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An application of a parametric transducer to measure acoustic absorption of a living green wall

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ABSTRACT

This work reports on a new method to measure the absorption coefficient of a Living Green Wall (LGW) *in-situ*. A highly directional parametric transducer and acoustic intensity probe are used to make this method robust against background noise and unwanted reflections. This method is tested under controlled laboratory conditions and *in-situ* on a real green wall. The methods is compared favourably against impedance tube data obtained for porous media which properties are relatively easy to measure using a standard laboratory setup. The new method is an alternative to the ISO354-2003 and CEN/TS 1793-5:2016 standard methods to measure acoustic absorption of materials.

1. Introduction

There has been strong evidence that some living plants (foliage) are able to absorb a considerable proportion of the energy in the incident sound wave. Some of this evidence were obtained through the standard laboratory experiment [1], some were derived through the application of a model (e.g. [2,3]) and some were collected *in-situ* [4]. However, there is still no valid theoretical model which is based on clear physics and which can explain the observed absorption spectra in a sufficiently broad frequency range. The evidence assembled so far suggest that three main mechanisms are responsible for the absorption of sound by living plants. In the lower part of the audible frequency range (e.g. below 100–400 Hz) the thermal dissipation mechanisms are important [5]. In the medium frequency (e.g. 400–2000 Hz) where the acoustic wavelength is still much larger that the characteristic leaf dimension (e.g. 15–250 mm for typical plants [3]) the viscous dissipation is the prime absorption mechanism [2,6]. In the higher frequency range (e.g. above 1–2 kHz) where the acoustic wavelength becomes comparable or smaller than the characteristic leaf dimension, the leaf vibration and multiple scattering begin to contribute to the dissipation of the energy in the incident sound wave [3,6].

One obstacle to the development of a unified model for sound propagation through foliage is the lack of reliable experimental data on the acoustic reflection/absorption coefficient spectra for a representative range of acoustic frequencies and angles of incidence. These data can then be related to the morphological characteristics of plants which can be directly measured so that a robust model can be developed and tested through a reliable experiment. An apparent lack of data on the acoustic reflection/absorption coefficient spectra for plants can be explained by the difficulties in measuring the absorption by plants in the laboratory or *in-situ*. This difficulty in laboratory conditions relates to the standard ISO 354 test [7] that requires 10 m^2 area of living plant or LGW specimen transported and installed in a reverberation chamber which is a rather cumbersome and expensive procedure. The alternative, ISO 10534-2 test [8] does not allow for a large enough LGW specimen to be tested in a broad enough frequency range. The difficulty of measuring the absorption of LGW or individual living plants *in-situ* is a lack of reliable standard methods for measuring the absorption of complex surface geometries such as plants and the strong influence of the ground from which these plants are grown. The BS 1793-5:2016 [9] method relies on an omni-directional source and microphones. As a result, it suffers from the interference between the sound reflected from the LGW, its edges and the ground. It is also recommended only for flat, homogeneous samples so that its application to volumetric absorbers such as living plants is questionable.

The aim of this work is to apply and validate a method which is able to measure the acoustic absorption of a large specimen of a

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vertical placed living plant in a broad frequency range which is representative of the spectrum of noise emitted by traffic and other common sources of noise. This method requires a parametric transducer and intensity probe which sensitivities are highly directional. In comparison with the BS 1793-5:2016 method [9], the method proposed in this paper is less prone to the effect of the ground reflection or to the edge effects and it can be used either in a laboratory conditions or *in-situ*. Laboratory applications of parametric transducer have been reported before to measure the complex reflection coefficient of flat material samples of limited dimensions [10,11] and sonic crystals [12] at normal and oblique angles of incidence. In this respect, the novelty of the parametric transducer method used in this paper is three-fold. Firstly, this method is applied to measure the absorption of a green wall which surface is far more complicated. Secondly, we use the sound intensity probe and signal deconvolution which makes this method particularly resistant to environmental noise. Thirdly, this method is now applied outdoors to a realistic section of a green wall which is typical to the conditions under which the acoustic absorption of green walls need to be measured.

