfect curves at 204cm (sensor IV)

Different defects, fatigue (sealed holes), failure and leak characteristics are compared with non-defective mode. Table 5.8 and Figure 5.9 compare stress-strain-vibration and acoustic emission characteristics of the steel pipeline system. The strength of the vibration and acoustic emission activity increased substantially at the point where the first primary crack was observed – see (b) and (c) above. These corresponded to a strain of 4 volts (5%) more than measured on the non-defect strain of the matrix. The cracking continued, with distinct shifts in the stress-strain characteristic, until tensile failure (e). It could be that the leak manifests itself as additional energy within certain frequency bands while deforming the shape of the waveform.

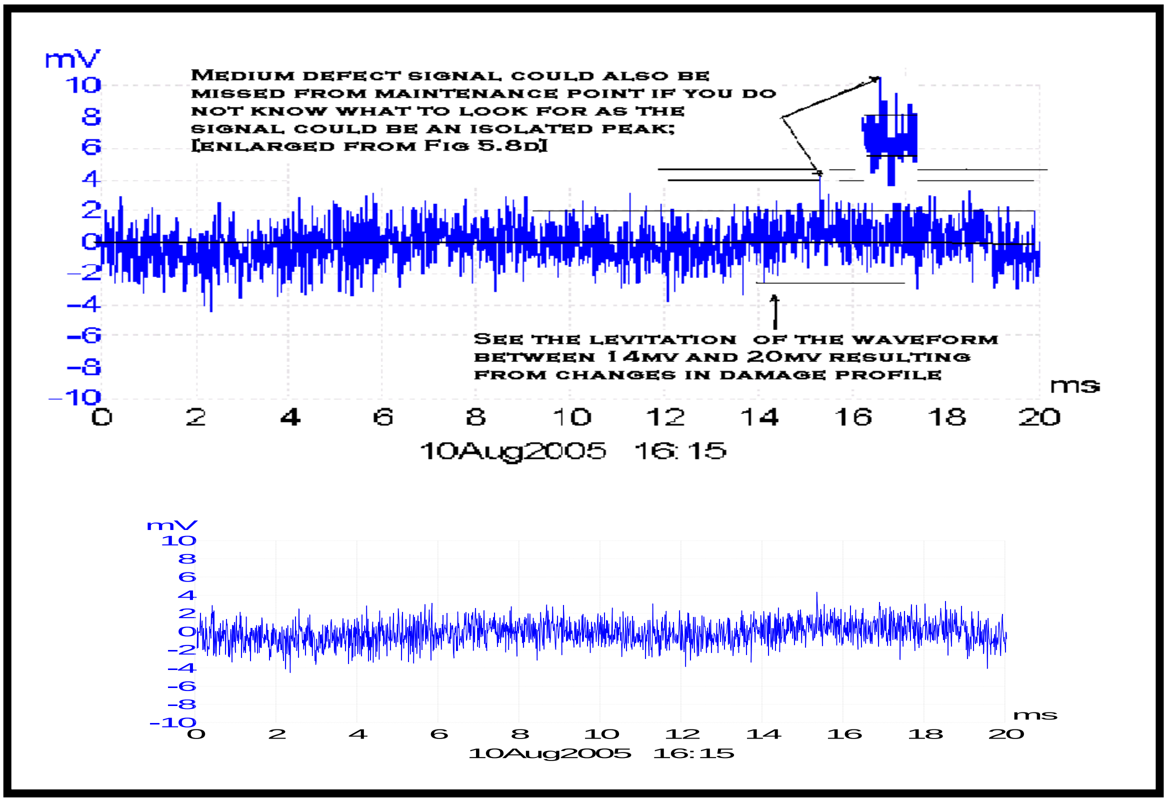
Figure 5.9: Time Domain Plots from Normal State, Defect to Leak Characteristics Test

Figure 5.9 elements (b) and (c) are typical measurements of a small defect at sensor locations II and III; they show a shift of the blue line below zero and this shift indicates that the pipeline system is no longer in a perfect state. In direct comparison with the natural voltage waveform in Fig 5.9 element (a), it is evident that the apparent oscillating pattern is indicating changes in performance of the pipeline. At element (d), it is shown that the medium-sized defect creates a greater difference in the voltage result**,** and the apparently oscillating signal that was centred on zero has disappeared (as was observed in all 10 samples set out in Appendix A). Figure 5.9 element (e) shows a massive variation in the failure voltage waveform; there was a substantial increase in the voltage at the point where the first (and primary) crack occurred. Thus the oscillation was independent of the point when the sample was taken.

Figure 5.9 element (f) describes progress during pipeline system failure. It was not clear what made the voltage oscillate and the oscillation pattern was not what was expected; hence more work would need to be done. However, it could be that by introducing the defect, the transducer was picking up the oscillation of the pump, especially at sensor location I at 43cm, just before the leakage source, and at sensor location V, which is the furthest from the source. In essence, the oscillation may have resulted from the changes in the leakage pattern (which is non-pulsatic – that is, the intervals between the outcoming fluids are irregular, similar to air flow in a flute as the finger interchanges are made) or as a result of bubbles of air struggling to rush in to occupy the lost oil space. The situation raised questions that should be further investigated; however, the most plausible answer at this point could be that the turbulent flow is by its nature erratic. What was evident is that the leakage of the fluid into the surrounding medium occurred because of the pressure/energy coupled to the wave in the transmitting pipe. As a result, some of the longitudinal wave energies generated were also transmitted with the fluid that was released by the leak. This is reflected in the bursting/failure signal shown in Figure 5.9 element (g).

5.5.4 Point-of-Failure Signal Analysis

The major difference between all the test results was that there were pronounced signals at the point when the pipeline system burst. From a maintenance perspective, the fact that the bursting was so distinguishable is useful because incipient defect signals are fine, but the signal at the point of failure with such a wavelength would help a pipeline facility’s manager to make the decision to mobilise for repairs instead of further surveying. In Figure 5.9L, the medium-defect signal could be missed unless the maintenance manager knows what to look for, because the signal could be just an isolated peak. If the sensors are well calibrated against steady flow, it should be possible (via signal strength) to see a change as the pipe deteriorates through wear; however, once the pipe bursts, a very large signal (see Figure 5.9M) is produced. In other words, at the point of failure there are large gaps in the waveform.



MEDIUM DEFECT SIGNAL COULD ALSO BE MISSED FROM MAINTENANCE POINT IF YOU DO NOT KNOW WHAT TO LOOK FOR AS THE SIGNAL COULD BE AN ISOLATED PEAK; [ENLARGED FROM FIG 5.8D]

SEE THE LEVITATION OF THE WAVEFORM BETWEEN 14MV AND 20MV RESULTING FROM CHANGES IN DAMAGE PROFILE

Figure 5.9L: Enlarged Medium-Defect Signal from Figure 5.9 element (d)

Notice, too, in Figure 5.9L the rise of the wave from 0mv to above 4mv and the levitation of the waveform between 14mV and 20mV, resulting in changes to the damage profile.

Figure 5.9M shows a 5ms section before average voltage and a 5ms section after average voltage. At the point of failure the signal could be missed because it happens in just about 1ms, as is evident from Figure 5.9; but the bigger signal at failure cannot be easily missed as the reverberation can be repetitive, as seen in Figure 5.9N. Even if it is missed despite the difference in this case being 50%, it is more than likely that it is a failure not a steady-state or an incipient-defect signal.

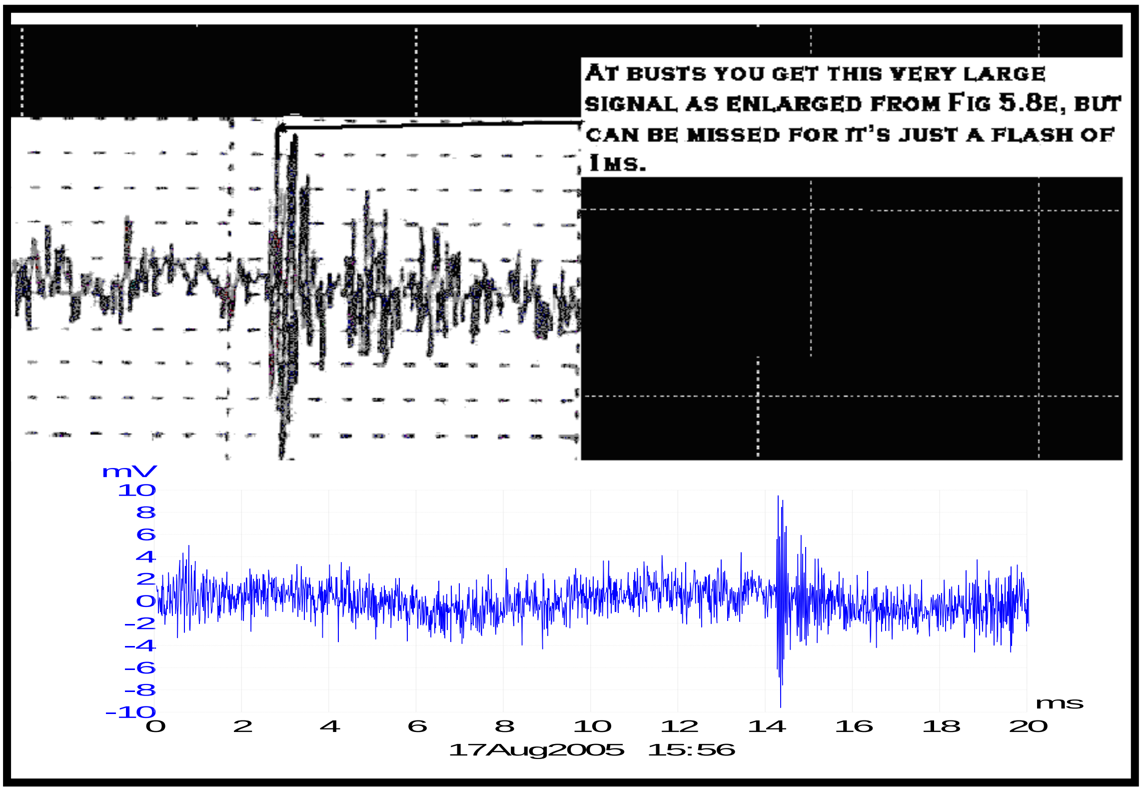


Figure 5.9M: Enlarged Burst Signal from Figure 5.9 element (e)

Note in Fig 5.9N how incoherent the waveform becomes, with huge gaps just before total pipeline system failure, reaching a maximum value of 10mV at the epicentre of the damage process. Note also that the intensity signal indications appear clearly defined in the relatively uniform characteristic between 6ms to 8ms; these conditions are identified in Figures 5.9L, 5.9M and 5.9N and are clearly distinguishable from each other.

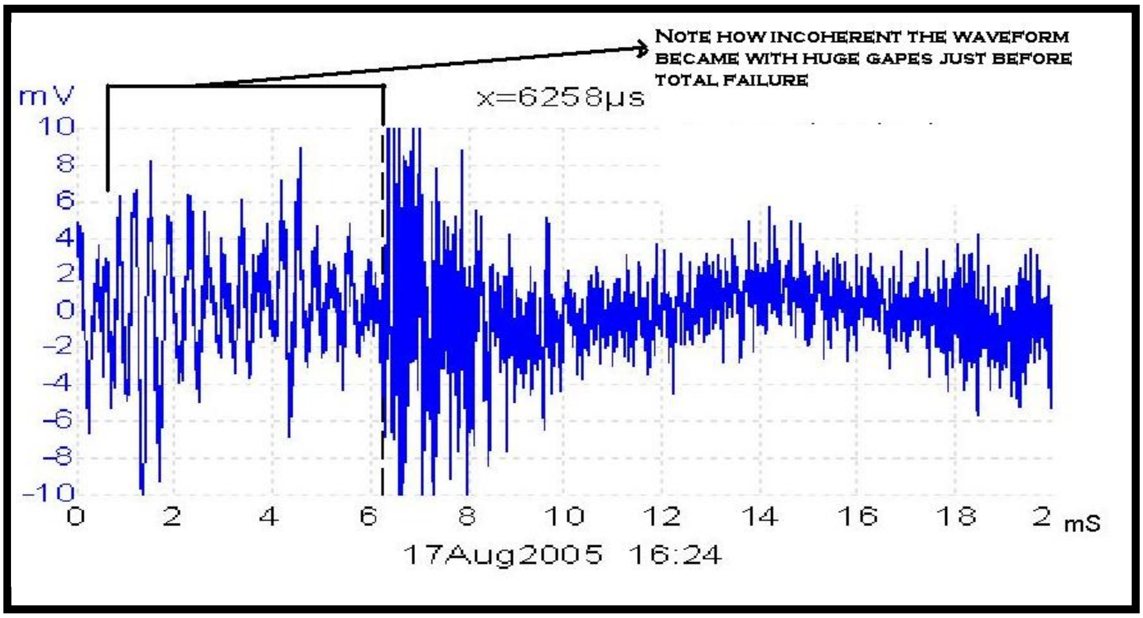


Figure 5.9N: Further Enlarged Burst Signal from Figure 5.9M

Leaked oil resulting in environmental, social and financial damage can thus be minimised with this knowledge, where changes in the performance of a pipeline system are related to changes in the defect severity parameters so as to produce the defect severity criteria shown in Table 5.13. From an analysis of five sets of ‘total failure’ results, it is clear that a distinguishable signal is generated with, at sensor location II, about 150% greater magnitude recorded (in millivolts) after total failure [4mV to 10mV is 2.5 times as much and an increase of 150%].

Table 5.13: Indication of Around 150% Greater Magnitude (in mV) after Total Failure

Xa Before **Failure**	*Xb After* **Failure**
4mV	*10mV [+150%]*
4mV	*10mV[+150%]*
3.7mV	*10mV[+150%]*
4mV	*10mV[+150%]*
3.9mV	*10mV[+150%]*

Normal	**Sealed Holes**	**Failure**
-0.135	*+0.012*	*+0.014*
-0.136	*-0.012*	*-0.029*
-0.139	*+5.89*	*-0.070*
-0.153	*-0.022*	*-0.022*
-0.152	*-0.029*	*+0.028*

5.5.5 Summary

The straight line barely seen in Figure 5.9 element (a) – the red line on the blue graphical representations – illustrates that the signal was centred on zero and the natural variation in the voltage reflects the natural variations in the pressure. It also indicates that the waveform and the Fourier transform shown (without defect) contained background noise (from Test 1). Table 5.3 depicts leakages recorded at sensor positions II and III, and Figure 5.9 shows the waveform and Fourier transform of the leakage signals: notice that these are also recorded at sensor positions II or III and are comparably similar. Figure 5.9 element (e) shows that the signal intensified as the pipe condition deteriorated from the medium defect (a sharp-pointed nail) to a blob solder seal. Time (horizontal axis) registered 14.2 seconds – that was the point at which the seal burst.

The experiment demonstrated also that, despite the challenges of detecting a sound signature far away from a defect source, it was possible to detect the vibrating sound emissions of incipient and advanced defect stages that were coupled to pressurised fluid. It was also possible to detect leakage across a wide range of frequencies. However, for these tests it is the low-frequency bounds that are useful for practical damage and leak detection methods, owing to the significant attenuation of the higher-frequency components.

5.6 The Influence of Distance from Defect Source

Rocha (1989) states that acoustic frequencies of the order of 10Hz can propagate in a gas over distances of the order of 100 miles (160 kilometres) and gives the following approximation: the amplitude of the wave is related to the properties of the oil or gas, the pressure at which the pipeline is being operated and the size of the leak. These conclusions by Rocha indicate that signals with frequencies generated at distances up to 100 miles are important when developing a sensor device for the performance-based method of pipeline assessment.

This section describes the influence of distance to defect source on the leak signals. The result may represent a solution to the problem of variable leak signals at different distances from damage locations. The vertical axis is calibrated in decibels while the horizontal axis is calibrated in kHz; the variations in the leak signals are as a result of defect size and sensor distance from the defect zone. It is important to emphasise that the results and the predictions presented in Figure 5.1 and Table 5.3 are not entirely applicable to the influence of distance from the defect source signals. There is an increase in the audible signal.

Figure 5.10 below, compared with Figure 5.8 shown earlier, and indicates the strain displacement signal for sensor II, which was located directly on top of the defect source. The distance of sensor location I (see Figure 5.10 element A) was 118cm before the defect source. Observe the event at 5kHz, and particularly note the duration of signal amplitude. This can be used to assess the influence that the distance from the defect source had on the failure signals. The effect meant a slight shift towards sensor location I (at 45cm), which decreased the frequency arrival registered just before 5kHz on the plot. This helped to estimate and confirm the position of the defect relative to the sensing device; further, it explained the characteristic of the defect location and the resonant frequency, i.e. the recorded signal, as the sensing element moves either towards or away from the excitation band with coupling.

