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Excitation and propagation of ultrasonic guided waves in pipes by piezoelectric transducer arrays

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Excitation and propagation of ultrasonic guided waves in pipes by piezoelectric transducer arrays

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Abstract. Ultrasonic guided wave inspection is one of the non-destructive testing (NDT) techniques available for the structural health monitoring (SHM) of engineering structures. Compared with other NDT techniques, guided waves can propagate over tens of metres with a relatively high sensitivity to defects in the structure. The general sensitivity range of the operation is up to 3% reduction of the cross-sectional area, depending on the signal-to-noise ratio. However, optimisation of guided wave testing method is still a requirement, as the technique is currently subject to a complex analysis due to wide number of guided wave modes generated. This can be done by optimising the transducer array design. In this paper, it is described the behaviour of a set of piezoelectric transducer arrays upon excitation in a tubular structure with simulated defects. This is achieved through a combination of finite element analysis (FEA) and experimental testing. The core objective of the work is to optimise the design of transducer arrays aimed at exciting the T(0,1) mode with a significant level of mode purity. This will significantly reduce the complexity of guided wave analysis, enhancing effectively the structural health of structures and subsequently reduce the industry maintenance cost.

1. Introduction

Structural integrity evaluation of oil and gas pipelines with NDT and SHM techniques is particularly attractive in industrial fields, since serious accidents of pipe failures have occurred due to its wall-thickness loss by corrosion or fatigue cracks, commonly. In NDT techniques, mostly used methods include acoustic emission (AE), X-ray inspection, ultrasonic testing (UT) and guided wave (GW) testing. For a long range ultrasonic testing, guided wave with a lower operation frequency range from 20 kHz to 100 kHz [1] has a high sensitivity and low attenuation when compared with UT under ideal conditions. Generally, the sensitivity of GW testing is working for reducing up to 3% of cross-sectional area depending on the signal-to-noise ratio [2]. The selected wave modes for guided wave excitation in pipe inspections are longitudinal wave modes L(0,1) and L(0,2), and torsional wave mode T(0,1). Gazis [3] investigated the propagation of these three wave modes with their flexural

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mode families F(*n*,1), F(*n*,3) and F(*n*,2), respectively. The dispersion curves were generated to describe a relationship between the selected modes and their flexural wave modes in a frequency range from 0 to 50 kHz [4] as shown in paper [5]. The constant phase velocity of torsional wave T(0,1) is 3260 m/s from dispersion curves in the frequency range.

In this paper, the finite element model is based on commercially available tool incorporating three circumferential arrays 'rings'. 24 transducers in each ring excited the torsional wave mode T(0,1). As with the tool, the numerical simulation in ABAQUS was set up with a 33-degree spacing between the start and end transducers of the ring. Ideally, transducers are equally spaced around a pipe that can excite a pure wave mode T(0,1) propagation without any other wave modes [6]. However, the torsional type flexural wave mode F(1,2) as shown in Fig. 2 and its higher order modes were also generated to interact with the wave mode T(0,1) by a transducer array with a 33-degree gap [7]. The transducer array was modelled to study its sensitivity analysis for circumferential notch detection [5]. This paper presents wave mode T(0,1) which was excited to propagate on a 4.45 m long, 8-inch (219.1 mm outer diameter), schedule 40 (8.18 mm wall thickness) steel pipe using the transducer array with a 33-degree gap and then verified through experimental validation. Also, its sensitivity analysis was evaluated for circumferential crack detection.

2. Modelling of transducer array sensitivity for circumferential crack detection

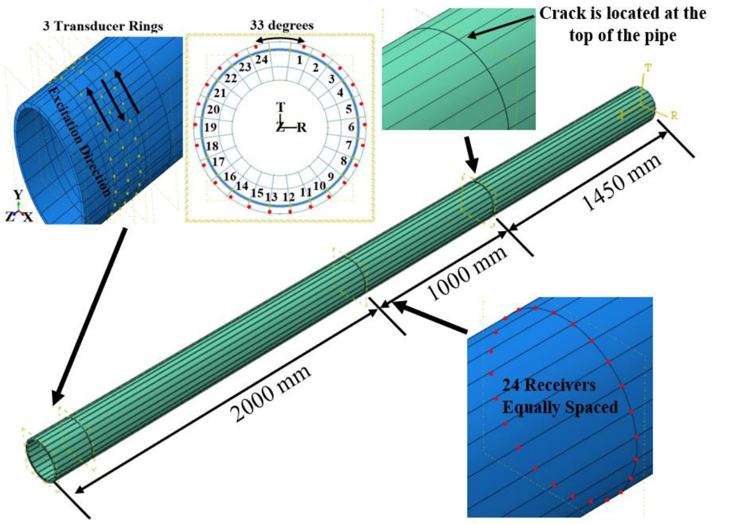

Figure 1. Guided wave testing of finite element model for 8-inch, schedule 40 steel pipe.