The paper is organised in the following manner. Section 2 describes the design of the Living Green Wall's (LGW) used in the experiments. Section 3 describes the experimental setup and specimen characterisation procedures. Section 4 presents the results. Section 5 draws conclusions.

2. Green wall arrangement

LGW module system for this work was provided by ANS Group Global Ltd - Living Wall & Green Roof Specialist company. The wall is arranged in the form of a rectangular heavy duty plastic modules which measure 100 mm deep, 250 mm wide and 500 mm tall with 14 compartments for plants (7 compartments tall and 2 compartments wide as shown in Fig. 1 – right). All modules are identical and have a special hook catchment at the back which allows the modules to be hung on the wall. There is a hood at the back to allow for water pipeline installation and to provide a click-in system for the module placed on top. There are trenches at both sides of the module to allow for firm fixing with screws. In total 8 modules and 96 plants are required to form a 1 m^2 of the wall. On average, when watered 1 m^2 of green wall section weighs 72 kg.

Fig. 1. Living Green Wall module, with plants and empty (ANS Group Global Ltd). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The modules are cladded on to the wooden rails that are firmly attached to the wall and/or facade. In between of the wall and the rail a specialised waterproof membrane is stitched to protect the building wall from excess water and damp (see Fig. 2). Advanced green wall options offer wireless wall moisture control with automated on/off water supply systems. When constructing the wall, the modules may come on site pre-planted, or alternatively planting can be done on site. The choice of plants for the Living Green Wall (LGW) is down to the designer's preference. However, factors such as the south or north side facing building wall, average temperature, humidity, average rainfall and wind are normally taken into account.

3. Experimental setup

3.1. Acoustic equipment

An intensity probe, Brüel & Kjær, type 4197 [13] with Brüel & Kjær NEXUS conditioning amplifier type 2690 and parametric transducer, a directional loudspeaker HSS-3000 Emitter [14] with HSS-3000 amplifier were used in the reported experiments. The intensity probe was firmly attached to a telescopic tripod and placed at a height of 0.9 m and 1.7 m away from the measured surface. The orientation of the intensity probe with respect to the wall was perpendicular as shown in Fig. 3. The directional loudspeaker was also attached to a tripod and it was placed 4 m away from the wall. The line connecting the centre point of the directional loudspeaker and the middle of the intensity probe was set perpendicular to the wall as shown in Fig. 3. The size of the loudspeaker was 180 mm wide and 300 mm long and 30 mm thick. According to the original theories developed by Westervelt for a parametric acoustic array in the form of a semi-permeable screen [15] and by Lockwood for a parametric acoustic disk [16] the process of generation of the difference wave is primarily confined to the vicinity of the transducer. This means that the amplitude and behaviour of the differential (low-frequency) sound wave away from this transducer is mainly controlled by the source strength density of the primary high-frequency sound field near the transducer's surface (see Eqs. (1), (2) and (4) in Ref. [16]). In the far field, i.e. where our measurements were taken, this differential wave propagates like a spherical wave radiated by a highly directional transducer. Because the source strength density of this wave is proportional to the squared sound pressure in the primary (high-frequency) wave (see Eq. (5) in Ref. [16]), the whole process of audible sound generation by a parametric transducer is biased towards the areas where this primary pressure is particularly high. The primary frequency of the parametric transducer used in this work was 44 kHz. The peak sound pressure of this primary wave was 440 Pa at 0.3 m from the transducer's center. This was sufficient to develop strong non-linear effects causing the emission of the differential wave. The sound pressure in the primary wave reduced to approximately 35 Pa at 4 m away from the transducer. At this position the non-linear effects were relatively weak so that the presence of either a green wall or another surface would be unlikely to affect noticeably the parametric sound generation process in the reported experiments.