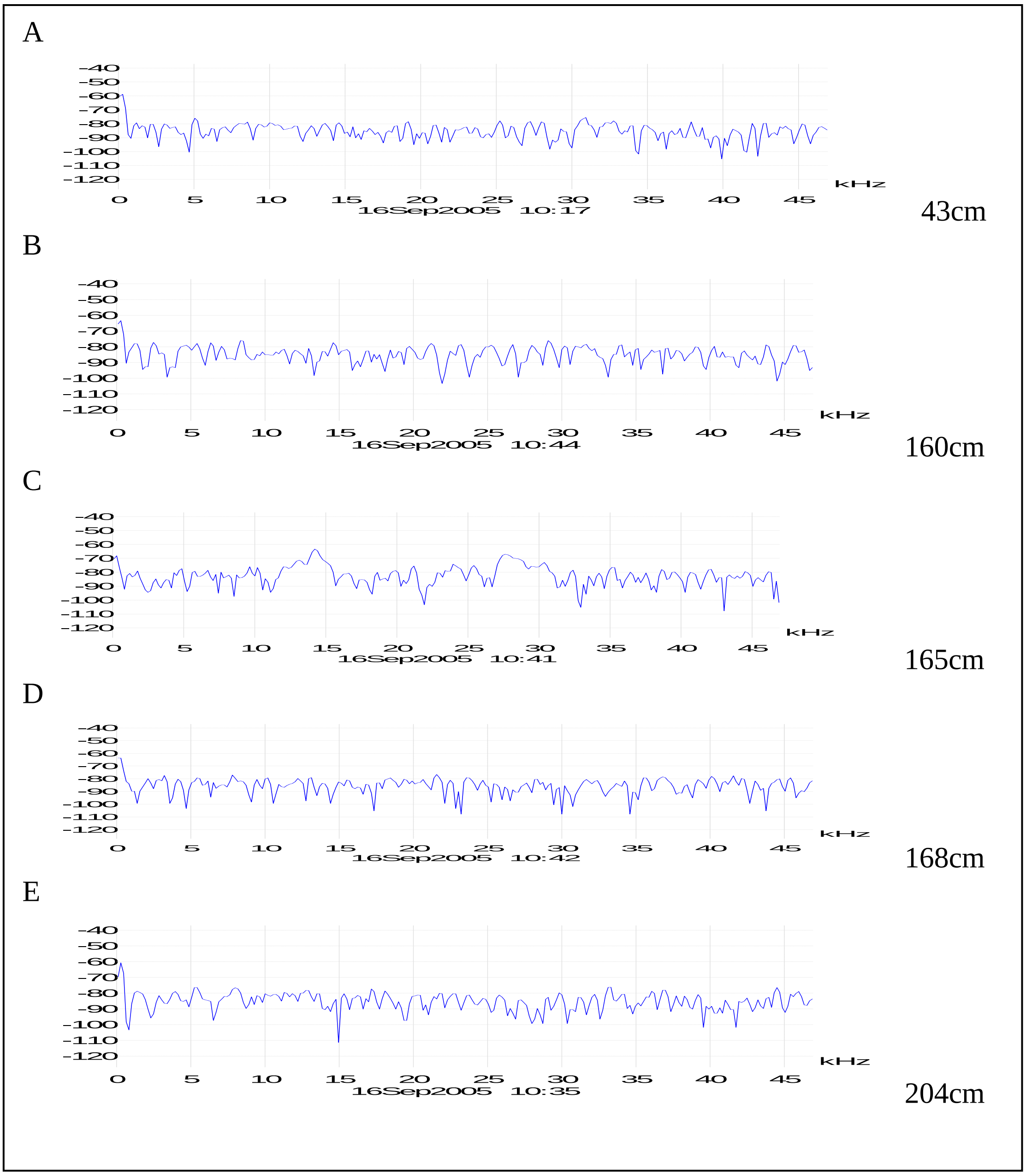


Figure 5.10: Indicators of Leak Signals at Different Sensors and Distances (Observed between 5 and 15 kHz)

Figure 5.10 element B shows the characteristic of the signal from the sensor mounted right on top of the defect zone at the 160cm mark (defined as the defect source). Again, observe the event at 5kHz, where the expanded scale view of the early part of the acoustic signal is distorted. When compared with Figure 5.10 element C, which was 5cm past the defect, there is an increase in the audible signal, as can be observed between 5kHz and 15kHz at about 79dB.

At 20kHz, there is a prolonged signal event and it shows that the signal can be clearly seen. However it is not clear why there is a massive shape variation (such as the magnitude range and cyclical) and an increase in the audible signal at Figure 5.10 element C and not the in others. This implies that for the signal to be audible the sensor has to be at close proximity to the defect source. What was evident is that the audibility decreased from 90dB to 70dB at a sensor location of 160cm (see Figure 5.10 element B), i.e. placed right on top of the defect source, and the same trend was repeated at sensor locations of 165cm and 168cm – and even lower audibility (60dB) at 204cm.

It could be that the applicable distance of the sensors and the pressure wave at play in the pipeline were indeed proportional to the energy in the structure and therefore the audibility parameter is proportional to the defect amplitude. If this is the case, it should be possible to predict the defect and leak source energy signals (i.e. wave peaks) for each of the five sensor locations on the pipeline. In contrast, it could also be that audibility increases as a result of the force of the liquid impacting a nail, sealant-blob or crack and that force creates these shapes in all the tests.

One thing is clear: the general trend in frequency shifts can be clearly seen to correlate with different sensor locations in Figure 5.10. What is not clear, however, is the discrepancies among these shapes in these interpretations. It may not be possible to fully investigate this in a laboratory-controlled environment; hence more work is necessary to further understand the phenomenon.

5.7 Other Major Observations

Test Series 2 (using diesel oil) was carried out to determine the detectable changes in vibration and acoustic signals, and then to associate these with the pipeline defect profiles – see Figure 5.10 elements A–E as well as Figures 5.5, 5.6 and 5.9.

It was observed in Test Series 2 that the diesel oil had a viscosity of 0.85η for clean diesel; however, the viscosity increased to 1.25η when the diesel oil leaked out into a container at failure. At first glance it was puzzling to notice this massive difference in viscosity for the leaked oil. Consequently, the measurement was repeated with the next set of leaked oil and a second viscosity reading was consistent with the first at 1.25η. Applying the same reasoning to the leaking oil specimen, a possible explanation could be that debris (for instance, fragments of the pipe and welding-seal elements) was contained in the leaking oil since there was no debris in the oil drained into the reservoirs. Nevertheless, this observation could have a fundamental contribution to further determining the performance of the pipe in transmitting its contents from one point to another and therefore more research is needed.

It was also observed that when the inlet valve was half open, the vibration sound emission did not show much difference to that of a fully open inlet valve, but the pump sound peaked higher than 60dB in amplitude. What was anticipated was that the amplitude and frequency spectrum and the attenuation characteristics would exponentially change as a result of the increase in the pipeline defect size. This was due to the sensitivity of the pressure oscillations that are produced by the transmitted fluid along the defect zone. As the valve 'sucked in' (resulting from a lack of sufficient pressure build-up in the tube) and the oil was consequently pushed along the tube, it produced leak signals that were incoherent, as can be seen in Figure 5.11.

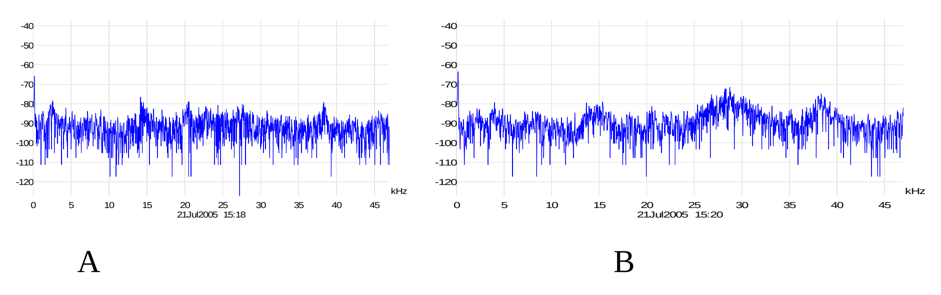


Figure 5.11: Surge Signal Representation as Fluid Rushes along the Pipeline

Figure 5.11 shows that the surge wave’s representations were picked up the moment the valves were first opened and the fluid rushed along the pipeline coupled with a defect characteristic. The medium-defect signal can be seen in Figure 5.11 element B as rising from 50dB to about 60dB, at which point the larger defect was introduced. This only became apparent when the medium nail and leak test waveforms were further analysed and were found to match.

Finally, it was also observed that the pitch of the pump became higher than normal when pipe failure occurred. It is supposed that more energy was probably required to transport the fluid along the pipeline system. There was no specific test during the experiment to confirm the reason for this occurrence; however, there was certainly greater energy input required as a result of pipeline deterioration.

5.8 Implications for Pipeline Maintenance

This experiment monitored the behaviour of a pipeline system with defects from their incipient stage to large scale and ultimately bursting characteristic. The tests were successful in the laboratory and relied on acoustic signals transmitted via the fluids (oil and water) used in the experiments. The experiment showed that the appearance of an incipient-to-large defect that could cause a leak usually generated an acoustic signal. In essence, knowing that the steel pipe system creates a significant acoustic signal that can produce a distinguishable characteristic as a defect develops and grows is a significant development.

From a maintenance perspective, the fact that the damage and leak profiles are distinguishable is a useful development, because knowing the characteristic of incipient defect signals and the signal at the point of failure can help in the development of a performance-based model and associated technologies that can monitor and report continuous performance**.** Knowing that any defect in a pipeline system can further result in a sudden leak, which can also produce a rapid change in fluid pressure; it was observed that this rapid change in fluid pressure in turn produces a ‘burst signal’ pressure transient (see again Figure 5.9N). Furthermore, the fundamental addition to knowledge is that once a leakage is established, the escaping fluid generates acoustic energy that can be associated with the defect. These acoustic emissions are continuous and have a wide frequency spectrum that can be integrated into a performance-based model to develop systems that provide an integrated wireless sensor device that is helpful to a facility’s manager in making decisions to mobilise repairs instead of further inspections.

Performance-based diagnostic tools would allow for continuous monitoring and configuration of a network, including sensor status at remote stations, without the need to visit sites personally in order to make minor changes. With vast lengths of pipeline to manage, frequent site visits are time consuming and cost prohibitive, and any way of monitoring performance more easily would help the pipeline owners, its staff and also residents living near the pipelines.

Locating and analysing the different defects in the experimental pipeline system were important, as it enabled the signal characteristics that were generated by the defects and the leak to be correlated with the five sensors; thereafter, the similarities and origin of the signals produced at each sensor’s location could be established. When a signal is recorded, then a catastrophic change in that signal can be associated with failure. What is important for the pipeline maintenance manager is that by monitoring the semi-continuous performance of a pipeline, a change in the performance-monitoring signal can be associated with a defect or failure. Consequently, this can change the bases of maintenance from; periodical inspection and checking, to continuously monitoring at low cost to detect a change in performance. A pipeline system could then be treated similarly to mechanical, electrical and aircraft systems, where monitoring is conducted using similar techniques to those of the some modern engine management systems. In essence, continuous monitoring of the system will be beneficial to the oil and gas industries at large.

It appears that the position of the sensor relative to the failure point is significant inasmuch as although the signal can be detected at a distance away from the failure, the signal is most distinct when closer to the failure. It should be pointed out that no specific spacing test was conducted to determine the best distance to measure. However, for a one-inch pipeline system it could be that its X-signal value multiplied by 50cm from the fault would give a detectable signal. It can be assumed that simply scaling up to a two-metre-diameter pipe would require a sensor spacing of every kilometre. Therefore the implication for the maintenance industry is to budget for integrated sensors to be deployed at such intervals over the full length of pipelines. And although an average pipeline distance across the Sahara might be about 5,000km and need about 5,000 sensors, in practice such an approach is not uneconomic (see also section 5.9 below) given that the sensors would operate in an array and therefore be able to transmit to a base station located, say, just 30km away. Thus it is not only technically possible to detect failure with such integrated sensors, but also economical and practical to do so. In effect, such a project is feasible.

Whether the test results could have been achieved using an alternative approach needs to be examined. However, one would be speculating in any conclusions since the limiting factor on the accuracy of any test results is always affected by (a) the degree to which the experiment was designed, (b) the equipment used, and (c) whether the test results can be applied in real life, especially when changes are made under defect simulation.

In these tests, the defect simulation consisted simply of drilled holes and inserted nails. This is difficult to improve upon in an oil pipeline operational environment. If the test is to be used in real life and on pipeline systems, more work must be done on the experimental design to address the robustness of the simulation techniques in order to develop a reliable method to detect failures in real situations. The answer to the test question set out in section 4.2.2 would be that, in this research, it has been possible to monitor the changes in oil pipeline performance (i.e. the ability of a defective in-service oil pipeline to carry out its task) in such a way as to predict failure. Additionally, it is possible to predict an imminent break in the pipeline, with respect to its location and severity.

Most importantly, the experiment confirmed a repeatable pattern for vibration and acoustic emission profiles, which can be used to distinguish between different pipeline damage and failure types. The experiment also seeks to confirm the primary assumptions behind this proposed technological development, which is that observations made in a laboratory can be repeated in real-world situations. However, until a planned field test by the author is conducted, there are still two primary assumptions: (1) that distinctive profiles exist for the wider range of failure modes observed in real-world situations; and (2) operational characteristics (e.g. a hostile environment) do not mask the ability of the sensors to detect acoustic and pressure profiles.

5.9 Industrial Implications

The ability to carry out a basic inspection, analysis and report on a pipeline using an integrated sensor device offers many benefits. The use of an integrated sensor device would provide valuable pipeline management information and the ability to detect and locate mechanical damage at an incipient stage, as well as providing an assessment of the overall pipeline operating condition and changes in performance profile. This has been shown to be a feasible part of a pipeline maintenance and rehabilitation programme.

What does this mean for the pipeline maintenance manager in a situation where there is one-kilometre sensor spacing for a pipeline that is 3,000 kilometres in length? Given an approximate current unit cost of integrated sensors of £100, this represents an initial outlay of £300,000. Ongoing costs of digging up the same pipeline stretch would amount to about £1.5 million and would need repeating every 6–12 months. So, considering existing monitoring costs, the integrated sensors would pay for themselves in three years. They pick up the point at which failure is about to occur and as a consequence reduce the impact of that failure, both economically and environmentally. Thus, in some parts of the world – the United States in particular, where litigation is rife – this is of true significance.

CHAPTER 6: IMPLICATIONS OF RESULTS

6.1 Introduction

This chapter reviews and addresses the findings of the experimental test series presented in Chapters 4 and 5 in the context of the maintenance approaches and theories outlined in Chapter 2; the literature review. In this investigation the influence that various defect sizes and characteristics had on the performance of an in-service pipeline system were examined. In Chapter 3, the methodology and experimental design were presented that were used to calculate the natural frequency of the oil pipeline in the experimental programme. Table 5.9 compared all the experimental results: normal state (theoretical) versus measured defects (small, medium, sealed holes and total failure). The implications of the findings for the oil industry and the built environment at large will be discussed in this chapter.

Figures 5.9 and 5.10 show the defect and leak vibrating signals coupled to the flow dynamics as fluid moves along the defective section of the pipe used in the experiment. With each frequency band, the strength of the vibration and acoustic emission activity was found to increase substantially as simulated damage increased. Estimates of the severity of the simulated damage were applied, based on the understanding that the sizes of the nails inserted in the pipeline related to the nature of the damage signals recorded. The relationship was calculated by the method described in Chapter 4 and is further set out in Tables 4.2 and Table 4.3. The values given in Table 5.3 and Figure 5.6 are for the measured sizes of the defects and comprise the percentage of the area of the structure over which damage was visible.

6.2 Implications for Industry

6.2.1 Introduction

It is evident that the experimental pipeline system’s condition deteriorated progressively. The pipeline system failure in the laboratory did not occur all at once but in phases. This raises two issues: performance and early detection. Firstly, the ability of the pipe to transport oil is diminished since some content is lost on failure. Secondly, it is imperative to know the possibility of finding defective characteristics in an oil steel-pipeline system before it fails completely. This knowledge would help to change the current reactive approach to maintenance to a proactive one that seeks to prevent the oil pipeline system failing.

It is important, too, to highlight some limitations that emerged from the analysis that are relevant to the thesis. The variation in defect profile values shown in Tables 5.9 to 5.12 and Figure A2 (in Appendix A) at first glance appears to represent the actual defect characteristics. However, the model of damage used did not take into account the length of the nails and steel material removed to form the hole, since this was negligible (and was not the main focus being addressed) in comparison with an analysis of the the changes in condition.

6.2.2 Test Series 1 and 2

The graphic representations in Figure 5.6 compared sets of damage characteristics, and also gave the output from the defective location routine for the three sets of damage (see also Table 5.10). The graphical representations in Figures 5.8 and 5.10 show that the damage was located in each case within the constraints imposed by the irregularity of the pipe wall. It is assumed that, should there be any changes in the damaged area of the pipeline, it would result in a significant change in the graphical representations produced.