Finite element analysis in ABAQUS have been undertaken on a 4.45 m long, 8 inches, schedule 40 steel pipe model for guided wave testing as shown in Fig. 1. The steel pipe was modelled as a linear isotropic material with a mass density ρ = 7932 kg/m^3, Young's modulus E = 216.9 GPa and Poisson's ratio υ = 0.2865. At the left pipe end, three transducer rings were installed to cancel the transmitted signal from the back of transducer arrays. The ring spacing is 30 mm. As with the tool, each ring has 24 transducers equally spaced on the pipe circumference except for a 33-degree gap between the transducers No.1 and No.24. The transducers were all simulated as point sources. The receivers, composed of 24 equally spaced points, are placed at 2 m away from the left pipe end. A part-circumferential crack, 0.5 mm width in the axial direction and through-thickness, is located at 1 m away from the array of 24 receivers. An average mesh size of 4.5 mm in the axial direction and 5 elements in the radial direction were meshed with a total of 810,950 Hex elements. The transmitted signal was excited by a 10-cycle Hanning windowed pulse. The pulse signal is with the centre frequency of 35 kHz and frequency bandwidth of ±7 kHz. A concentrated force at each point source in the circumferential direction was used to excite the torsional wave T(0,1). The excitation was inverted by the middle ring, and the unconverted signal had a time-delay (9.2 us) that was excited by the back ring.

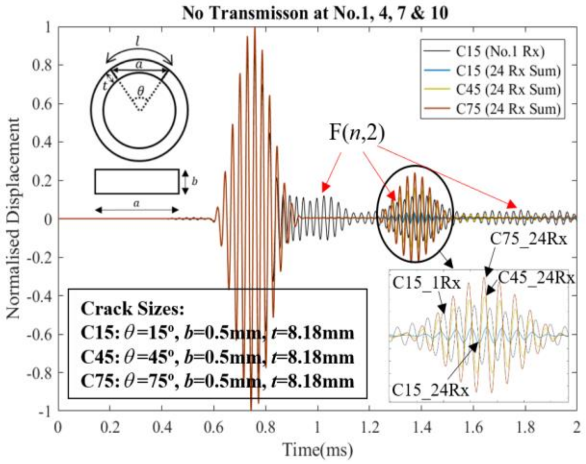

Figure 2. Normalised displacement in time domain.

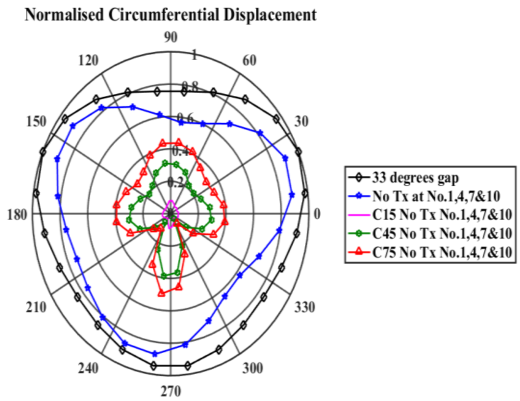

Figure 3. Polar plot of normalised maximum circumferential displacements.

Transducer arrays with no transmission at No.1, 4, 7, and No.10 of each ring were simulated to detect different circumferential crack sizes including C15 (15 degrees), C45 (45 degrees) and C75 (degrees). Figure 2 gives results for the wave modes T(0,1) with F(*n*,2) amplitude of normalised circumferential displacements at No.1 receiver in the case with crack C15 (No.1 Rx), and a single T(0,1) normalised circumferential displacement amplitudes by summing up the results at 24 receivers in the cases with cracks C15/C45/C75 (24 Rx Sum). From the results in the case with a part-circumferential crack 15 degrees on the top of pipe, the wave mode T(0,1) interacts with undesired flexural wave modes F(*n*,2) since the transducer spacing is non-uniform. The normalised amplitudes of circumferential displacement reduce by cancelling flexural wave modes. From the cases with different crack sizes, the related values increase when the crack size is extended in the circumferential direction. Figure 3 shows that the maximum amplitude of normalised circumferential displacement decreases when no transmission at that position and the total energy also reduces when compared with the maximum displacement amplitudes upon the initial status of transducer arrays. For sensitivity analysis of transducer arrays with a 33-degree gap and no transmission at No.1, 4, 7 and No.10, the reflection coefficient for the T(0,1) mode upon the increased through-thickness crack size is 3.5%, 16% and 24%, respectively whereas the reflection coefficient for the T(0,1) with F(*n*,2) modes is 11%, 44% and 56%, respectively. Results show that a 0.5 mm width, through-thickness crack size can be detected by exciting wave mode T(0,1) at 35 kHz in numerical simulations, even the detection is without complete signal transmission from the transducer arrays. The sensitivity of transducer arrays is around 4% for inspecting the simulated flaw. Further experimental measurements will be evaluated in the future work.