For each of the experiments, the intensity probe was shifted left or right and up or down to measure the directivity of the incident and reflected sound waves. The horizontal offset values were: 0; 50; 70; 100; 150; 250; 500 and 750 mm. The vertical offset values were: ±60 mm. The exact locations of the loudspeaker and intensity probe were measured by means of measuring tapes and a set of lasers with level indicators. The choice of these offsets was based on the transducer directivity and typical scattering pattern measured at 1.7 m. The maximum values of the horizontal offset corre-

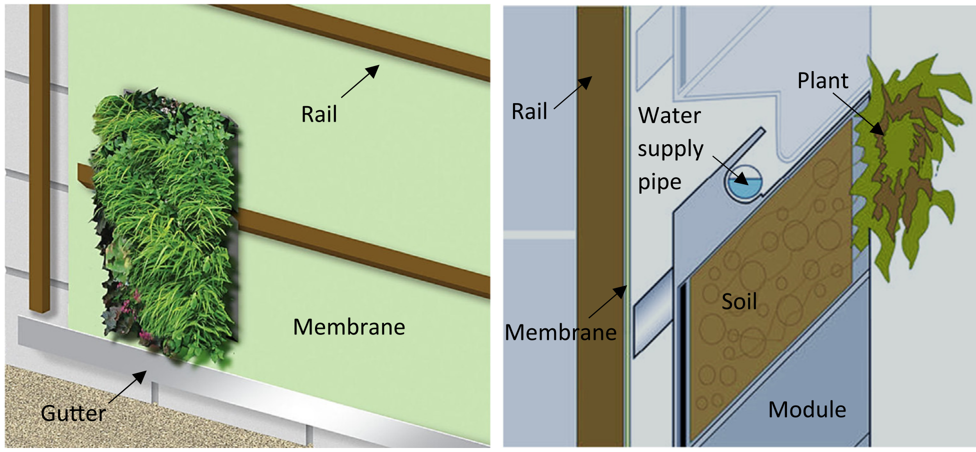

Fig. 2. Living Green Wall module installation front and side view (ANS Group Global Ltd). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

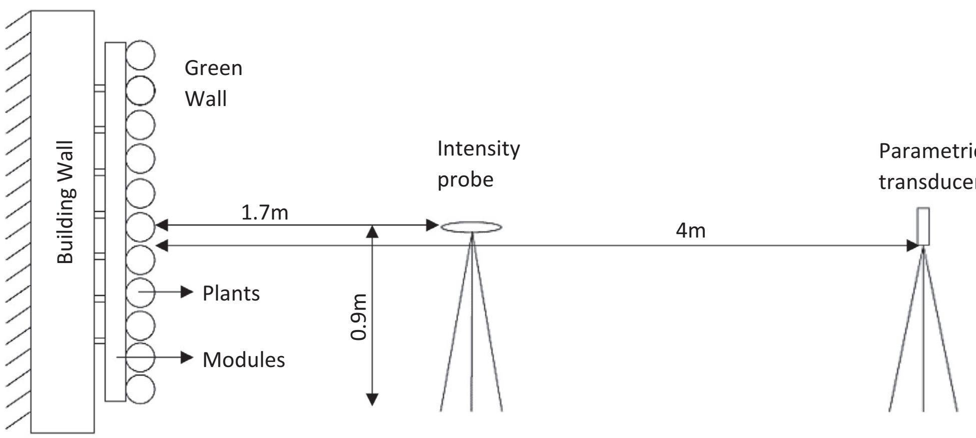

Fig. 3. Experimental set-up schematics.