One of the similarities noted in the signals recorded at each sensor location was the intermittent time shift, i.e. delay, in the signal arrival time. Such intermittent time shifts could have been caused by the fluid flow (see Figure 6.1) through the damaged pipe; or the leak being periodically accessed, for example by fluid flowing into the (uneven) interior surface of the pipe); or bubbles being forced through the leak orifice. These intermittent time shifts in signal arrival time were detected using a threshold detection circuit on each sensor's output, and then by measuring the time difference between the intermittent time shift at sensor location I and its counterpart arriving at sensor locations II, III, IV and V. The defect-and-leak location was clearly revealed as a peak in the frequency profile chart (Figure 5.1 sensor1A-1B to sensor 5A-5B), showing the shift of time domains, which were detected with specific arrival time differences between the sensors. The cross-correlation function produced the difference between the arrival times of similar signals between two sensors. This gave information that can be used for locating defect-and-leak position along the pipeline.

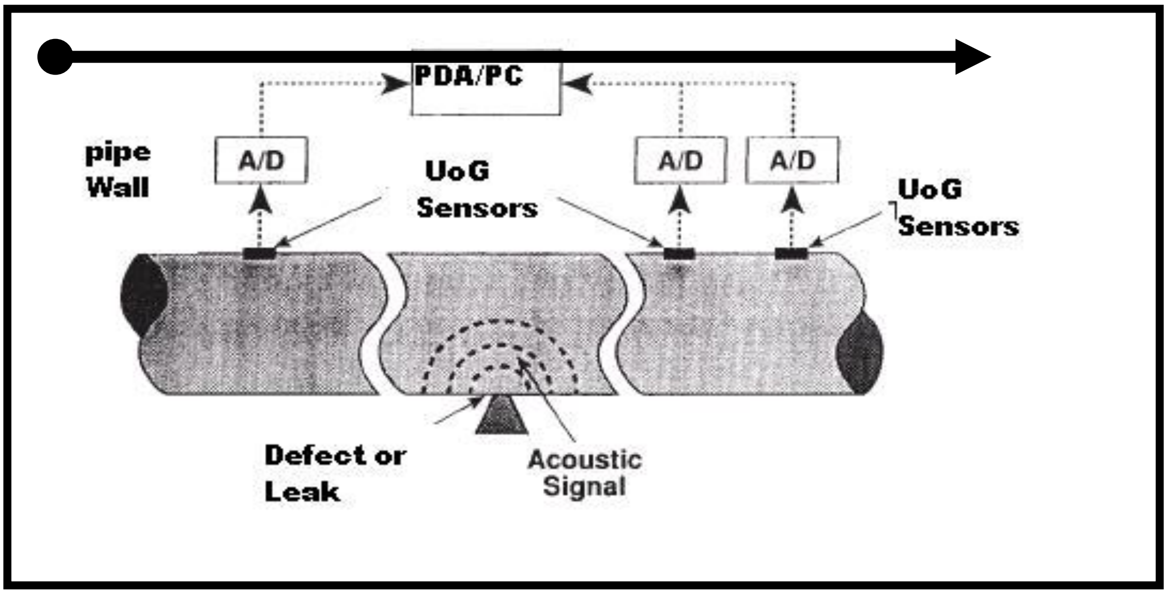


Figure 6.1: Sensor Locations and Delay in the Signal Arrival Time

6.2.3 Pipeline System Fault Detection

The results of the research show the possibilities for further integrating and developing a miniaturised sensor solution capable of delivering continuous information about an in-service buried pipeline system’s change in performance in real time. The data is converted into information (the device logic is coded to execute rules that extract raw corrosion/defect characteristics and processes data *in situ*) before reporting the performance changes to remote locations without third-party assistance. Therefore, monitoring and examining the relationship between the vibration sound energy and the defect characteristics can help differentiate any changes in performance of the pipeline system. This approach is innovative and enhances the existing knowledge of the subject.

As was stated in section 5.5.4, when the sensors are well calibrated against steady flow, it should be possible to see a change in signal strength as the pipe deteriorates. Further, when the pipeline bursts, a very large signal is produced. In other words, another innovation and contribution to existing knowledge is that, at the point of failure, there are large gaps in the acoustic (waveform) (as Figure 5.9N indicates) that can be used to quantify pipeline failure. It was possible to examine the effect of the defect on the pipeline’s natural frequencies (see Table 4.6) and a distinction could be drawn between detection, characterisation and quantification of the defect and leaks. The location of the defect is shown graphically in Figures 5.6 and 5.8.

It became clear by implication, that the characterisation of an oil steel-pipeline system defect (e.g. a crack) requires greater sensitivity from the vibration sensor than just detecting the presence of the crack. It would also be necessary that the defect location be accurately identified and estimated along the pipeline. It can be assumed that there is a linear dependence between the vibration signals and the induced damage on the pipeline system.

6.2.4 Prediction versus Detection

The time needed in the laboratory for understanding the detection and characteristics of changes in the performance of a pipeline system was longer than anticipated. This made it impossible to complete the study for predicting the system condition and changes in performance as was proposed in section 1.4.

However, within this study, technical indicators were shown to provide a unique perspective on the condition and performance characteristics of the underlying pipeline system’s maintenance prediction. These perspectives form the core of the next phase of post-PhD development, which will deal closely with the issues outlined above and expand the key ideas behind signal recognition as well as the development of other indicators. These can in turn serve as warning that a pipeline system’s performance is about to change.

These technical indicators act as a confirmatory signal to validate previously detectable signals or reinforce a recognised developing trend in the pipeline transmission condition and continuous performance assessments. Detection (see Figure 2.6) would become most effective when used in conjunction with pattern analysis and identification, behavioural identification, and other technical analysis tools for which this study has laid the foundations. By researchers and oil industry operatives being aware of the broader picture, detected signals can be put into context. It would be feasible to integrate the experimental results into an integrated-sensor device with inbuilt analysis and reporting capabilities and associated change–in-performance protocols. As a result, the chances of success for predictive maintenance can be greatly enhanced.

6.2.5 The P-F Curve

In the first stage of the experiment, a P-F curve (see Figure 2.9) was created showing an incipient defect, its failure characteristics and the deterioration occurring to the point where failure can be detected (the potential failure point P). According to Wiseman of RCKnowledge.com, it is the P-F interval that governs the frequency with which the predictive task must be done.

The use of these experimental findings to continuously monitor the P-F interval in relation to the different failure modes on a transmitting oil steel-pipeline system is a significant contribution to the maintenance effort needed to detect a potential defect before it becomes a functional failure. The P-F curve characteristics are integrated into the proposed objective performance maintenance needs (see Figures 6.2 and 6.2B below), making it possible to detect defects and for suitable remedial action to be taken. This could help prevent the pipeline system's continual deterioration, usually at an accelerating rate that could well lead to the system reaching a point of functional failure (F).

In essence, the time needed to respond to any discovered potential failure with an integrated monitoring device is an added improvement from condition-based task intervals. It will enable consistent responses, correct planned action, and better organisation of the resources needed to rectify potential failure, so that action can be taken without disrupting the oil transmission and other maintenance activities.

It is possible to define a potential failure condition for a pipeline related to corrosion and other failure factors. Monitoring the system continuously is the preferred option in other industries. It is the most cost-effective option because, for example, pipeline pigging, or dig-ups after a pipeline failure, currently costs the oil and gas industry more than £2 billion each year. Monitoring continuously using the P-F interval in relation to different failure modes would enable a facility manager to arrange for the pipeline system to be serviced only when it is needed, instead of an area inspection and manual digging as part of an annual scheduled survey task. It is reasonable in this case to say that a predictive task is much more cost-effective than scheduled restoration.

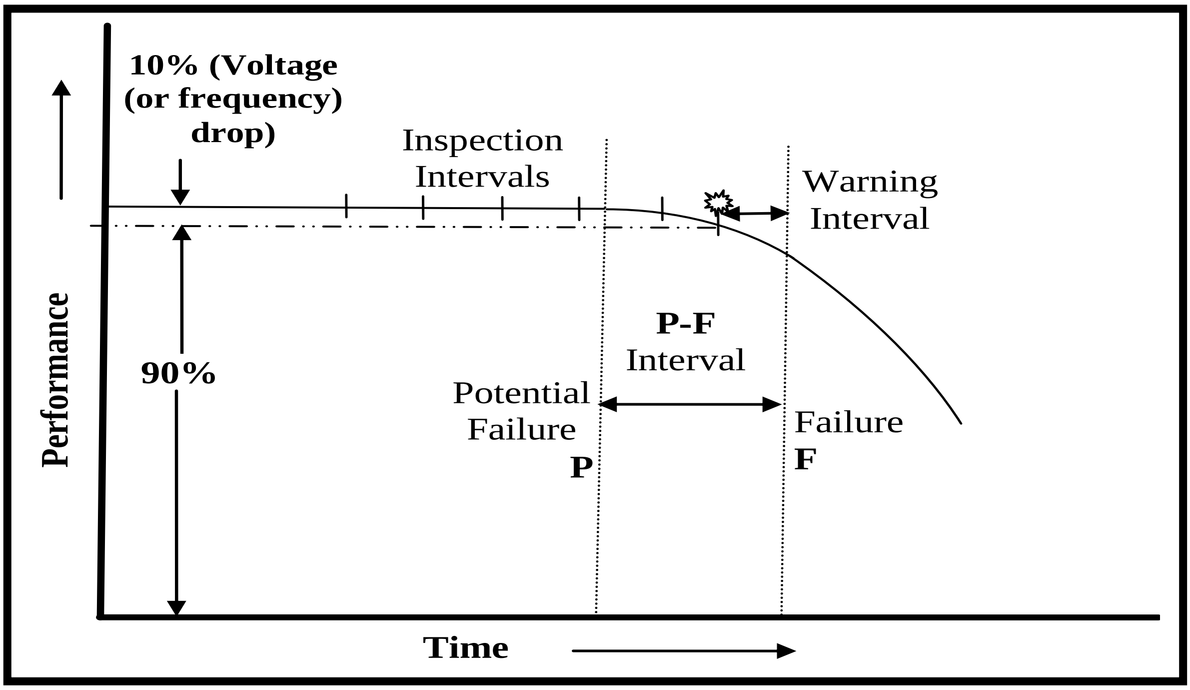


Figure 6.2: P-F Curve Indicating a 10% Drop in Voltage in the Pipeline's Performance

Figures 6.2 and 6.2A show the relationship between operating time and the condition of a pipe in a pipeline system. At point FM1 in Figure 6.2A (where a small defect is deemed to exist), a failure of the pipeline system starts to appear but is not visible to the sensor device**.** At point FM2 (where a medium-to-large defect exists), it becomes possible to detect that a pipeline failure will occur as the curve slopes down (FM3–FM4). At the bottom of the curve is the point (FM5) that corresponds to the time when a functional failure has occurred to the pipeline system, FM5 should be designed out in this new model when integrated with the performance model that might be able to predict the failure between the P-F intervals.

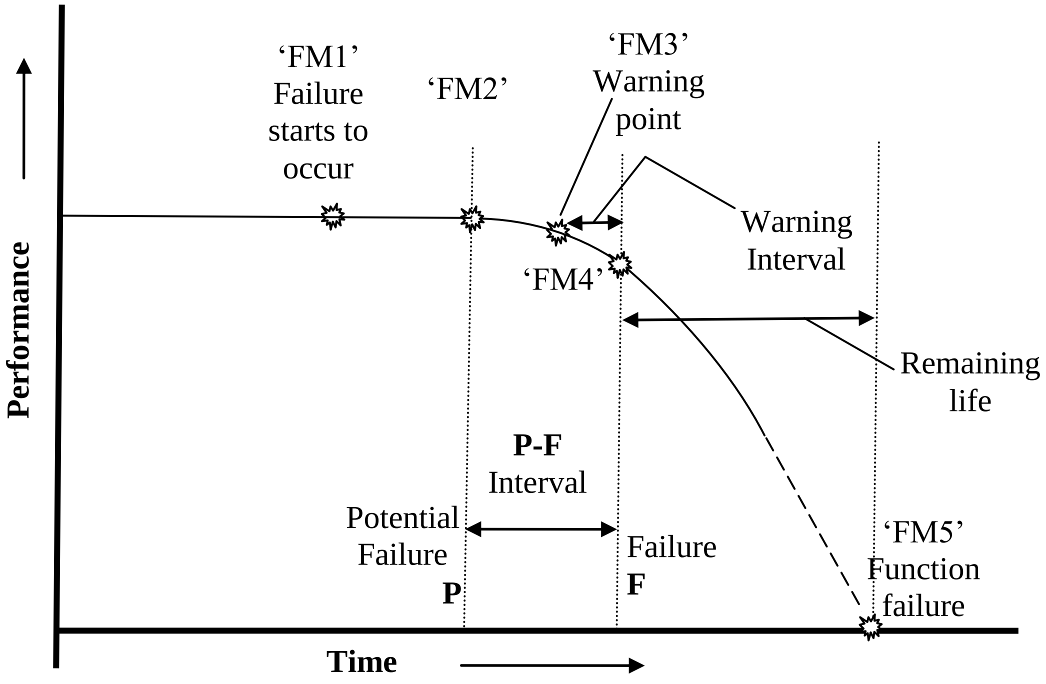


Figure 6.2A: P-F Curve Indicating the Relationships between Times and Changing Performance of a Pipe

The crucial issue in the P-F interval is the alarm periods. This is when it is possible for the sensor device to detect, from the frequency signal or voltage drop, that a functional change in performance has occurred, and then predict the time until complete failure. Here, continuous monitoring using the performance-based model of the in-service pipeline will detect potential failure and be able to alert the facility manager of the remaining P-F interval as indicated in Figure 6.2A. This is the time left until a functional failure occurs. In essence, it is the crucial time available to the facility manager to prevent a functional failure from occurring after the performance model detects and sends an alarm of the potential failure. The fact is that even if the facility manager knows a crack is present on the pipe, there is nothing practically that can be done about it. However, by predicting the time remaining before complete failure and identifying the type of failure, the system will allow the facility manager to mobilise a response team in readiness for failure. This represents a shift to a 'just in time' (JIT) approach to maintenance being implemented.

The general assumption has been that, with an age-related pipeline system failure, the probability of failure should increase at some point in time – which can be constant in time, or can start at a specific age when the pipeline system or a component is wearing out due to fatigue, corrosion, oxidation or evaporation. Continuous monitoring using a performance-based model of the in-service pipeline that integrates the P-F Curve and the existence of an obsolescence cycle (see Figure 6.2B) will be best equipped to deal with failures that are not due to age but, rather, to surrounding factors such as a non-uniform stress or handling errors, which may occur at random times.

It is important, though, also to consider other kinds of failure that are not noticed under normal pipeline operating conditions, such as hidden failures. Essentially, hidden failures alone may cause minor problems but in cases of multiple failures they can be disastrous. The continuous flow of information along with the data loops, the knowledge acquired from these studies, and the adoption of a physical performance measure-mode method will help to plot the P-F curve and the decay curves over time for any given pipeline system. Knowledge acquired from this research collectively would make it possible to discriminate against the different failure modes, and therefore will make it possible to categorise maintenance decisions and the related planning process at all times.

Points FM2, FM3 and FM4 (see Figure 6.2A) are crucial intervals on the P-F curve. These intervals can be used as an indicator when developing a physical performance model and the proposed monitoring device. From the voltage difference and drop-trend of the curve, and as found in the experiment performed for this research (see Figure 5.6), it is evident that there is a statistical regression of about -33.33% in relation to a pipe’s performance as a result of deteriorating conditions. The voltage drops between the aforesaid intervals, when compiled together, can be used to compare the defect signals indicating the deteriorating performance (as a trend curve) against the normal-state signal at the corresponding intervals.

The failure mode with the dominant energy (i.e. maximum amplitude on the Voltage ~ Time graph) that created the corresponding vibration signal can give useful information to a facility manager.

Viewed from an obsolescence perspective, as the P-F curve progresses downwards over time, corresponding to decreasing resistance to failure, obsolescence in the pipe system is increasing. Therefore a new concept of expression of the failure process, i.e. an ‘obsolescence P-F curve’, as shown in Figure 6.2B, can be achieved if the P-F curve from Figure 6.2A is mapped onto the obsolescence curve from Figure 2.3. The resultant obsolescence P-F curves, shown in Figure 6.2B, are indicating three sets of obsolescence occurrences and corresponding maintenance cycles, which can be used to reduce the respective three obsolescence gaps to bring the system back as close as possible to its normal state.