3. Experimental validation

To verify the related finite element models, an experimental set-up was designed as shown in Figs. 4-5. The torsional wave mode T(0,1) was excited by a piezoelectric transducers collar (part of Teletest® MK3 system). In this experiment, each ring was set with a gap of 33 degrees between transducer modules No.1 and No. 24. A 4.45 m, 8-inch, schedule 40 steel pipe without defects was used as specimen. A non-scanned laser vibrometer which was used to measure the circumferential displacements at 24 equally spaced receivers, were located at 2 m away from the left pipe end. Figure 6 shows a good agreement between experimental and FEA results. The numerical modelling for guided wave propagation are then verified from the experimental measurement.

Figure 4. Experimental setup.

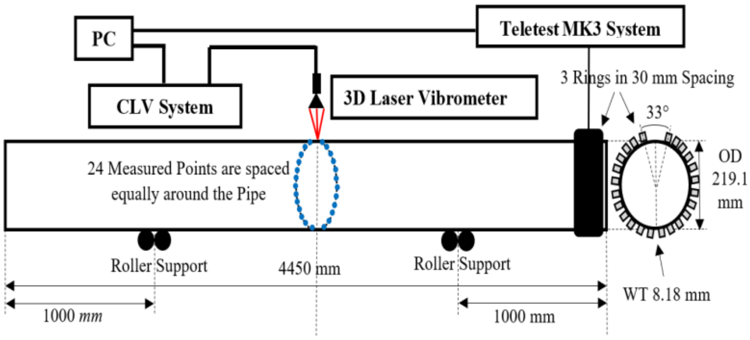

Figure 5. A detailed sketch of experimental setup.

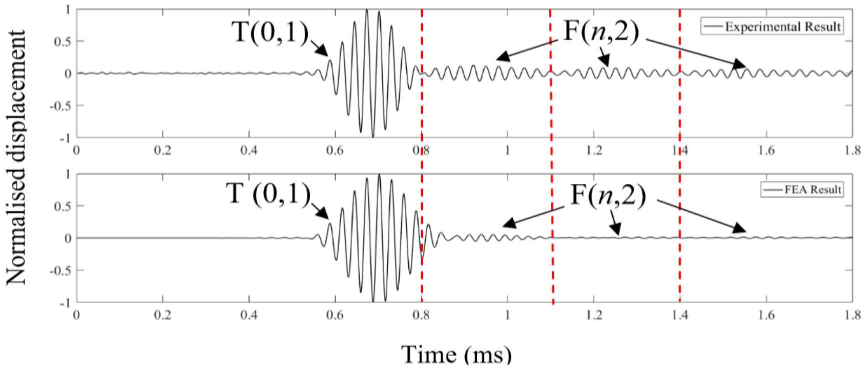

Figure 6. Comparison between Experimental and FEA results.

4. Conclusion

The numerical simulations of guided wave testing in ABAQUS have been verified from the experimental validation. The torsional wave mode T(0,1) interacts with the flexural wave modes F(*n*,2) that shows higher sensitivity when compared with the single mode T(0,1) by cancelling flexural modes for a part-circumferential through-thickness crack (0.5 mm width in the axial direction) using transducer arrays with non-uniform transducer spacing on the circumference.

5. Acknowledge

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6. References

[1] Mudge P 2001 *Insight – Non-Destructive Testing and Condition Monitoring* **43** 2 74-77
[2] Sharan P K, S S, Chaitanya S K and Maddi H K 2015 http://www.nde2015.com/papers-1/paper-83.pdf
[3] Gazis D 1959 *J. Acoust. Soc. Am.* **31** 573-8
[4] Duan W, Kirby R and Mudge P 2016 *Ultrasonic* **65** 228-41
[5] Niu X, Marques H R and Chen H P 2017 *The 8th Int. Conf. on Structural Health Monitoring of Intelligent Infrastructure* (Brisbane)
[6] Niu X, Chen H P and Marques H R 2017 *The 8th ECCOMAS Thematic Conf. on Smart Structures and Materials* (Madrid)
[7] Niu X, Marques H R and Chen H P 2017 *The 2017 World Congress on Advances in Structural Engineering and Mechanics* (Seoul)