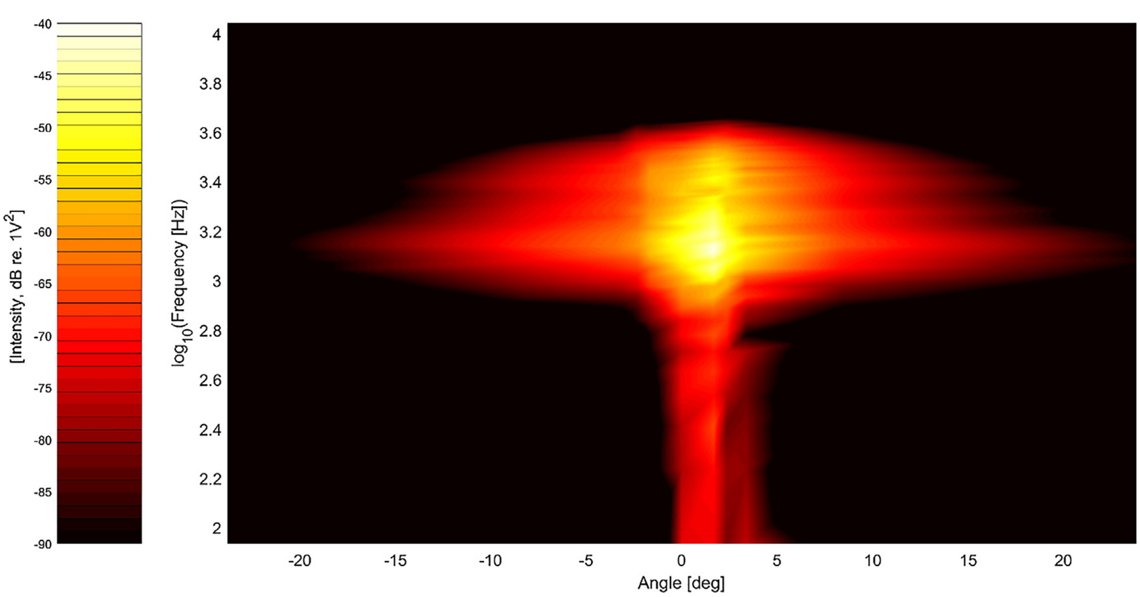

Fig. 4. The horizontal transducer directivity pattern measured at 1.7 m from the transducer centre.

sponded approximately to ± 24 deg in terms of the azimuth angles. The horizontal transducer directivity and the horizontal scattering pattern of a brick wall are shown on Figs. 4 and 5, respectively. These results suggest that the 90% of the emitted acoustic energy in the horizontal plane is contained within ±10–12 deg segment. The horizontal directivity of the reflected sound is broader, but

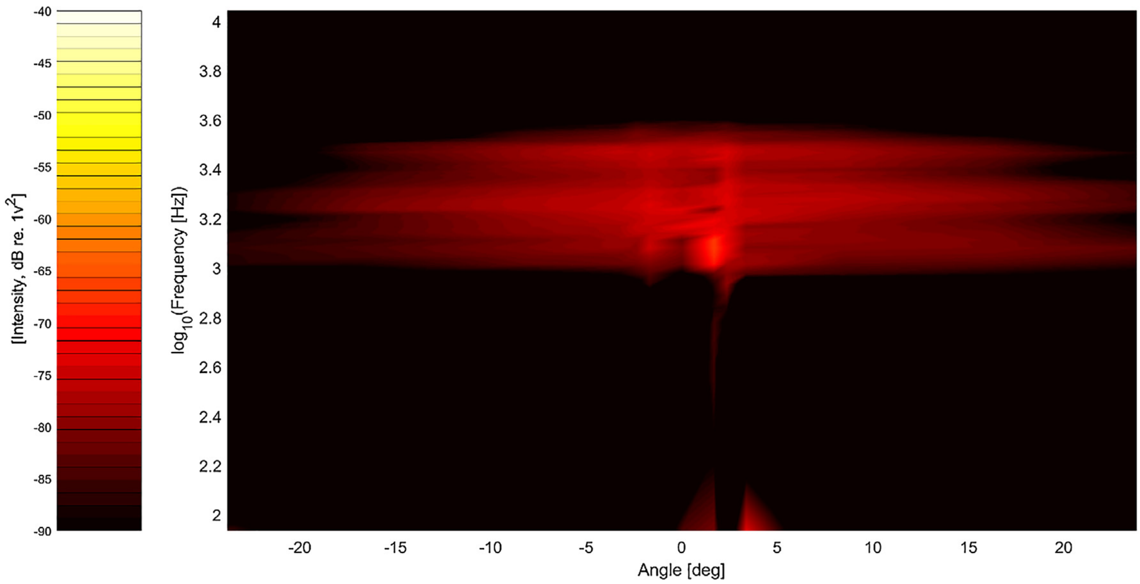

Fig. 5. The horizontal pattern of the acoustic intensity scattered by a brick wall being 4 m away from the transducer centre and measured at 1.7 m away from the transducer centre.