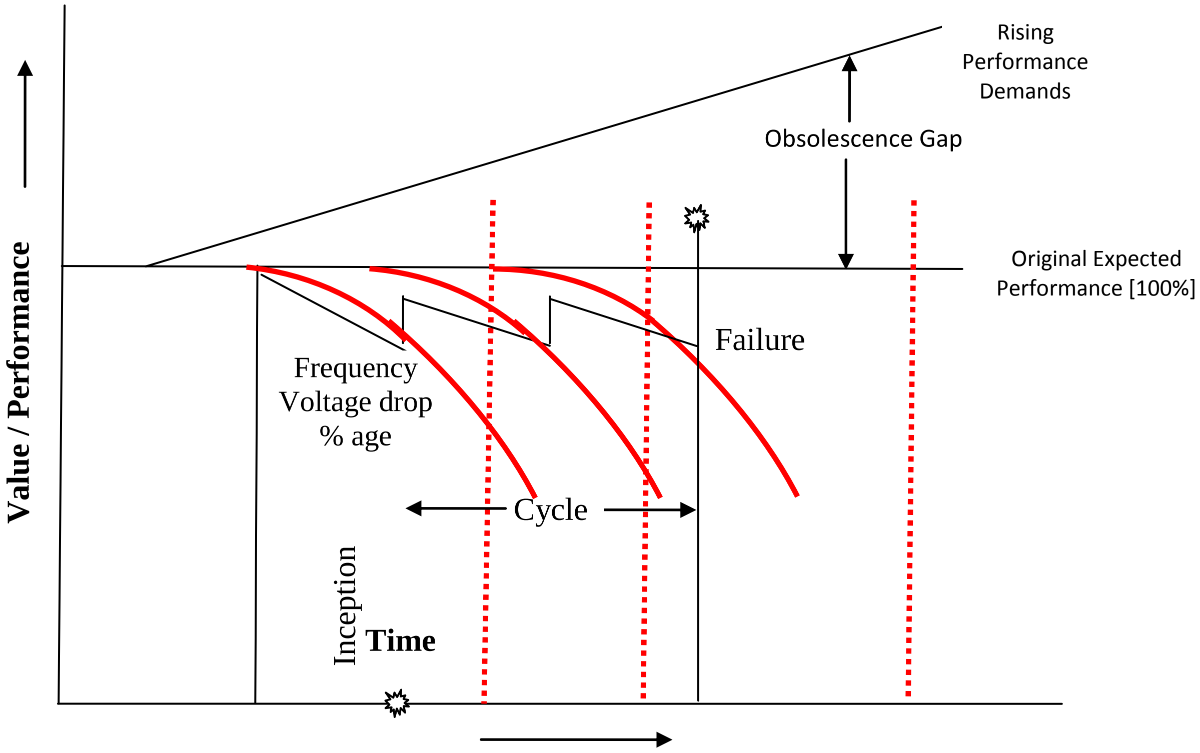


Figure 6.2B: Integration of Obsolescence and P-F Curve Models (*Source*: Umeadi and Jones, 2008b)

6.2.6 Obsolescence and Maintenance Decision-Making Theory

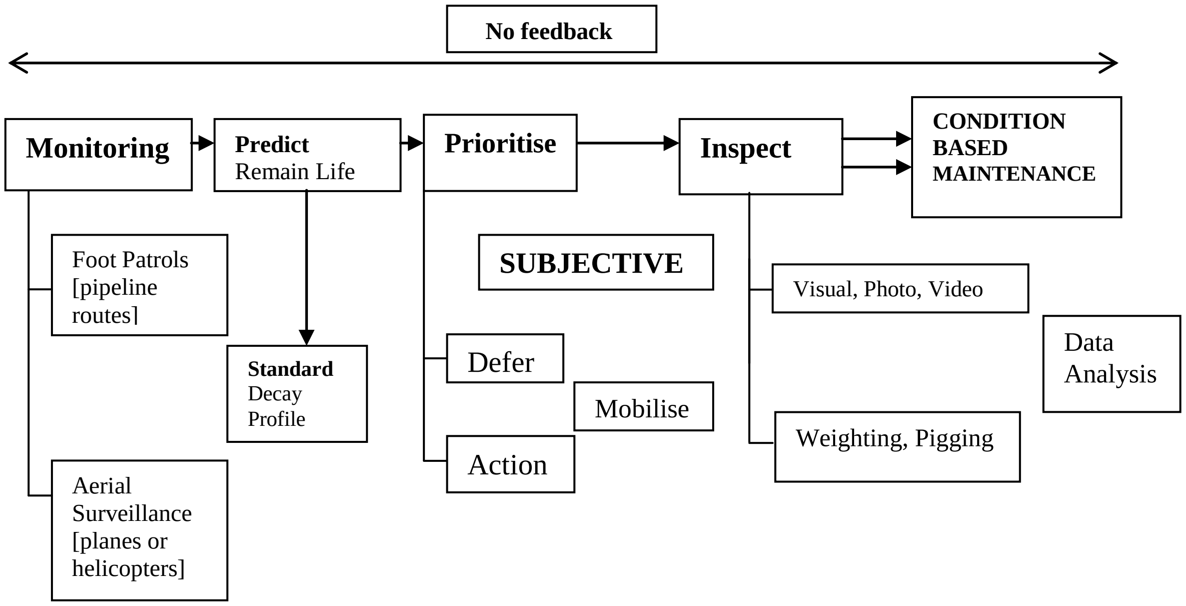
Sections 2.1.1 and 2.1.2 noted the theoretical implications of the Chartered Institute of Building (1990) and Jones's (2002) hypothesis that highlighted the existence of obsolescence and at the same time proposed an alternative definition for maintenance and refurbishment. They noted that "work undertaken in order to keep, restore, or improve every facility, its services and surrounds to a currently acceptable standard and to sustain the utility and value of the facility" fails under maintenance and refurbishment. In this definition, maintenance and refurbishment was explicitly linked to improving the value of the built asset. Jones (2002) reinterpreted Finch's (1996) model to one that more accurately reflects practical options (see Figure 2.3).

Thus, in Jones's model, maintenance cycles were repeated until the point at which a building (or, in our case, an oil pipeline system) fails to satisfy the owner's requirements and a major refurbishment is needed. However, it should be noted that even after refurbishment some residual obsolescence remains, and this often grows over repeated refurbishment cycles until the obsolescence gap is too great for an organisation to bear. At this point the organisation either relocates, the building is demolished and rebuilt, or the building is refurbished beyond its original purpose and a change of use occurs.

In the oil and gas industry, this process of continued obsolescence within Jones's model is not an option in that it would be uneconomical and hazardous to allow oil pipeline systems to deteriorate to the point at which they fail to satisfy the oil/gas industry's demands and for a major refurbishment to take place. However Jones's model can easily be adapted to suit the new maintenance model proposed in this thesis. The experimental test specimen used here was designed to produce well-defined, failure modes. Given that the in-service pipeline system's condition and performance progressively deteriorate and can be detected, it is possible to be remedied 'just in time' before total failure**.** Therefore, there will be no need for the pipeline system to be shut down for repairs or replacement, which often leaves the industry with no alternative routes to transport the oil.

The outcome of this thesis would, instead, result in the designing-out of unnecessary cycles of the obsolescence gap by integrating all the maintenance processes into the proposed objective performance maintenance model within Jones's (2002) maintenance cycle's characteristics (Figure 2.3). The integration of the P-F curve with the Obsolescence model to develop a continuously monitoring sensor device (Figure 6.2B; Umeadi and Jones, 2008a) would transform pipeline integrity surveys and help to eliminate the queuing culture currently associated with condition-based maintenance processes (top portion of Figure 6.2C; Umeadi, 2005a). Issues raised by Jones (2002) in relation to 'value' in the context of built-asset maintenance decision-making and building technology can be finally acknowledged (Umeadi, 2005a). Jones's argument is that 'value' should be explicitly linked to the ability of the built asset to support organisational performance, and built-asset maintenance should be viewed as a strategic issue managed within the broader context of an organisation's strategic planning framework.

TRADITIONAL CONDITION-BASED MAINTENANCE



PROPOSED PHYSICAL PERFORMANCE-BASED MAINTENANCE

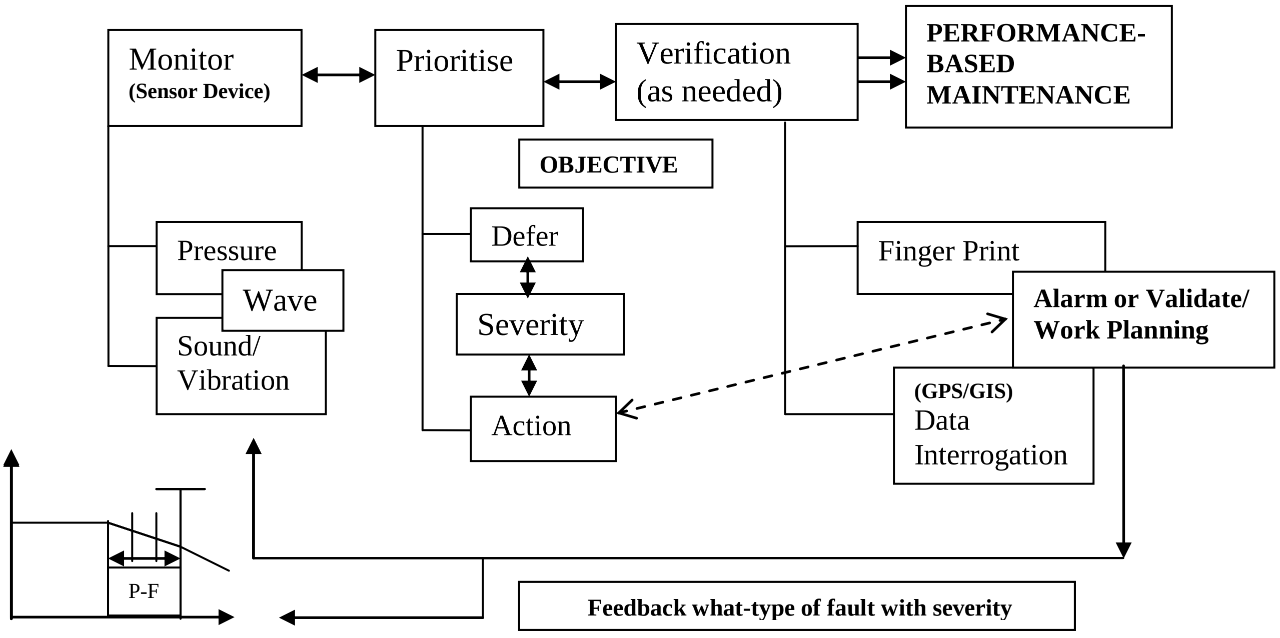


Figure 6.2C: Performance-Based Integrated Maintenance Model for Oil and Gas pipeline System

(*Source*: Umeadi and Jones, 2008b)

Hence this modified theoretical model for performance-based maintenance (lower portion of Figure 6.2C), which eliminates the queuing process, is presented as a result of new knowledge generated and could be used to bind together the different stages of the maintenance/process model, the result of which will effectively be fully integrated into a multi-criteria-model-based device capable of holistic examinations of the root cause of a pipeline system's problems (Figure 6.2B).

As a result, the appropriate technical and business solutions can be developed to address the business case for maintenance action. This is achieved by implementing continuous monitoring to assess, evaluate and report any in-service changes in a pipeline system's performance. The maintenance decision-making process would be based on the pipeline system's physical performance using any of these parameters from amongst frequency, voltage drop, or percentage age. As a general rule, a 10% drop in performance is more than enough to trigger the overseeing authority to fix the system or component so that the performance could be brought back to the 100% original expected performance level.

6.2.7 Physical Performance-Based Maintenance Models

Oil and gas pipeline maintenance traditionally includes techniques for assessing the condition of an existing distribution system. The areas for review in this research include: damage and leak surveys (including site visits), data acquisition and analysis (digging – locate and mark; failure analysis), valve inspection, and pipeline repairs (involving prioritisation /mobilisation].

The general activities include:

- an audit of internal maintenance practices to identify areas for efficiency gains or process improvements;
- evaluation of the physical system to identify potential maintenance requirements; and
- the project management of necessary maintenance activities and/or routine maintenance work.

Generally, pipeline maintenance and reinstallation models may include: preliminary routine feasibility assessments; regulatory permitting strategies and implementation; replacement selection for the pipeline and associated materials; right-of-way planning and acquisition; and design and construction supervision. System expertise also includes regulator stations, cathodic protection systems, and metering facilities. It is important to fully understand these processes in order to design an effective and efficient objective-maintenance model capable of monitoring, analysing and reporting any changes in performance of an in-service pipeline system.

To best explain performance-based maintenance, a new theoretical model was produced in this research (lower portion of Figure 6.2C). In chapters 1 and 2, it was argued that maintaining the integrity of facilities grows in importance and becomes more difficult as existing infrastructure ages and new facilities become larger and more technically complex. Increased scrutiny of the protection of the well-being of the environment and the communities surrounding the oil and gas facilities only heightens the importance of conducting proper maintenance. The condition-based method was not the best way of predicting maintenance action, in that it was periodic, it missed incipient defects that developed between periods, it was disruptive and expensive, and it utilised different protocols that could not be integrated. In one instance, it could not predict the high-profile explosion at the Buncefield oil storage complex in North London, when the ensuing depot fire raged for several days as a cloud of toxic gas covered 4,000 square kilometres of South East England. This failure in service had severe social and economic consequences, and it raised doubts about the quality and reliability of the detection techniques used. These impacts place a greater need on learning about the performance of in-use pipeline systems and the reliability to deliver oil and gas from upstream, midstream, and downstream without loss of content.

6.2.8 Improving Current Pipelines Monitoring

The most widely used condition-based methods for pipeline monitoring includes foot patrols along the pipeline routes and aerial surveillance using small planes or helicopters. These patrols perform facility inspections, check for construction activity in the vicinity of the pipeline, and maintain the pipeline’s right-of-way.

This monitoring of the thousands of kilometres of pipeline systems worldwide is most commonly performed in line with a sporadic schedule using visual observation from aircraft flying over the lines. Conventional flight-observation frequency is in the order of once every 1–2 months for most of the pipeline length. Detection of unauthorised intrusion and security risk events with this practice is low, due to a number of limitations inherent in this approach.

These limitations include infrequent coverage, human error in detection, limited historical data-analysis capability, high mobilisation costs and limited trend analysis.

Fundamentally, the condition-based method is very simple; it merely enables prioritisation of action – for example, to untaken maintenance action (such as to inspect a length of pipeline) or to defer such inspection. The methodology is not designed to carry out P-F modelling.

6.3 Implications for Other Pipeline Industries

In order for intelligent prioritisation within a performance-based measurement model, a method is required to evaluate continuously the in-service performance of projects in terms of their overall severity/importance. The most important question would be: Which maintenance action will help achieve prioritisation of objectives most efficiently? Based on knowledge gained from this study, it is suggested that a physical performance-based maintenance model integrating the current processes with the outcome of this thesis (lower portion of Figure 6.2C; Figure 2.2c), an integrated sensing, analysis and reporting device would be the most efficient method instead of the condition-based method.

Whilst performance-based maintenance in this case measures the physical performance of the pipeline, an integrated sensor records and analyses the pressure and sound wave transmitted through the pipe from an array. It allows the flow of the physical performance of the pipeline information in real time to be made available to a facility's manager. This is a major contribution to the improvement of the maintenance planning process.

In contrast with the condition-based maintenance model, the integration of defect severity into prioritisation in the performance measure model allows it to carry out P-F modelling evaluations (Figure 6.2C). By acquiring and analysing information continuously in order to determine the severity of each defect, it is possible to classify the severity of the pipeline's physical performance and report to a base station. This flow of information and the feedback loop will help the maintenance decision and planning process. With the ability to use the performance measure to plot the P-F curve or the decay curves over time (see Figures 6.2 and 6.2C), it would be possible to learn and understand these curves and eventually to know what each interval within the curve means in terms of pipeline integrity. With the knowledge acquired from the P-F curves, a sensor is then able to calculate the severity of the expected physical performance and to prioritise intervention where appropriate.

The objectivity of the performance measure comes from the fact that the P-F curve or the decay curve can be plotted, and from this it is possible to move into full in-service autonomous pipeline integrity monitoring. In doing so, it would be possible to establish the standard 'six sigma' errors (Wikimedia.org) that would eliminate any false-positive alarms. Consequently, it should be possible to improve the quality of the maintenance process outputs by identifying and removing the causes of defects and variations in the maintenance process. Prioritising with a performance measure that follows a defined sequence of ‘six sigma’ steps helps eliminate queuing and related maintenance cost. This also means that, by plotting continuously, one might make this improved process relevant to overcoming the subjectivity involved in maintenance decision-making.

There would also be a noticeable difference when commissioning works with the performance-based maintenance model. Under the condition-based maintenance models, most works are one-offs – for example, a project to replace a 15-metre section of damaged pipeline. Commissioning works using the performance-based maintenance model on a continuous basis might mean that partnering, i.e. having a monitoring partner with shorter repair contracts, becomes the norm. A remote-access method, integrated with an appropriate algorithm, would deliver the benefits of a centralised performance-based maintenance information system capable of eliminating many of the limitations in the condition-based maintenance model.

The ability to predict defect growth with the physical performance-based maintenance model helps to eliminate the problems of isolated data sources that are present in current condition-based maintenance models. In essence, oil and gas pipeline system maintenance is crucial to the reliability and performance of the physical assets that produce, transport, and process the transmitted oil and gas. Operating companies face difficult decisions, particularly meeting the need for safe operations while taking into account the costs of making necessary maintenance improvements.

With its integrated sensor detection and analysis, the performance-based monitoring model fuses the processed information to estimate the pipeline system’s reliability measures. This means that built-asset physical performance in-service information will be continuously available when needed, which helps to focus the resources and information required to prioritise maintenance activities and hence optimise a return on investment.

Similarly to the automobile and the aerospace industries, when the outcome of this research is integrated into the maintenance process, it would mark a move away from prevention (the ‘run-to-failure’ approach), and towards prediction (i.e. just in time repair work). The principle applies that an objective measure of continuous in-use performance can start to develop an objective measure of the obsolescence gap. This means that predicting the defect growth is no longer subjective, and it should be possible to plan long-term interventions. It is necessary to take a step beyond preventive maintenance, because the current practice is not sustainable. The monitoring of an oil pipeline system’s delivery status is just one of the ways that reliability-centred maintenance can be applied to built assets and the built environment at large. Reliability-centred maintenance techniques enable the built asset’s owner to observe the pipeline system performance during transmissions in a variety of complex operational environments.

The use of a fully integrated multi-criteria model-based device capable of holistic examination of the root causes of a pipeline system’s problems empowers the built-environment industries with accurate information that can lead to substantial cost avoidance and savings. Their uptake makes it possible to divert monies set aside for unnecessary maintenance activities, such as field surveys, off-location data analysis and deployment of digging in subsections, to be spent on further research and the introduction of new maintenance processes that eliminate queuing. It requires more than evolving from a condition- or defect-finding exercise; most importantly, the process needs to fully integrate performance of the physical asset maintenance models with ‘real-time’ information processing. Effectively the new maintenance processes will comprise strategic planning and decision-making capabilities with real-time information and will not depend on historical data.

In a pressured pipeline a very small leak can erode the steel at the leak point, and fairly quickly this can result in a much larger defect. Also, once oil escapes from a pipeline, it can flood the areas surrounding the pipe system and spread to other locations. This study has shown that the use of a fully integrated multi-criteria model-based device is capable of detecting an incipient defect and tracking this defect as it grows until failure (i.e. leakage) occurs.

6.4 Implications for Other More General Built-Environment Maintenance

The results of this research at the very least should help provide built-environment maintenance teams with the means to integrate a sensor device on a micro/nano-chip so as to provide real-time information on the in-service performance of built assets. However, owing to time constraints, the planned real-time wireless test was not carried out within the test programme but is expected to be performed as part of post-PhD field tests.

An objective performance-based maintenance methodology could also be used to predict the performance of other buried utilities, such as a gas or water infrastructure or their subsystems. This implies that by examining the relationship between the vibration sound energy and the defect characteristic of the in-service infrastructure, its performance can easily be monitored and, in turn, this helps to differentiate between gradual or rapid increases in deterioration through the vibration sound peak amplitude as the transported oil flow transits the defective areas in the pipe wall.

The peak amplitude of the individual vibration sound event was noticeably different in magnitude (measured in decibels), as shown in Figures 5.4 and 5.6; the total energy for each vibration event increases gradually. What was important was that the measured parameters associated with the vibrational energy were similar to the predicted vibration sound emission measures.

From this result, the change of vibration sound energy with defect size and shape could be one of the effective means of monitoring pipeline performance parameters. This result is also useful to estimating any changes in condition and changes in performance in an in-service pipeline system; it therefore helps in answering the question raised in section 2.3.3. Those questions, and their answers from this research, are as follows:

- **What happens to oil flow?** It becomes the source of information gathering; the vibrating sound emission is transmitted along the fluid flow.
- **Does the flow pattern change?** Yes, there are indications that when the defect type changes the modulation frequency changes. The more the defect grows in size, the more the depth of modulation is influenced (see Chapter 4).

- **Does the pressure change?** The flow dynamics vary with line pressure**:** flow rate fluctuates when the pipeline pressure changes. Hence the frequency of modulation could be said to define the type of defect, its development, and the depth of modulation.
- **Does the pipeline vibrate more or less?** Different deteriorations have different influences on signal propagation. The sensitivity was strongly dependent on the pressure of the working medium and, according to Liu et al. (2000), the size of the deterioration and leakage can influence the outcome of the measured signal. As was observed, the modulation frequency changed when the steel pipe ruptured; there was a reaction force that was supposedly created by the high-velocity fluid jetting out, resulting in the observed signal displacement.

The knowledge of what happens to oil flow dynamics in damaged pipeline systems, when integrated into sensors, should provide the capability of monitoring and reporting deviations in the pipeline transition signatures in a variety of challenging locations. This is a prerequisite for predicting changes in performance, as was shown in the tests in situations where there were leaks from a defective zone in the pipeline system. The results from the location routine were a bit unclear at the beginning of the test, especially with the small nails; but when the defect became much more severe, the defective location was predicted more readily. However, even when the location routine gave erroneous results, the presence of a defect was always detected by the frequency modulation.

The recorded equivalent of the defective zone, shown in Tables 5.4 and 5.7, increased with increasing damage. Table 5.8 gave an indication of the severity of the damage even though the routine that estimates the magnitude of the defect also assumed a single defect zone instead of three separate defects (resulting from the nail insertions). It can be seen that it is possible to define performance measures and set performance thresholds for an oil steel-pipeline system by measuring its physical performance.

These experimental tests were also a validity investigation into a non-destructive testing method, especially vibration sound emission detection techniques of oil steel-pipeline defects and leakage. It was shown that the method has successfully been used to locate defects, fatigue and failure. At the same time, the ability and effectiveness of piezoelectric elements in defect detection were evaluated and shown to be able to predict changes in oil and gas pipeline system performance using the prepared oil rig and flow station. These changes in performance were due to the low attenuation rate of signals in steel pipes. However, the devices used are time-consuming and expensive; they required the assembly of different combinations of technologies, with both cost implications and configuration issues.

Lastly, as was observed in Figure 5.6 as compared with Figures 4.4 and 5.10, the surge resulted in pressure and flow-rate oscillations that not only generated excessive vibration and reduced performance, but also threatened the structural integrity of the pipeline, along with other components of the system, with high-frequency noise that triggered the alarm threshold. The importance of this observation is that it was possible to detect signals associated with the defective sections of the pipeline system as fluid flow pass cracked sections of the pipeline system.

These intense oscillations in the pressure and flow rate in the entire system occurred each time the valve that fed the pipe system was opened. For the first ten seconds, an absolute silence was observed, followed by recorded discharge pressure oscillations with amplitudes as high as 4bar (full pump transfer pressure).

There were no circumstances observed under which backflow occurred in the toughened-flexible transparent hose during this test. Although little is known of the dynamics of backflow phenomena, it is not appropriate to make a case here or to argue the limits associated with strong oscillations in backflow phenomena – the issue is beyond the scope of this research.

The benefits of using acoustic vibration sensors to detect pipe defects and their failure modes are numerous. Nonetheless, it is not clear yet how multiple failure modes might affect a sensor’s ability to identify a problem, as this was not investigated owing to time constraints. Further work is suggested to identify any weakness that might exist.

The same note of caution is required with regard to scaling-up findings to larger-diameter pipes. This test was conducted on a 1-inch diameter pipe, but it is not yet clear whether there are potential issues that could negate the laboratory findings for scaling up. Although proven large-scale system design principles such as replication and layering improve scalability, their application to pipelines and their systems or to sensor devices should be considered for further study in the design work carried out toward the planned field tests. Furthermore, the design principles should be independent and separate from safety-related issues.

Other challenges being faced in applying this research include contaminants existing in a real-world oil-flow situation. For example, leaking oil in the experiment was observed to have transferred some debris, possibly from the weld-sealant, to other parts of the set-up, which influences the viscosity of the oil significantly. Should this occur in a real-life situation, the sensor and data analysis would have to be equipped to learn and concurrently process complex signals. The device capabilities should be focused on understanding different failure modes of the pipe system and fluid flow behaviour in order to improve usability, characterise full/partial flow, and predict future detection patterns.

6.5 A New Approach to Pipeline Maintenance

Chapter 2 anticipated the cost of monitoring a pipeline system to be daunting, especially with many of these pipeline systems being in inaccessible and hazardous locations. The proposed integrated wireless sensor would provide an effective, low-cost solution for continuous pipeline system monitoring in order to ensure continuity, save wasted and expensive gases, and prevent unwanted emissions. Integrated wireless sensors are also generally known to be well suited for gas emission detection from a variety of vents, storage tanks, etc. A major benefit of continuous monitoring is the prevention of expensive and potentially dangerous leaks.

For the sensor to be effective, it must to include a diagnostic component that can attribute an acoustic and pressure profile to a specific failure mode. Artificial ‘neural network’ specifications can be used to describe the most important faults detected with an automated diagnostic and reporting system. The specifications include an electronic document to (a) describe rules and variables used for performance assessment and diagnosis, (b) identify degradation and failure modes and conditions associated with each mode, and (c) identify all ranges of variables used to categorise the corroding buried oil steel-pipeline performance as was described in Chapter 2.

This artificial intelligence system is capable of learning from experience without third-party intervention. Such an approach is novel: there have been fragmented efforts that have combined one or two of the rules listed above, but not all in one device. The implication of this finding is that it may be possible for some interesting applications to be developed. The system would sample at high data rates, and at the same time must be antagonistic in data collection duty cycles. Therefore, the application would be able to conserve power for continuous operations – especially to enable essential information to be transmitted wirelessly from below to above ground level and then on to predetermined base stations**.** This new maintenance technique would take the strain out of built-environment maintenance systems by converting data into information at source, making it available to the relevant facility managers, and freeing valuable time to focus on core business activities. This is in contrast to the present data-acquisition practice that the oil and gas industry is dependent upon: limited wired/remote monitoring systems, digging and fly-over data loggers operated with low-battery duty lifecycles.

The proposed maintenance technique integrates sensing, self-powering, analysis and reporting capabilities. It will enable local processing, high-data rate acquisition and high-bandwidth two-way transmission protocols. In essence it will mean a substantial contribution to pipeline maintenance strategy. The technique being proposed would also contribute to meeting Western/OECD environmental regulations, which are becoming increasingly stringent. As demand for fossil fuels continues to increase, oil and gas companies need improved technologies to optimise production, streamline operations, and expand refining capacity; they also need lower-cost solutions that meet compliance standards. In the oil and gas industry, pipeline-monitoring applications have long been focused on custody transfer and pipeline pressure monitoring. As a result, nearly all of current monitoring and automated applications are process and operations related rather than maintenance related, so the proposed new approach to pipeline maintenance is a step in the right direction.

The data from this experimental programme, when integrated with an algorithm that is being developed for the post-PhD field trials, forms a semi-continuous monitoring system that not only recognises imminent failure characteristics but also identifies the probable cause and estimates severity of impact. The outcome of this research, when integrated with a smart system, forms an intelligent sensor for monitoring the integrity of steel-pipeline systems for oil, gas and water.

The next stage in development is to translate the research model into a working prototype suitable for a large-scale field test. It would help to improve current inspection technology and detect incipient defects, leaks and potential failures before they occur. The projected impact for the pipeline industry at large is high. Take, for example, a failure in large-scale pipeline distribution systems causing disruption to supply, damage to the environment and economic loss to the industry. In the oil steel-pipeline industry alone, the financial implications for the industry of pipeline failures are estimated at £2.5 billion a year (corrosionsource.com, 2001). The 2004 annual report of the strategic Centre for National Gas of the United States stated that most gas transmission lines are made of coated steel and that damage to the line's protective coating is likely to cause a corrosion leak at some stage. The report further highlighted a statistic from 1994–2001, namely that, of 224 third-party incidents on transmission lines, there were 7 deaths, 35 injuries, and $167 million in property damage – indeed, one incident cost $25 million (Huebler, 2002). Evidently, the current methods of detection rely on periodic inspection, which misses more occurrences of failure than it identifies.

The proposed intelligent-sensor system will comprise a micro/nano-chip that can be retrospectively attached to pipe components to monitor, analyse and communicate any change or interference with pipeline function to a central computer base by mobile communication technology. The sensors in such a system will be fully integrated for processing data and communicating it, and they will operate without third-party intervention. The sensors will be self-powered and utilise two-way wireless comminication channels capable of operating over distances of 110 kilometres (70 miles). Furthermore, the sensors will be integrated with the global positioning system (GPS) protocol as part of a single-gateway node, so as to locate and establish defective pipe sections. The first stage is to develop a working prototype of the data capture and transmission aspects of the intellegent sensors.

Furthermore, the research results, when integrated with an intelligent sensor for monitoring the integrity of pipeline systems, would present possibilities for developing an objective solution that would help minimise or eliminate the severe financial, environmental and safety liabilities of pipeline system failure. Most importantly, the miniaturised sensor would give industry the option to adopt fully preventive approaches that would translate into significant savings of up to £2.5 billion each year, as well as replacing a ‘snapshot’ approach to asset maintenance with an engineered solution, thereby limiting disruption to users and the attendant social costs. Consequently, commercialisation of the physical performance-based maintenance method will mean further developments in the oil and gas industry. Even so, the outcome of this research should not be taken as an end in itself but as a means to an end.

CHAPTER 7: CONCLUSIONS

7.1 Summary of Work to Date

The primary aim of this thesis was to investigate whether the latest developments in sensor technology can provide a basis for an objective-based change-of-performance assessment of an oil steel-pipeline system's maintenance needs. As per the review of literature to date, this research into a performance-based approach is a first attempt in developing an integrated technological system accompanied by a corresponding sensor device. This system enables the continuous assessment of the performance of a built asset, thereby assisting in managing maintenance actions accordingly. It is achieved by relating the impact that a maintenance action has on the performance of the built asset in service. Therefore this approach seeks to re-address many of the weaknesses ingrained in the current condition-based approach to built-asset maintenance. It will help to further improve current maintenance practices, hopefully changing the norm from those that are periodical and disruptive, to those that are seen to be objective and of added value.

The investigation and data acquisition took the form of two test series, the results of which were summarised within Chapter 4. Piezoelectric vibration sound emission sensors were used for these tests, which were able to detect changes in the flow characteristics of water and diesel oil. The flow characteristics were analysed using spectrum analysis of the resulting sound emission signals across a number of frequency bands. These were then compared with the theoretical predictions for normal, undamaged, flow conditions. The results show that a piezoelectric vibration sound emission sensor can detect changes in the flow characteristics of water and diesel oil to a level of accuracy that could form the basis of an integrated wireless sensor device.

Laboratory experiments have found that changes occur to the flow dynamics of oil as it passes damaged or deteriorating sections of pipeline. The vibration, acoustic and pressure sensors attached to the outside of the pipeline are able to detect the changing performance patterns resulting from the changes in the pipeline's condition.

7.2 Summary of the Overall Test Results

The findings of the first test series confirmed the feasibility of applying non-destructive testing (NDT) methods using vibration and acoustic techniques on an oil steel-pipeline system for the diagnosis and detection of corrosive defect characteristics and severity. The second test series simulated defects by nails of different sizes being drilled into the pipeline system, where measurements were taken for small defects, medium-sized defects, sealed holes and total failure (leakage) to compare the relevant signals against those arising for the normal state. In general, the sizes of the nails drilled into the pipe in order to simulate the defects were shown to be equivalent to likely damage, as specified on Tables 5.5 and 5.12 and Figure 5.3. In this series of tests it was shown that the percentage increase in the voltage peak from sealed holes was dependent upon the damage profile.

Furthermore, during the laboratory experiment it was observed that the pipeline system released fluid into its surroundings when a hole or fissure appeared as a result of pipeline failure. It was established in the experiment that the bigger the size of the fissure, the more the leakage; and if the pipe system bursts altogether, the leakage will be at its maximum.

Based on this observation from the experiment, it can be said that in a given buried pipeline system, if a failure of any size occurs, the oil leakage will lead to financial as well as environmental costs, where the degree of these costs will depend respectively on the amount of oil lost and the sensitivity of the environment around the leak. These losses can also lead to social costs such as health and safety issues, and even human life loss. For instance, in the Alaska oil spill that occurred in 2005–6, 15 people died and the company that was held responsible was fined $25 million. With vibration and acoustic integrated-sensor technology, the effect of events such as occurred in Alaska could be minimised and/or prevented, thereby cutting down on economic, social and environmental costs to satisfy sustainable-development principles.

Currently, determining the accurate location of defects and possible leaks in buried oil steel pipelines is challenging, time-consuming and expensive. The lab experiment undertaken in this research project has shown that it is possible to use the progression of the degradation frequency to monitor different defect profiles and changes in performance, in order to validate the accuracy of the defect-source calculation and location techniques used for an oil steel-pipeline system. Thus, this experiment presents an effective and efficient proposition in the form of a new NDT-vibration and acoustic integrated-sensor technology.

As established in Chapter 1, worldwide repairs and maintenance of steel pipeline infrastructures generally run into many billions of pounds each year, with the cost of repairs including not only the materials and labour cost, but also the costs of disruption to users and social costs. To prevent and/or correct such disruptions, many companies carry out unnecessary repairs and replacements, which are inherently unsustainable. The proposed integrated-sensor technology will save not only social, environmental and financial costs but also the costs and fatigue associated with unnecessary preventive and/or corrective maintenances, thus effectively and efficiently satisfying sustainable development philosophy.