the bulk of energy is contained within the ±24 deg segment. The vertical directivity of the transducer was not measured in the reported experiments. It was assumed that the vertical directivity pattern is sufficiently narrow to neglect the ground interference and wall edges reflection and scattering effects. Given the fact that the vertical dimension of the parametric transducer was 60% wider than its horizontal dimension, one can assume that the directivity would broaden proportionally. Extrapolating the results shown in Fig. 4 into the vertical direction suggests that the 90% of the acoustic energy emitted in the vertical direction should be contained within ±16–19 deg segment. For the experimental setup shown in Fig. 3 it is possible to estimate that no more than 3% of the emitted acoustic energy would fall on the ground at the foot of the green wall we measured. The procedures for signal processing used to generate the data shown in Figs. 4 and 5 are described in Section 3.3.

3.2. Material specimens

The absorption properties of five different material specimens were studied. These were: (i) brick wall (Fig. 6); (ii) 100 mm thick, hard-backed melamine foam (Fig. 7(a)); (iii) green wall filled with 100 mm slightly moist soil without any plants (Fig. 7(b)); (iv) green wall planted with *Hedera helix* (Fig. 7(c)); and (v) green wall planted with *Bergenia cassifolia* (Fig. 7(d)). The basic morphological characteristics of the two plants are summarised in Table 1. The soil and the two types of plants were planted in the nursery in a green wall which dimensions were 2.5 m wide and 1.8 m high. The soil without the plants had 5 L of water per 1 m^2 and in all of the experiments with the plants the soil had 32 L of water per 1 m^2. Table 1 presents basic morphological characteristics for the two plants studied in this work. The values presented in Table 1 are taken as the average values for the selected plants used in the experiments on the day.

It was assumed that the absorption coefficient of the brick wall does not exceed 5–7% in the adopted frequency range. Therefore, the brick wall was used to simulate a rigid surface to serve as a reference to determine the absorption coefficient of the layers of soil, two plants and melamine foam. The hard-backed layer of melamine foam used in the experiments was 2 m x 2 m and its thickness was 100 mm. A 100 mm diameter sample of melamine was

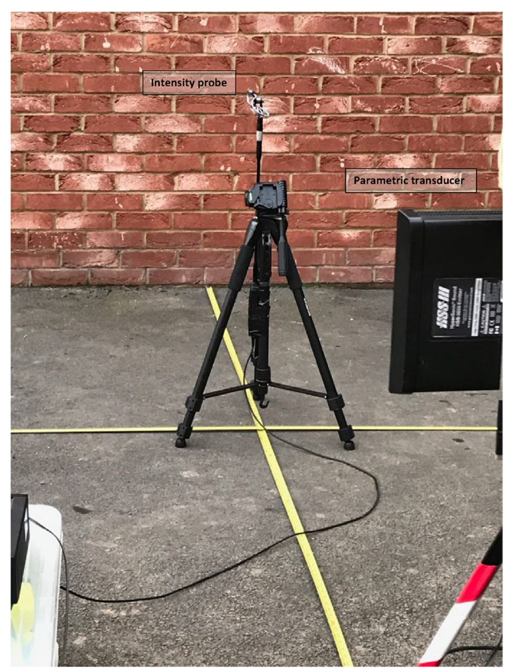

Fig. 6. The arrangement of the acoustic equipment in the experiment on sound reflection from a brick wall.

cut out and its absorption coefficient was tested in the impedance tube in accordance with the ISO 10534-2 method [17].

The absorption coefficient of melamine foam measured in a standard 100 mm diameter impedance tube in the frequency range of 100–1600 Hz. The impedance tube results were then compared against that measured *in-situ* with the measurement method proposed in this paper. In addition, the absorption of a 100 mm thick sample of soil was measured in the impedance tube. The bulk density of dry soil was 200 kg/m^3. The soil absorption measured in the impedance tube was also compared against that measured *in-situ* for the purpose of validation of the proposed method against a standard experiment.

Fig. 7. The arrangement of the acoustic equipment in the experiment on sound reflection from: (a) 100 mm layer of hard-backed melamine foam; (b) Modules with soil wall without plants; (c) Hedera helix green wall; (d) Bergenia cassifolia green wall. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
The basic morphological characteristics of the tested plant specimens.