This work has focused on three main areas. Firstly, it evaluated the ability and the effectiveness of piezoelectric elements for further integration into advanced leak prediction technology. Secondly, it validated the vibration sound emission detection technique. And thirdly, experimental validation was made of the natural frequency (and amplitude) of damage using the prepared oil rig and flow station.

In Figure 5.1 and equation (5.3), two hypotheses describing the amplitude and phase spectrum methods were tested. Time domain methods were successfully used for defect characteristics and for detection of the defective steel pipeline system. Simultaneously, the performance was evaluated of the effectiveness of piezoelectric elements in defect (crack) detection for changes in component performance of the prepared oil rig and flow station. The ability to evaluate pipeline system in-service performance is validated: a low attenuation rate of signals originating from a defective section of steel pipe was found.

The test required access to only one point of the defect, with one sensor positioning at a time. It was potentially very quick to cross-correlate (see Figure 4.1). The piezoelectric actuator was used to measure one set of frequencies before the oilrig and flow station was subjected to a series of in-service test regimes. Subsequent measurements were taken to determine whether there were changes in performance as the simulated damage from this state was systematically increased up to total failure.

From these analyses, both the existence of defects and changes in performance of the pipeline system were detected, although there were changes in the oilrig and flow station’s natural frequencies as the defect progressed. The oilrig and flow station were carefully designed so that the defect zone and modulation of the defect severity would always progress at the same location. It can be assumed that the damage and associated signals originated from the same place for all tests. However, the oil steel-pipeline system requires continuous dynamic analysis as it transports fluid. Several such analyses were required for each defect size/type investigated, and the tests has shown that a piezoelectric sensor that measured natural frequencies can adequately identify a defect zone and its size in the pipeline system.

The results of the performance analysis were stored on a PC and CD, along with the experimentally measured natural frequencies, using the input (PICOScope) to the defect location program. This program was readily adapted to run on a PC.

Each of the sensor location routine tests was carried out to determine the localised defect pattern and whether signals originating from the defect zone of the pipeline could be judged accurate. The required evaluation of the theoretical frequency change varied owing to changes in pipeline system performance. Again, assuming that the steel pipeline system's degrading condition at the defect location was the same for all the tests, it could be deduced that the signal differences computed for the damage at the sensor point must have originated from that same source.

It was further expected that the (induced) corrosion defect would degrade and subsequently crack, causing leakage. The final failure generated a massive vibration sound signal (see Figure 5.8) beyond expectations. It was evident that the crack initiation and the subsequent micro-gap in the crack growth on the pipe wall created the significant vibration sound emission. In other words, as the diesel oil and air competed to escape, the transducer energy output was between 5μV to several tens of millivolts, and even beyond. According to Bassim (1994), the amplitude and frequency spectrum and the attenuation behaviour are all functions of the pipe-wall material properties.

In light of this, one can suggest that the change in condition of the pipe wall results in a sudden change in its performance; alternatively put, cumulative crack growth reduces transmissibility of an in-service pipeline system. It is this change in condition that is likely to influence leakages, which can also be associated with the rapid change in fluid direction and pressure (see Figures 5.8 to 5.11).

Physically, the rapid changes in the pipe wall and the fluid dynamics may have produced the transient pressure change (the burst signal detected), as the jets of escaping diesel oil continuously generated vibrational sound energy. The tests illustrate the need for caution in the interpretations: for most of the vibration signal measured, there was a fairly significant variation of frequency peaks within a single measurement band and frequency.

At some locations, the identified characteristics (for example, the amplitude-modulated components at sensor location I) are clearly visible above the background noise (Figure 5.8). However, whilst some deductions can be made from the present experimental tests, more investigation is needed – especially if the ultimate aim is the integration of these data onto an integrated-sensor device with an algorithm able to qualitatively evaluate and determine defect signal thresholds.

Most importantly, the results show that a piezoelectric vibration sound emission sensor can detect changes in the flow characteristics of water and diesel oil to a level of accuracy that could form the basis of an integrated wireless sensor device. Quantitative diagnosis theory provides the basis of an algorithm that could be used to associate the changed flow characteristics with the underlying pipeline defect, crucially without third-party intervention. After establishment of a clear relationship between the reliability of an oil pipeline system, changes in condition, and its transmission performance; the results demonstrate that performance-based maintenance techniques may be one of the keys to increasing performance and productivity.

In relation to the primary aim of this research, the investigations have shown it to be possible to detect, locate, and roughly quantify damage in the steel pipeline system by using measurements of the pipeline system’s natural frequencies. Tests have been carried out successfully on the experimental transmitting pipeline system, identifying changes in the flow dynamics of oil as it passed through the damaged areas of the pipe.

As per the evaluation of the effectiveness of piezoelectric detection to changes in the oil steel-pipeline system performance, it has also been possible to differentiate a variety of types of damage, including defect characteristics. This includes small- and medium-damage fatigue tests, as well as deterioration of sealed holes without nails leading to total failure. The laboratory experiments have validated the ability and effectiveness of piezoelectric sensors and the non-destructive (vibration sound emission) detection techniques across a range of oil steel-pipeline defect and leakage conditions. The results represent an improvement and could provide the basis for an objective-based assessment of an oil steel-pipeline system’s maintenance needs.

CHAPTER 8: RECOMMENDATIONS

8.1 Future Work – General

As has become clear from Chapter 7, several areas for further work can be identified to complement the work presented in this thesis, in order to allow the technique to be extended to accommodate full integration with advance sensor technology, artificial intelligence and wireless communications. Furthermore, the data resulting from this current investigation needs more refinement.

Academically, it is becoming clear that the project can contribute to two areas of knowledge. The first is knowledge about the application of integrated sensor technology, particularly the advantages and limitations of condition assessments and changes in performance approaches. The second is knowledge about pipeline infrastructure damage evolution in real time. It is hoped, therefore, that the lessons that apply to those buried and surface utility-pipeline networks might extend to other built-environment elements such as buildings and their fabric.

The data collected in the work to date (Phase I) will be used in Phase II (post-PhD work) to develop and test an integrated wireless communication device and reporting system for steel pipelines. The sensor technology, when developed around the capability of diagnosing, analysing and reporting changes in performance, will be able to predict a transmitting pipeline system's condition and performance in real time.

The performance-based maintenance techniques could form part of an objective and reliable built-environment maintenance practice. A continuous monitoring device with the productive capability, directly embedded for real-time testing, could increase knowledge of a transmitting oil pipeline system, and identify and report changes in state before accidents occur – particularly in relation to pipelines and storage tanks. Furthermore, such a device makes numerous monitoring and predictive applications feasible that were previously not possible owing to remote and hazardous environments.

8.2 The Integrated-Sensor Device

The experimental test series required many types of equipment with different capabilities to be integrated, and this was time consuming.

The author is presently developing algorithms that will allow the fragmented experimental techniques to be integrated to give fast and real-time data acquisition, monitoring, analysis and reporting protocols. These will be formed within an integrated-device-on-a-microchip solution that does not require third-party intervention. Indeed, the most immediate and important task for the next phase of this research project is to complete the commercial proof-of-concept prototyping, so as to enable a small-scale field test

There remains some uncertainty over the magnitude of improvement in reporting protocols in real time that can be achieved by developing integrated-device-on-microchip solutions. Thus there is a significant need for future research in this area. This will be undertaken in the next phase of the research project, as part of reliability-centred maintenance, and will be conducted in line with the overall proactive and innovative approach argued in Chapters 1 and 2.

Wider field-test relevance is particularly strong if one believes that the effect of corrosion on buried coated oil steel and/or water pipeline systems may not allow reliable and precise inspection in not only existing pipeline networks but also in new pipeline systems. This research recommends that the integrated-device-on-a-microchip solution be developed to enable buried oil steel-pipeline integrity surveying in a variety of complex operational environments worldwide.

8.3 Oil Composition

In relation to the proposed field test, more attention should be paid to the content of fluid used, given that most heavy fuel oil consists largely of residues from crude oil and therefore it is important to refine the test to suit the different pipeline-integrity surveying variables.

In order to further confirm these findings from the laboratory tests, it is important for the field operations that samples of the crude-oil content is taken from the particular field-test pipeline stretch before and after test runs – for comparison purposes. Past experience has shown that residues are blended with suitable gas–oil fractions in order to achieve the viscosity required for convenient handling.

Close attention should also be paid to the crude-oil contents – the heavy metals types such as nickel and vanadium, as well as other sediments and water – and the temperature of the oil, for the simple reason of establishing whether or not these impurities influence the pipe contents as they leak out or just that oil collects extra contaminants from the pipe wall as it escapes from the leak canals.

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APPENDIX A: EXPERIMENTAL DATA

A.1 Details of the Experimental Test Programme

Tables A and B herein give details of the experimental programme which was used to study the various factors outlined in section 1.1.5 and comprise more than 300 results.

Table A

Test Ref	***Normal frequency***	***Small Defect* f**	***Medium Defect* f/td**	***Large Defect* f/td**	***Failure*** ***Time Domain***
1	*	*			
2	*	*			
3	*	*			
4	*	*			
5	*	*			
6	*	*			
7	*				
8	*				
9	*				
10	*				
11	*				
12	*				
13	*				
14	*				
15	*				
16	*				
17	*				
18	*				
19	*				
20	*				
21	*				
22	*				
23	*				
24	*				
25	*				
26	*				
27	*				
28	*				
29	*				
30	*				
31	*				
32	*				
33	*				
34	*				
35	*				
36	*				
37	*				
38	*				
39	*				
40	*				

The tests were used for defective condition assessment analysis and establish the impact of the defect on oil steel pipeline system in-service to perform

Table B

Test Ref	***Normal frequency***	***Small Defect* f**	***Medium Defect* f/td**	***Large Defect* f/td**	***Failure Time Domain***
41	*				
42	*				
43	*				
44	*				
45	*				
46	*				
47	*				
48	*				
49	*				
50	*				
51	*				
52	*				
53	*				
54	*				
55	*				
56	*				
57	*				
58	*				
59	*				
60	*				
61	*				
62	*				
63	*				
64	*				
65	*				
66	*				
67	*				
68	*				
69	*				
70	*				
71	*				
72	*				
73	*				
74	*				
75	*				
76	*				
77	*				
78	*				
79	*				
80	*				
81	*				
82	*				
83	*				
84	*				
85	*				
86	*				
87	*				

Test Ref	*Normal frequency*	*Small Defect* f	*Medium Defect* f/td	*Large Defect* f/td	*Failure* *Time Domain*
88	*				
89	*				
90	*				
91	*				
92	*				
93	*				
94	*				
95	*				
96	*				
97	*				
98	*				
99	*				
100	*				
101		*			
102		*			
103		*			
104		*			
105		*			
106		*			
107		*			
108		*			
109		*			
110		*			
111		*			
112		*			
113		*			
114		*			
115		*			
116		*			
117		*			
118		*			
119		*			
120		*			
121		*			
122		*			
123		*			
124		*			
125		*			
126		*			
127		*			
128		*			
129		*			
130		*			
131		*			
132		*			
133		*			
134		*			

Test Ref	***Normal frequency***	***Small Defect* f**	***Medium Defect* f/td**	***Large Defect* f/td**	***Failure*** ***Time Domain***
135		*		*	
136		*		*	
137		*		*	
138		*		*	
139		*		*	
140		*		*	
141		*		*	
142		*		*	
143		*		*	
144		*		*	
145		*		*	
146		*		*	
147		*		*	
148		*		*	
149		*		*	
150		*		*	
151		*		*	
152		*		*	
153		*		*	
154		*		*	
156		*		*	
157		*		*	
158		*		*	
159		*		*	
160		*		*	
161		*		*	
162		*		*	
163		*		*	
164		*		*	
165		*		*	
166		*		*	
167		*		*	
168		*		*	
169		*		*	
170		*		*	
171		*	*	*	
172		*	*	*	
173		*	*	*	
174		*	*	*	
175		*	*	*	
176		*	*	*	
177		*	*	*	
178		*	*	*	
179		*	*	*	
180		*	*	*	
181		*	*	*	
182		*	*	*	

Test Ref	*Normal frequency*	*Small Defect* f	*Medium Defect* f/td	*Large Defect* f/td	*Failure* *Time Domain*
183			*		
184			*		
185			*		
186			*		
187			*		
188			*		
189			*		
190			*		
191			*		*
192			*		*
193			*		*
194			*		*
195			*		*
196			*		*
197			*		*
198			*		*
199			*		*
200			*		*
201			*		*
202			*		*
203			*		*
204			*		*
205			*		*
206			*		*
207			*		*
208			*		*
209			*		*
300			*		*

A.2: Details of the Experimental Test Envelope Signal

Table C details the experimental test runs made, The first 100 show the NORMAL STATE.

Sensor/ Test No.	**Enveloped Signal (dB)**		**Variables**	
	Amplitude	**Frequency**	**Non-Defective State**	
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	Normal	kHz
1 I	O=63.14dB	X=82.56dB	Normal	11.7kHz
2 II	O=67.70dB	X=86.07dB	Normal	11.7kHz
3 III	O=64.91dB	X=87.59dB	Normal	11.7kHz
4 IV	O=65.82dB	X=85.33dB	Normal	11.7kHz
5 V	O=60.91dB	X=84.89dB	Normal	11.7kHz
6 I	O=65.14dB	X=85.51dB	Normal	23.95kHz
7 II	O=64.70dB	X=87.07dB	Normal	23.95kHz
8 III	O=67.91dB	X=88.69dB	Normal	23.95kHz
9 IV	O=65.92dB	X=86.21dB	Normal	23.95kHz
10 V	O=62.76dB	X=85.95dB	Normal	23.95kHz
11 I	O=64.13dB	X=88.51dB	Normal	46.9kHz
12 II	O=65.69dB	X=89.05dB	Normal	46.9kHz
13 III	O=67.93dB	X=86.69dB	Normal	46.9kHz
14 IV	O=64.69dB	X=87.24dB	Normal	46.9kHz
15 V	O=64.67dB	X=87.95dB	Normal	46.9kHz
16 I	O=66.14dB	X=89.53dB	Normal	46.9kHz
17 II	O=64.73dB	X=89.10dB	Normal	46.9kHz
18 III	O=66.94dB	X=88.67dB	Normal	46.9kHz
19 IV	O=64.68dB	X=88.50dB	Normal	46.9kHz
20 V	O=64.70dB	X=87.94dB	Normal	46.9kHz
21 I	O=65.14dB	X=89.51dB	Normal	46.9kHz
22 II	O=67.70dB	X=89.05dB	Normal	46.9kHz
23 III	O=66.94dB	X=88.69dB	Normal	46.9kHz
34 IV	O=64.69dB	X=88.21dB	Normal	46.9kHz
25 V	O=63.67dB	X=87.95dB	Normal	46.9kHz
26 I	O=64.67dB	X=88.91dB	Normal	46.9kHz
27 II	O=60.23dB	X=88.49dB	Normal	46.9kHz
28 III	O=67.63dB	X=89.07dB	Normal	46.9kHz
29 IV	O=66.91dB	X=86.69dB	Normal	46.9kHz
30 V	O=64.67dB	X=86.95dB	Normal	46.9kHz

31 I	O=66.14dB	X=89.54dB	Normal	46.9kHz
32 II	O=68.70dB	X=88.04dB	Normal	46.9kHz
33 III	O=67.89dB	X=89.69dB	Normal	46.9kHz
34 IV	O=64.69dB	X=89.30dB	Normal	46.9kHz
35 V	O=64.67dB	X=86.95dB	Normal	46.9kHz
36 I	O=65.14dB	X=89.51dB	Normal	46.9kHz
37 II	O=67.70dB	X=89.05dB	Normal	46.9kHz
38 III	O=66.94dB	X=88.69dB	Normal	46.9kHz
39 IV	O=63.71dB	X=87.24dB	Normal	46.9kHz
40 V	O=65.62dB	X=88.93dB	Normal	46.9kHz
41 I	O=65.11dB	X=87.57dB	Normal	46.9kHz
42 II	O=67.72B	X=88.08dB	Normal	46.9kHz
43 III	O=66.86dB	X=87.64dB	Normal	46.9kHz
44 IV	O=64.66dB	X=88.27dB	Normal	46.9kHz
45 V	O=64.70dB	X=86.95dB	Normal	46.9kHz
46 I	O=65.14dB	X=89.51dB	Normal	46.9kHz
47 II	O=67.70dB	X=89.05dB	Normal	46.9kHz
48 III	O=66.91dB	X=88.69dB	Normal	46.9kHz
49 IV	O=64.69dB	X=88.21dB	Normal	46.9kHz
50 V	O=64.67dB	X=87.94dB	Normal	46.9kHz
51 I	O=65.14dB	X=89.51dB	Normal	46.9kHz
52 II	O=67.70dB	X=89.05dB	Normal	46.9kHz
53 III	O=66.94dB	X=88.69dB	Normal	46.9kHz
54 IV	O=64.69dB	X=88.22dB	Normal	46.9kHz
55 V	O=64.67dB	X=87.95dB	Normal	46.9kHz
56 I	O=64.13dB	X=88.51dB	Normal	46.9kHz
57 II	O=65.69dB	X=89.05dB	Normal	46.9kHz
58 III	O=67.93dB	X=86.69dB	Normal	46.9kHz
59 IV	O=64.70dB	X=87.27dB	Normal	46.9kHz
60 V	O=64.67dB	X=87.95dB	Normal	46.9kHz
61 I	O=64.09dB	X=88.50dB	Normal	46.9kHz
62 II	O=65.67dB	X=89.02dB	Normal	46.9kHz
63 III	O=68.93dB	X=86.69dB	Normal	46.9kHz
64 IV	O=64.69dB	X=87.24dB	Normal	46.9kHz
65 V	O=65. 76dB	X=85.97dB	Normal	46.9kHz

66 I	O=64.13dB	X=87.55dB	Normal	46.9kHz
67 II	O=65.69dB	X=88.05dB	Normal	46.9kHz
68 III	O=67.93dB	X=86.68dB	Normal	46.9kHz
69 IV	O=64.69dB	X=87.24dB	Normal	46.9kHz
70 V	O=64.67dB	X=88.95dB	Normal	46.9kHz
71 I	O=66.10dB	X=88.49dB	Normal	46.9kHz
72 II	O=65.69dB	X=89.05dB	Normal	46.9kHz
73 III	O=67.93dB	X=86.69dB	Normal	46.9kHz
74 IV	O=64.69dB	X=87.24dB	Normal	46.9kHz
75 V	O=64.67dB	X=87.95dB	Normal	46.9kHz
76 I	O=66.07dB	X=88.57dB	Normal	46.9kHz
77 II	O=65.69dB	X=90.01dB	Normal	46.9kHz
78 III	O=67.93dB	X=86.67dB	Normal	46.9kHz
79 IV	O=64.69dB	X=87.31dB	Normal	46.9kHz
70 V	O=64.67dB	X=88.92dB	Normal	46.9kHz
81 I	O=64.08dB	X=86.61dB	Normal	46.9kHz
82 II	O=67.67dB	X=90 01dB	Normal	46.9kHz
83 III	O=68.90dB	X=84.71dB	Normal	46.9kHz
84 IV	O=66.79dB	X=87.52dB	Normal	46.9kHz
85 V	O=62.69dB	X=86.90dB	Normal	46.9kHz
86 I	O=64.10dB	X=88.56dB	Normal	46.9kHz
87 II	O=65.69dB	X=89.05dB	Normal	46.9kHz
88 III	O=67.93dB	X=86.69dB	Normal	46.9kHz
89 IV	O=64.69dB	X=87.24dB	Normal	46.9kHz
90 V	O=64.67dB	X=87.95dB	Normal	46.9kHz
91 I	O=64.15dB	X=87.55dB	Normal	46.9kHz
92 II	O=67.69dB	X=89.05dB	Normal	46.9kHz
93 III	O=67.95dB	X=86.69dB	Normal	46.9kHz
94 IV	O=64.70dB	X=87.31dB	Normal	46.9kHz
95 V	O=64.67dB	X=88.91dB	Normal	46.9kHz
96 I	O=60.23dB	X=88.49dB	Normal	46.9kHz
97 II	O=67.63dB	X=89.07dB	Normal	46.9kHz
98 III	O=66.91dB	X=86.69dB	Normal	46.9kHz
99 IV	O=65.68dB	X=87.24dB	Normal	46.9kHz
100 V	O=62.69dB	X=88.93dB	Normal	46.9kHz

Table D details the experimental test runs made for the SMALL DEFECT.

Sensor Location	**Enveloped Signal (dB) Amplitude Frequency**		**Variables Defect Type [SM]**	
	$\bar{X}_{\max}(t)$	$\bar{X}_{\min}(t)$	Small	kHz
1 I	O=72.77dB	X=89.96dB	Small	46.9kHz
2 II	O=71.94dB	X=89.87dB	Small	46.9kHz
3 III	O=71.83dB	X=89.88dB	Small	46.9kHz
4 IV	O=71.80dB	X=88.85dB	Small	46.9kHz
5 V	O=71.74dB	X=87.95dB	Small	46.9kHz
6 I	O=72.79dB	X=89.94dB	Small	46.9kHz
7 II	O=71.98dB	X=89.89dB	Small	46.9kHz
8 III	O=71.85dB	X=88.90dB	Small	46.9kHz
9 IV	O=71.79dB	X=87.87dB	Small	46.9kHz
10 V	O=71.73dB	X=87.97dB	Small	46.9kHz
11 I	O=73.78dB	X=88.94dB	Small	46.9kHz
12 II	O=72.95dB	X=89.86dB	Small	46.9kHz
13 III	O=70.84dB	X=88.87dB	Small	46.9kHz
14 IV	O=71.76dB	X=88.89dB	Small	46.9kHz
15 V	O=71.73dB	X=87.99dB	Small	46.9kHz
16 I	O=72.77dB	X=89.97dB	Small	46.9kHz
17 II	O=71.94dB	X=89.89dB	Small	46.9kHz
18 III	O=71.87dB	X=86.87dB	Small	46.9kHz
19 IV	O=71.80dB	X=89.88dB	Small	46.9kHz
20 V	O=70.71dB	X=86.94dB	Small	46.9kHz
21 I	O=72.79dB	X=88.93dB	Small	46.9kHz
22 II	O=71.98dB	X=88.89dB	Small	46.9kHz
23 III	O=72.90dB	X=89.89dB	Small	46.9kHz
34 IV	O=71.80dB	X=88.90dB	Small	46.9kHz
25 V	O=71.75dB	X=85.93dB	Small	46.9kHz
26 I	O=73.79dB	X=88.94dB	Small	46.9kHz
27 II	O=71.96dB	X=89.90dB	Small	46.9kHz
28 III	O=71.87dB	X=89.91dB	Small	46.9kHz
29 IV	O=72.79dB	X=88.87dB	Small	46.9kHz
30 V	O=71.71dB	X=87.95dB	Small	46.9kHz
31 I	O=72.80dB	X=89.95dB	Small	46.9kHz
32 II	O=71.98dB	X=89.88dB	Small	46.9kHz
33 III	O=71.83dB	X=88.89dB	Small	46.9kHz
34 IV	O=71.81dB	X=88.87dB	Small	46.9kHz
35 V	O=72.74dB	X=87.96dB	Small	46.9kHz
36 I	O=72.75dB	X=90.95dB	Small	46.9kHz
37 II	O=72.97dB	X=89.89dB	Small	46.9kHz
38 III	O=71.88dB	X=87.88dB	Small	46.9kHz
39 IV	O=70.74dB	X=87.85dB	Small	46.9kHz
40 V	O=71.75dB	X=87.97dB	Small	46.9kHz
41 I	O=72.81dB	X=88.96dB	Small	46.9kHz
42 II	O=71.93dB	X=90.89dB	Small	46.9kHz
43 III	O=71.88dB	X=87.88dB	Small	46.9kHz
44 IV	O=71.76dB	X=88.89dB	Small	46.9kHz
45 V	O=71.77dB	X=89.97dB	Small	46.9kHz

Table E details the experimental test runs made for the MEDIUM DEFECT.

Sensor & Test No.	**Enveloped Signal (dB) Amplitude Frequency**		**Variables Defect Type [MD]**	
	$X_{\max}(t)$	$X_{\min}(t)$	Medium	Hz/kHz
1 I	O=87.95dB	X=83.96dB	Medium	46.9kHz
2 II	O=81.88dB	X=85.96dB	Medium	46.9kHz
3 III	O=86.89dB	X=82.87dB	Medium	46.9kHz
4 IV	O=83.87dB	X=89.88dB	Medium	46.9kHz
5 V	O=83.95dB	X=87.96dB	Medium	46.9kHz
6 I	O=88.97dB	X=84.98dB	Medium	46.9kHz
7 II	O=81.90dB	X=85.98dB	Medium	46.9kHz
8 III	O=86.89dB	X=82.89dB	Medium	46.9kHz
9 IV	O=84.88dB	X=88.85dB	Medium	46.9kHz
10 V	O=83.95dB	X=88.98dB	Medium	46.9kHz
11 I	O=88.96dB	X=82.96dB	Medium	46.9kHz
12 II	O=81.88dB	X=85.97dB	Medium	46.9kHz
13 III	O=86.87dB	X=82.89dB	Medium	46.9kHz
14 IV	O=83.87dB	X=88.85dB	Medium	46.9kHz
15 V	O=83.95dB	X=88.97dB	Medium	46.9kHz
16 I	O=89.97dB	X=82.96dB	Medium	46.9kHz
17 II	O=81.85dB	X=85.96dB	Medium	46.9kHz
18 III	O=86.89dB	X=82.89dB	Medium	46.9kHz
19 IV	O=83.87dB	X=88.85dB	Medium	46.9kHz
20 V	O=84.95dB	X=87.97dB	Medium	46.9kHz
21 I	O=89.95dB	X=81.95dB	Medium	46.9kHz
22 II	O=81.88dB	X=85.98dB	Medium	46.9kHz
23 III	O=86.88dB	X=82.88dB	Medium	46.9kHz
34 IV	O=84.87dB	X=88.85dB	Medium	46.9kHz
25 V	O=83.99dB	X=87.97dB	Medium	46.9kHz
26 I	O=88.93dB	X=82.97dB	Medium	46.9kHz
27 II	O=81.89dB	X=85.96dB	Medium	46.9kHz
28 III	O=87.90dB	X=82.88dB	Medium	46.9kHz
29 IV	O=83.87dB	X=88.87dB	Medium	46.9kHz
30 V	O=83.95dB	X=87.97dB	Medium	46.9kHz
31 I	O=89.98dB	X=82.97dB	Medium	46.9kHz
32 II	O=82.88dB	X=86.97dB	Medium	46.9kHz
33 III	O=86.87dB	X=82.89dB	Medium	46.9kHz
34 IV	O=83.88dB	X=87.84dB	Medium	46.9kHz
35 V	O=83.95dB	X=87.98dB	Medium	46.9kHz
36 I	O=88.94dB	X=82.97dB	Medium	46.9kHz
37 II	O=81.90dB	X=85.95dB	Medium	46.9kHz
38 III	O=87.89dB	X=82.86dB	Medium	46.9kHz
39 IV	O=83.90dB	X=88.86dB	Medium	46.9kHz
40 V	O=83.95dB	X=88.97dB	Medium	46.9kHz
41 I	O=89.95dB	X=82.96dB	Medium	46.9kHz
42 II	O=81.87dB	X=85.98dB	Medium	46.9kHz
43 III	O=86.90dB	X=82.88dB	Medium	46.9kHz
44 IV	O=83.87dB	X=89.85dB	Medium	46.9kHz
45 V	O=83.95dB	X=88.97dB	Medium	46.9kHz

Table F details the experimental test runs made for the SEALED HOLES.

Sensor & Test No.	**Enveloped Signal (dB) Amplitude Frequency**		**Variables Defect Type [Fatigue]**	
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	Large	Hz/kHz
1 I	O=88.95dB	X=85.98dB	Large	46.9kHz
2 II	O=85.88dB	X=88.99dB	Large	46.9kHz
3 III	O=87.82dB	X=86.79dB	Large	46.9kHz
4 IV	O=85.83dB	X=88.82dB	Large	46.9kHz
5 V	O=84.93dB	X=88.97dB	Large	46.9kHz
6 I	O=89.95dB	X=85.97dB	Large	46.9kHz
7 II	O=85.87dB	X=87.99dB	Large	46.9kHz
8 III	O=86.81dB	X=86.80dB	Large	46.9kHz
9 IV	O=85.82dB	X=89.81dB	Large	46.9kHz
10 V	O=84.91dB	X=88.95dB	Large	46.9kHz
11 I	O=89.95dB	X=85.98dB	Large	46.9kHz
12 II	O=86.87dB	X=87.97dB	Large	46.9kHz
13 III	O=88.81dB	X=86.77dB	Large	46.9kHz
14 IV	O=84.81dB	X=89.84dB	Large	46.9kHz
15 V	O=85.92dB	X=88.97dB	Large	46.9kHz
16 I	O=89.95dB	X=85.98dB	Large	46.9kHz
17 II	O=86.88dB	X=88.98dB	Large	46.9kHz
18 III	O=87.81dB	X=86.78dB	Large	46.9kHz
19 IV	O=83.80dB	X=89.85dB	Large	46.9kHz
20 V	O=84.90dB	X=87.96dB	Large	46.9kHz
21 I	O=89.95dB	X=85.96dB	Large	46.9kHz
22 II	O=86.87dB	X=87.98dB	Large	46.9kHz
23 III	O=87.83dB	X=87.79dB	Large	46.9kHz
34 IV	O=84.82dB	X=89.82dB	Large	46.9kHz
25 V	O=84.93dB	X=88.98dB	Large	46.9kHz
26 I	O=89.95dB	X=85.97dB	Large	46.9kHz
27 II	O=85.85dB	X=87.95dB	Large	46.9kHz
28 III	O=87.81dB	X=87.78dB	Large	46.9kHz
29 IV	O=86.82dB	X=80.83dB	Large	46.9kHz
30 V	O=86.91dB	X=89.96dB	Large	46.9kHz
31 I	O=89.95dB	X=84.98dB	Large	46.9kHz
32 II	O=86.87dB	X=87.97dB	Large	46.9kHz
33 III	O=88.81dB	X=85.77dB	Large	46.9kHz
34 IV	O=84.82dB	X=89.85dB	Large	46.9kHz
35 V	O=85.91dB	X=88.96dB	Large	46.9kHz
36 I	O=89.95dB	X=84.97dB	Large	46.9kHz
37 II	O=85.89dB	X=87.98dB	Large	46.9kHz
38 III	O=85.80dB	X=86.78dB	Large	46.9kHz
39 IV	O=85.82dB	X=90.84dB	Large	46.9kHz
40 V	O=84.91dB	X=89.97dB	Large	46.9kHz
41 I	O=89.95dB	X=84.97dB	Large	46.9kHz
42 II	O=84.86dB	X=87.98dB	Large	46.9kHz
43 III	O=87.81dB	X=86.78dB	Large	46.9kHz
44 IV	O=85.83dB	X=89.83dB	Large	46.9kHz
45 V	O=83.91dB	X=88.96dB	Large	46.9kHz

Table G details the experimental test runs made for the FAILURE CONDITION.

Sensor & Test No.	**Enveloped Signal (dB) Amplitude Frequency**		**Variables Defect Type [Failure]**	
	$\overline{X}_{\max}(t)$	$\overline{X}_{\min}(t)$	Failure	Hz/kHz
1 I	O=88.79dB	X=86.41dB	Failure	23.4kHz
2 II	O=83.00dB	X=87.96dB	Failure	46.9kHz
3 III	O=75.26dB	X=85.55dB	Failure	46.9kHz
4 IV	O=83.85dB	X=88.71dB	Failure	46.9kHz
5 V	O=86.91dB	X=83.03dB	Failure	11.7kHz
6 I	O=89.84dB	X=86.46dB	Failure	23.4kHz
7 II	O=83.04dB	X=88.98dB	Failure	46.9kHz
8 III	O=72.24dB	X=86.45dB	Failure	46.9kHz
9 IV	O=84.87dB	X=87.76dB	Failure	46.9kHz
10 V	O=86.92dB	X=82.01dB	Failure	11.7kHz
11 I	O=88.82dB	X=85.42dB	Failure	23.4kHz
12 II	O=84.01dB	X=88.98dB	Failure	46.9kHz
13 III	O=75.25dB	X=84.45dB	Failure	46.9kHz
14 IV	O=84.88dB	X=87.77dB	Failure	46.9kHz
15 V	O=85.90dB	X=83.04dB	Failure	11.7kHz
16 I	O=88.85dB	X=86.52dB	Failure	23.4kHz
17 II	O=84.02dB	X=87.88dB	Failure	46.9kHz
18 III	O=72.23dB	X=87.45dB	Failure	46.9kHz
19 IV	O=83.90dB	X=87.69dB	Failure	46.9kHz
20 V	O=87.93dB	X=84.07dB	Failure	11.7kHz
21 I	O=88.85dB	X=86.42dB	Failure	23.4kHz
22 II	O=82.03dB	X=87.97dB	Failure	46.9kHz
23 III	O=74.30dB	X=83.45dB	Failure	46.9kHz
24 IV	O=85.86dB	X=88.73dB	Failure	46.9kHz
25 V	O=86.97dB	X=82.03dB	Failure	11.7kHz

Table H: Comparison of Three Means and Standard Deviation of Steady State
(Test Series I)

Test No.	Sensor	Amplitude	Frequency	Amplitude	Frequency	Amplitude	Frequency
1	I	65.12	82.56	65.14	85.51	64.13	88.51
2	II	67.7	86.07	64.7	87.07	65.69	89.05
3	III	64.91	87.59	67.91	88.69	67.93	86.69
4	IV	65.82	85.33	65.92	86.21	64.69	87.24
5	V	62..91	84.89	62.76	85.95	64.67	87.95
Total		326.46	424.44	326.43	433.83	327.77	439.44
Mean		65.292	85.288	65.286	86.686	65.422	87.888
SD		1.269419	1.837993	1.873014	1.256455	1.511	0.948167
Condition and Measurements @		Steady State	11.7kHz	Steady State	23.95kHz	46.9kHz	Steady State