	Leaf length mm	Plant height Mm	Area of one leaf mm^2	Leaf thickness mm	Number of leafs per m^2	Leaf area density m^{-1}
Hedera helix	45	160	1800	0.3	700	20.16
Bergenia cassifolia	70	180	4200	2	400	30.24

3.3. Signal processing and data analysis

The signal used with the described experimental setup was a 10 sec sinusoidal sweep in the frequency range of 100–5000 Hz. Below 500 Hz the sensitivity of the parametric loudspeaker was too low to overcome the background noise. Above 5000 Hz the directivity pattern of the parametric loudspeaker was found too complex and the sensitivity of the intensity probe too low to apply the proposed method. The signals recorded on the microphone pair in the intensity probe were sampled using a National Instrument USB-4431 card at the sampling rate of 22.05 kHz. The recorded signals were processed with Matlab® to obtain the acoustic instantaneous intensity using the same deconvolution method as detailed in Chapter 5 in ref. [18]. The application to deconvolution enabled us to achieve a very high signal to noise ratio which is important in the presence of high levels of ambient noise while taking measurements *in-situ*.

The instantaneous acoustic intensity was calculated as

$$I(t) = p(t)u(t) \tag{1}$$

where $p(t)$ is the time-dependent mean sound pressure recorded on the two microphones in the intensity probe and $u(t)$ is the acoustic particle velocity estimated from the sound pressure data, $p_{1,2}(t)$, recorded on microphones 1 and 2

$$u(t)\frac{1}{\Delta\rho_0}\int_{-\infty}^{t}(p_2(\tau) - p_1(\tau))d\tau \tag{2}$$

where $\Delta = 12$ mm is the microphone separation in the intensity probe and ρ_0 is the equilibrium density of air.

Fig. 8 shows an example of the normalised (to 1 V^2) impulse response of the acoustic intensity recorded in the presence of the partition wall. This figure also presents a similar set of data, but for the case when the 100 mm hard-backed layer of melamine was installed in front of the intensity probe. The graphs on the left show the incident and reflected instantaneous intensity signals. The graphs on the right show a blow-up pictures of the reflected intensity only. Note that the scale on the figure showing the intensity signal reflected from the layer of melamine is 10 times more sensitive than that for the reflection from the brick wall. The negative signals correspond to the incident sound wave. The positive signals correspond to the wave reflected from the material layer. Any small variations from this pattern can be explained by reflections from the structural elements of the intensity probe and supporting tripod. There is a clear variation in the amplitude of the acoustic intensity recorded at different probe positions. This variation is explained by a relatively strong directivity of the source and complexity of the acoustic field which this parametric transducer radiates. In the bottom right graph there are two reflected waves. The first wave corresponds to the reflection from the front of melamine. The second reflection is the wave reflected from the rigid backing.

Fig. 9 present examples of the normalised narrow band intensity spectra which were calculated for the instantaneous intensity

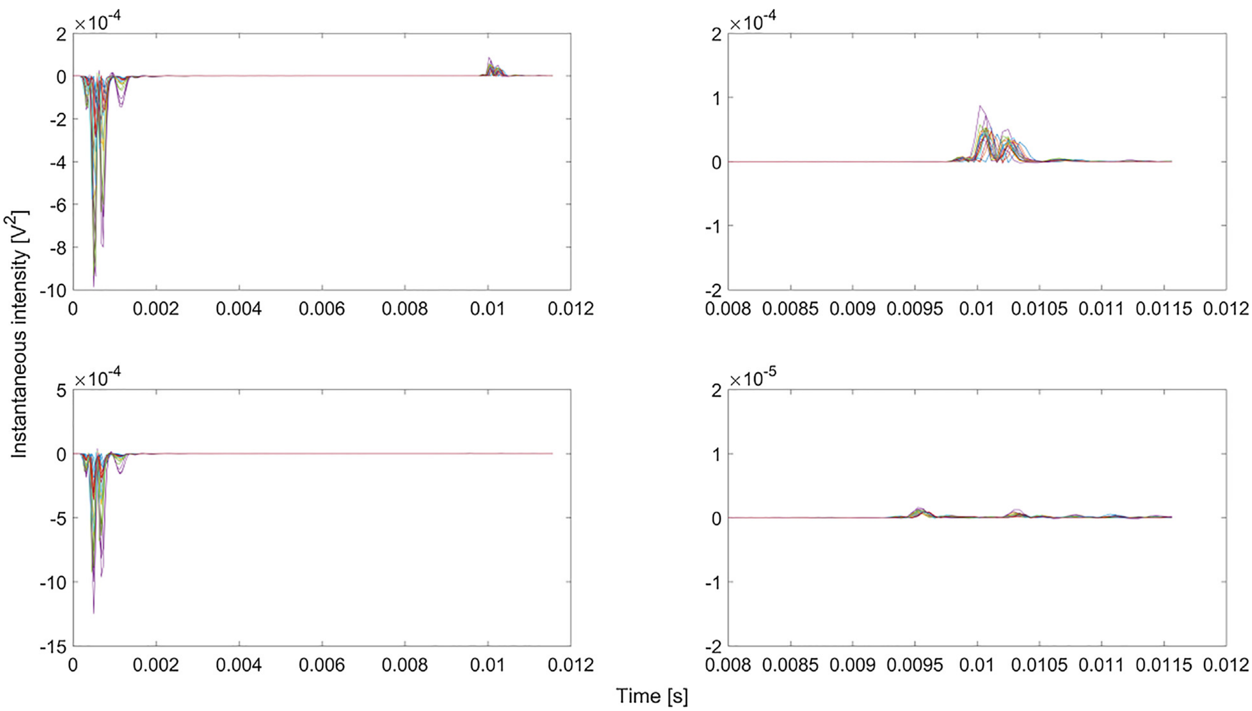

Fig. 8. The time histories for the instantaneous intensity recorded in the presence of the brick wall (top graphs) and in the presence of the 100 mm layer of melamine (bottom graphs). The graphs on the right hand side are the blow-up of the signal reflected from the material.

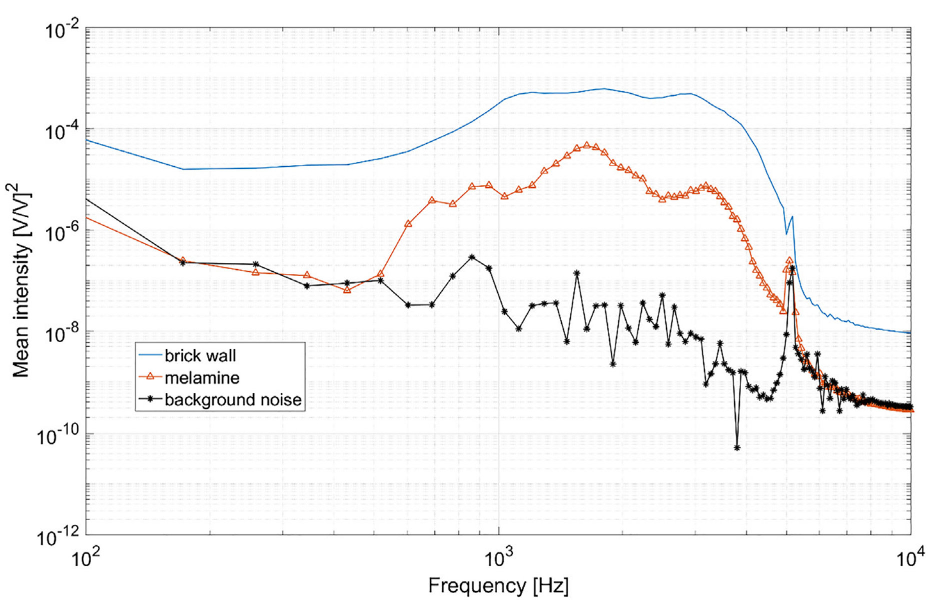

Fig. 9. The intensity spectra for the sound waves reflected from the wall and melamine. These spectra are the total intensity over 45 intensity probe positions.