Table I: Mean/SD Amplitude and Frequencies at 5 Different Conditions
(Test Series 2 in Frequency Domain)

Amplitude	Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude	Frequency	Test No.
72.77	89.96	88.95	82.97	88.95	85.98	88.79	86.41	1
71.94	89.87	81.88	85.98	85.88	88.99	83	87.96	2
71.83	89.88	86.89	82.89	87.82	86.79	75.26	85.55	3
71.8	88.85	83.87	88.85	85.83	88.82	83.85	88.71	4
71.74	87.95	83.95	87.97	84.93	88.97	86.91	83.03	5
360.01	446.51	425.56	428.66	433.41	439.55	417.81	431.66	**Total**
72.016	89.302	85.108	85.732	86.682	87.91	83.562	86.332	**Mean**
0.427703	0.883442	2.794194	2.761235	1.649051	1.422797	5.192858	2.226324	**SD**
Small Damage	46.9kHz	Medium	46.9kHz	Large	46.9kHz	Failure	46.9kHz	**Measured @**

Table J: Test Series 2 Results in the Time Domain

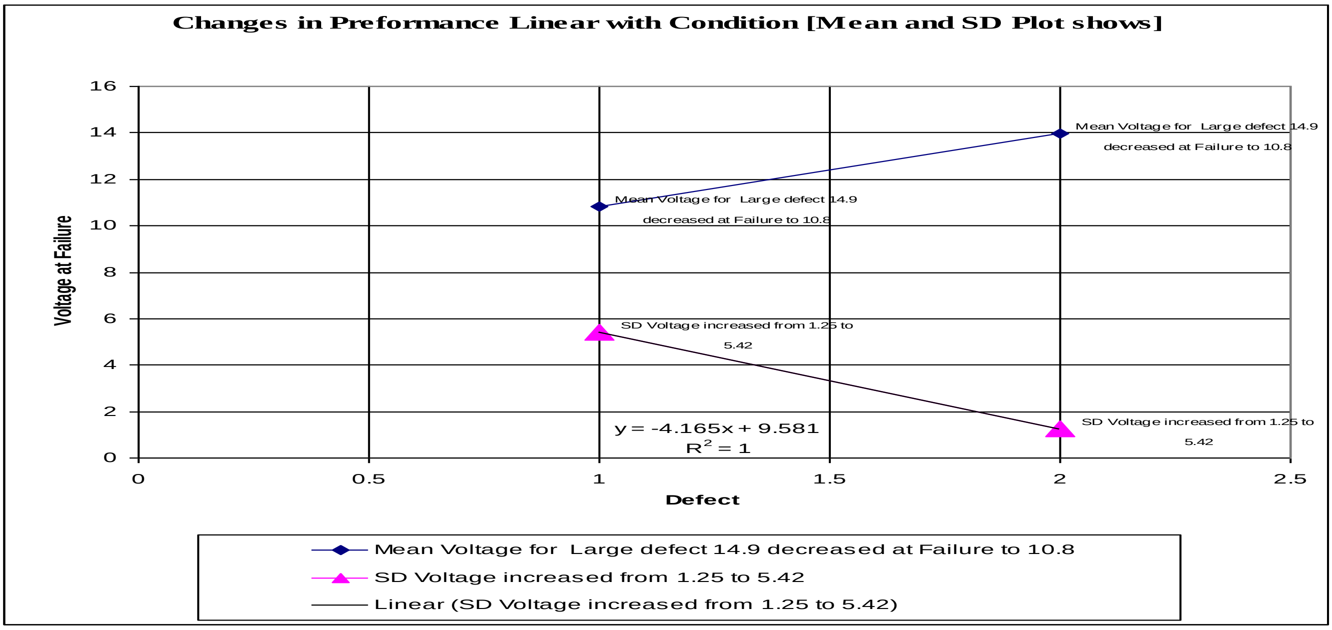
Test No.	Sensor	Xmax	Xmin	XO=mV	V-Peak		Xmax	Xmin	XO=mV	V-Peak
1	I	6	6	12	0.0658	6258	9	9	18	16.33
2	II	6	9	15	14.38		10	10	20	13.98
3	III	7	6	13	13.77		9	10	19	13.75
4	IV	6	5	11	13.15		8	8	16	13.11
5	V	5	5	10	12.87		8	7	15	12.75
6	I	6	6	12	0.0658	6259	9	9	18	16.32
7	II	6	9	15	14.39		10	10	20	13.97
8	III	7	6	13	13.76		9	10	19	13.76
9	IV	6	5	11	13.14		8	8	16	13.12
10	V	5	5	10	12.88		8	7	15	12.74
	Total	60								
	Mean	6	6.2	12.2	10.847	6258.5	8.8	8.8	17.6	13.983
	SD	15.6	1.46969	1.720465	5.4159	0.5	0.748	1.17	1.8547	1.2509

Table2Defect –Failures

Table1Defect –Large

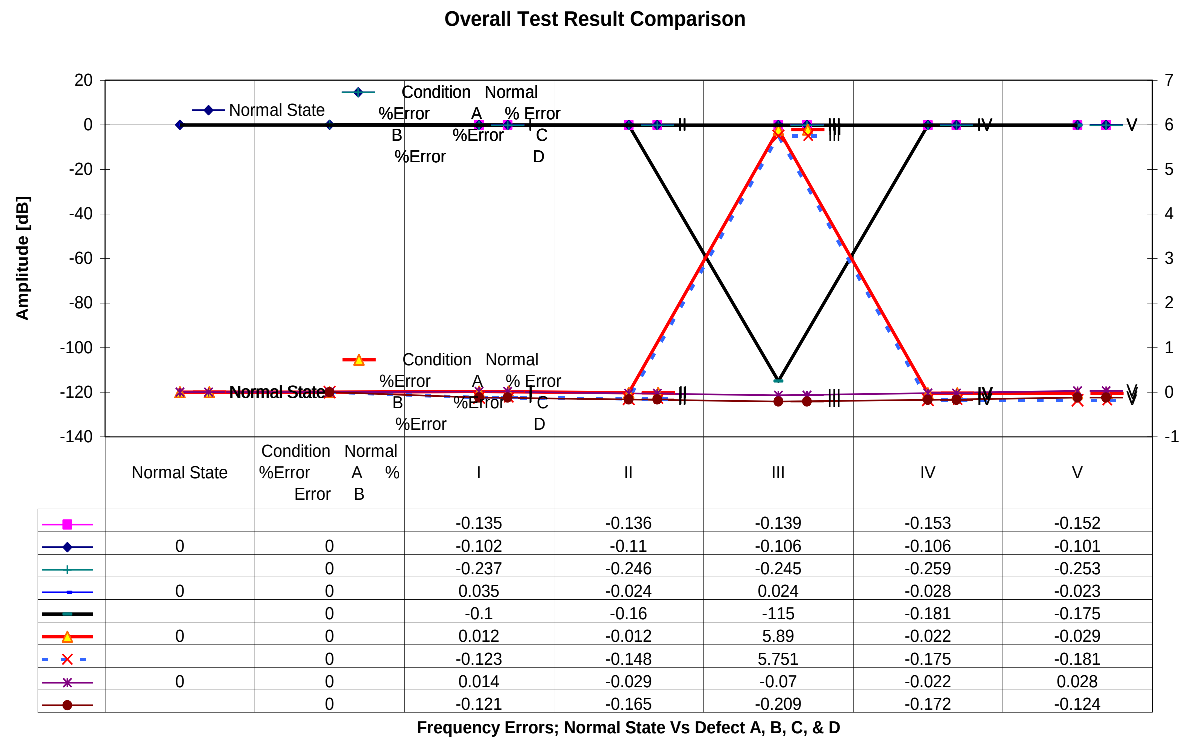
Enveloped Signal(dB); Amplitude Xmax Frequency Xmin voltage measured at 20ms

Figure A.1: Changes in Performance Shown to Be Linear with Condition (Test Series 2)



The overall test results are summarised here in Table J and Figure A.1. When the waveforms from all the nodes were integrated, the effect was to merge the individual resonances together. It produced a twofold response: small-defect (at sensor I) and medium-defect (at sensor II) frequencies appeared to be linear and predictable in most test runs; but as the defect progressed the spread of frequencies increased and resonance peaks became somewhat erratic although linear, and it appeared as though the flow damping, or the pipe wall condition factor, had decreased.

Figure A.2: Overall Test Results Comparison



	Normal State	Condition %Error Normal A % Error B	I	II	III	IV	V
■			-0.135	-0.136	-0.139	-0.153	-0.152
◆	0	0	-0.102	-0.11	-0.106	-0.106	-0.101
+		0	-0.237	-0.246	-0.245	-0.259	-0.253
-	0	0	0.035	-0.024	0.024	-0.028	-0.023
▬		0	-0.1	-0.16	-115	-0.181	-0.175
▲	0	0	0.012	-0.012	5.89	-0.022	-0.029
✕		0	-0.123	-0.148	5.751	-0.175	-0.181
✳	0	0	0.014	-0.029	-0.07	-0.022	0.028
●		0	-0.121	-0.165	-0.209	-0.172	-0.124

Convolution – that is, the intertwining of vibration and acoustic emission response and excitation – is clearly evident in Figure A.2 from the shift in the frequency of maximum amplitude. The maximum response in the received signal occurred at 5.58 from -0.115 and back down to -0.07, corresponding to the signal generator set at 5kHz on a time base of 7.5kHz with 2ms by 10mV ×5 (see Table 4.3). The estimated severity of the defect characteristics (small, medium, sealed holes and failure, against the normal state), in terms of the sizes of the nails drilled into the pipe, was equivalent to the damage shown in Tables K–N below: it always increased with increasing damage, so the progress of the degradation was monitored.

Table K: Measured Averaged Natural Frequencies; Sensor Location I (Test Series 1)

Test Scenarios.	Sensor	Amplitude	Frequency
1	I	35.2dB	4.66KhZ
2	I	37.7dB	4.67KhZ
3	I	34.1dB	4.59KhZ
4	I	32.2dB	4.53KhZ
5	I	32.1dB	4.89KhZ
	Average		**4.66Khz**

Table L: Measured Averaged Natural Frequencies; Sensor Location III (Test Series 1)

Test No.	Sensor	Amplitude	Frequency
1	III	35.0	4.59
2	III	36.9	4.67
3	III	33.7	4.52
4	III	32.2	4.50
5	III	30.9	4.83
	Average	33.74dB	5Khz

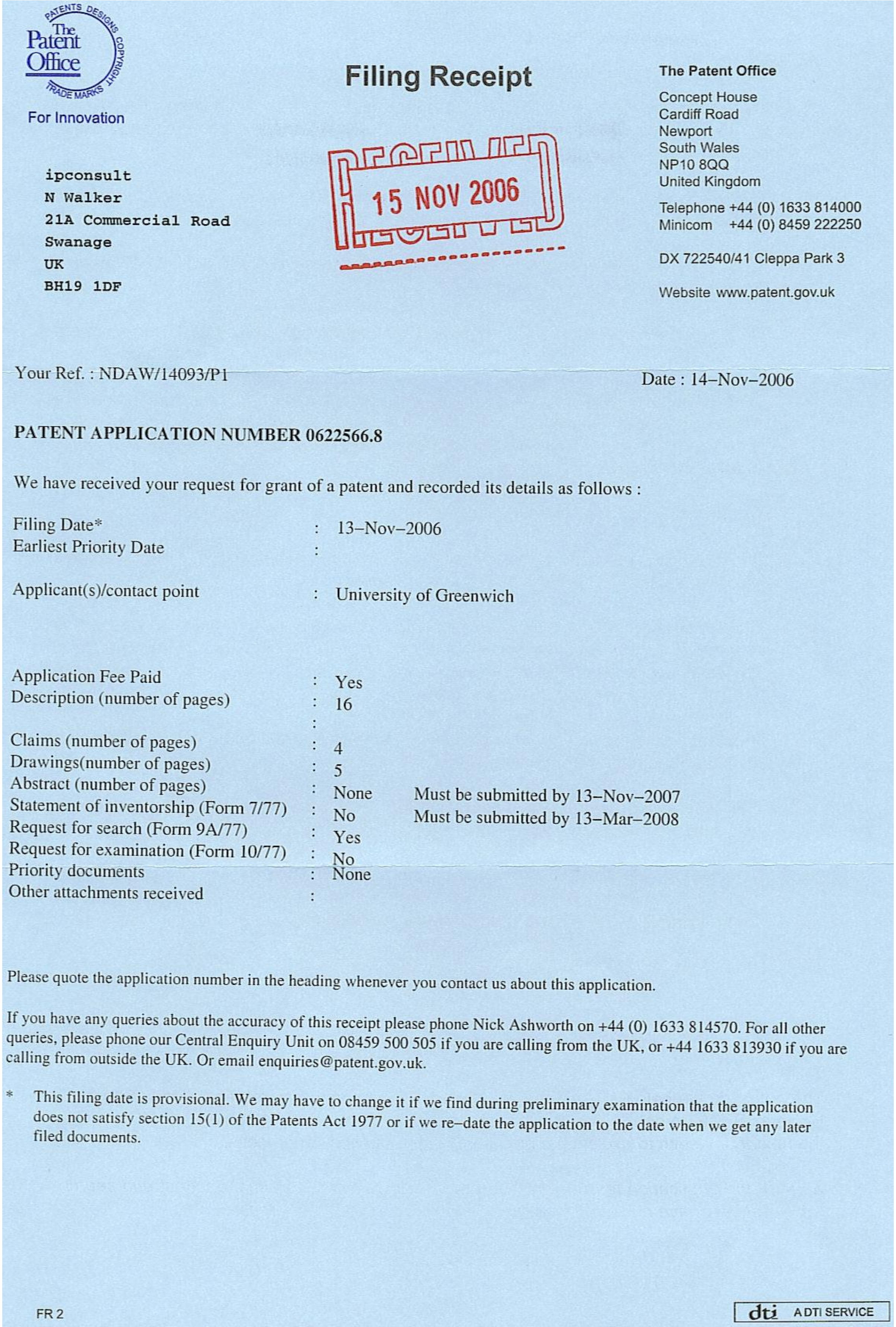
Table M: Measured Averaged Natural Frequencies; Sensor Location IV (Test Series 1)

Test No.	Sensor	Amplitude	Frequency
1	I	35.2	4.66
2	I	37.7	4.67
3	I	34.1	4.59
4	I	32.2	4.53
5	I	32.1	4.89
	Average	34.26dB	4.66Khz

Table N: Measured Averaged Natural Frequencies; Sensor Location V (Test Series 1)

Test No.	Sensor	Amplitude	Frequency
1	I	35.2	4.66
2	I	37.9	4.69
3	I	34.2	4.58
4	I	32.2	4.54
5	I	32.1	4.89
	Average	34.32dB	4.67Khz

APPENDIX B: PATENT INFORMATION



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Priority documents : None
Other attachments received :

Please quote the application number in the heading whenever you contact us about this application.

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* This filing date is provisional. We may have to change it if we find during preliminary examination that the application does not satisfy section 15(1) of the Patents Act 1977 or if we re–date the application to the date when we get any later filed documents.

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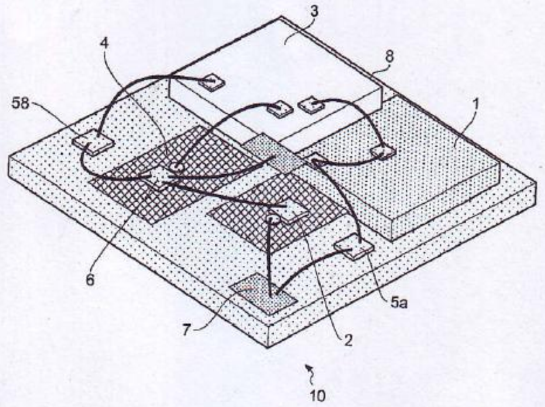
(54) Title: A SENSOR



(57) Abstract: The invention relates to a remote sensor for use in detecting integrity in structures and more specifically pipes. Examples of existing sensors are able to detect so-called defect characteristics that are encountered in corrosion products that are found in pipelines and originate from pipe walls. In one embodiment the invention provides a sensor adapted to be located on a structure. The sensor comprises a sensing element capable of providing a signal to a microprocessor. The microprocessor is adapted to run software in order to evaluate signals in order to indicate a status of the structure. A communication device transmits a signal to a remote recipient. Energy for operating the sensor is derived from a vibration emission array which is in contact with the structure. Thus the sensor is able to detect vibration, temperature and other variables, convert these signals into recognisable data and alert a remote location in the event of a hazard or fault. The sensor is also able to perform other functions such as self-testing, remote interactive training and self-updating of upgraded software and control systems.

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APPENDIX C: PUBLICATIONS