signals reflected from the brick wall and melamine. The spectra shown in this figure were for a 256-samples time window and averaged over the 45 intensity probe positions. According to the ISO 10534–2 [8] impedance tube experiment, the normal incidence plane wave absorption coefficient of the 100 mm layer of melamine is >90% in the frequency range of above 500 Hz. The maximum random incidence absorption of the brick wall in this frequency range is <7% [19]. These two cases enable us to set the high and low absorption limits which can be attained with the proposed method. Fig. 9 also shows the background noise intensity. These data suggest that below 500 Hz and above 5000 Hz the intensities of the reflected signal and background noise are comparable so that these frequencies should be avoided in the analysis.

The spectra shown in Fig. 9 were used to calculate the absorption coefficient which was determined as the following ratio

$$\alpha(\omega) = 1 - \frac{\tilde{I}_a(\omega)}{\tilde{I}_r(\omega)} C(\omega) \quad (3)$$

where $\tilde{I}_a(\omega)$ is the intensity spectrum reflected from an absorbing layer (e.g. melamine), $\tilde{I}_r(\omega)$ is the intensity spectrum reflected from the brick wall which was assumed rigid and $C(\omega)$ is the correction which takes into account the peculiarities in the propagation and attenuation of the sound wave radiated by the parametric transducer. This coefficient was calculated based on the assumption that the brick wall is a perfectly reflecting surface, i.e.

$$\frac{\tilde{I}_a(\omega)}{\tilde{I}_r(\omega)} C(\omega) = 1 \quad (4)$$

in the case of the brick wall. In this calculation the intensity spectrum reflected from the brick wall was effectively used as a reference. It was also assumed that the ambient conditions for the generation and propagation of the ultrasonic career resulting in the audible parametric sound were identical in all of the reported experiments.

4. Results

Fig. 10 presents the absorption coefficient for the 100 mm hard-backed layer of melamine foam calculated in accordance with Eq. (2). This figure also shows the absorption coefficient of the same melamine foam measured using the impedance tube method [8]. This comparison suggests that in the frequency range of 500–1600 Hz the two methods agree within 7%. At the frequencies lower than 500 Hz the proposed intensity method overestimates the absorption coefficient significantly. Therefore, the results obtained with the proposed measurement method are shown only down to 350 Hz here because of a low confidence in the data due to a low signal-to-noise ratio observed in this frequency range.

Fig. 11 presents the absorption coefficient for the green wall with and without plants as shown in Fig. 7. Fig. 11 also presents the absorption coefficient of soil substrate which was measured in the impedance tube in accordance with the method described in ref. [8]. Fig. 11 also presents the absorption coefficient of *Bergenia cassifolia* which was predicted using the 2-layer Pade approximation model [20] with the parameters listed in Table 2. The values of the parameters for the bottom layer of soil were inverted using the impedance tube data. The values of the parameters for the top layer of *Bergenia cassifolia* were predicted using the morphological characteristics of this plant listed in Table 1 and the model suggested in ref. [2].

The results for the absorption coefficient for soil suggest that there is a close (within 12%) agreement between the proposed method and impedance tube method in the frequency range between 400 and 1250 Hz. Above 1250 Hz the green wall data are affected by a number of resonances. Around 1380 Hz there is a distinctive drop in the absorption (see Fig. 11) which can be explained by the half-wavelength resonance in the 250 mm wide plant compartment (see Fig. 1) which is predicted at 1360 Hz if we assume that the sound speed in air is 340 m/s. This drop in absorption consistently occurs in the system filled with soil, *Hedera helix* and with *Bergenia cassifolia*. Around 2200 Hz there is another drop in the absorption which can be explained by a half-wavelength resonance in the 72 mm high plant compartment (see Fig. 1). This drop appears consistently in the data for the wall with soil alone and for the wall with *Hedera helix*. In the case of the green wall with *Bergenia cassifolia* this minimum disappears. There is another minimum which appears in the soil data only around 3200 Hz. This minimum is hard to explain by the cell geometry alone and it can be attributed to either the diffraction of sound on the wall edges or by the transmission through the gaps between

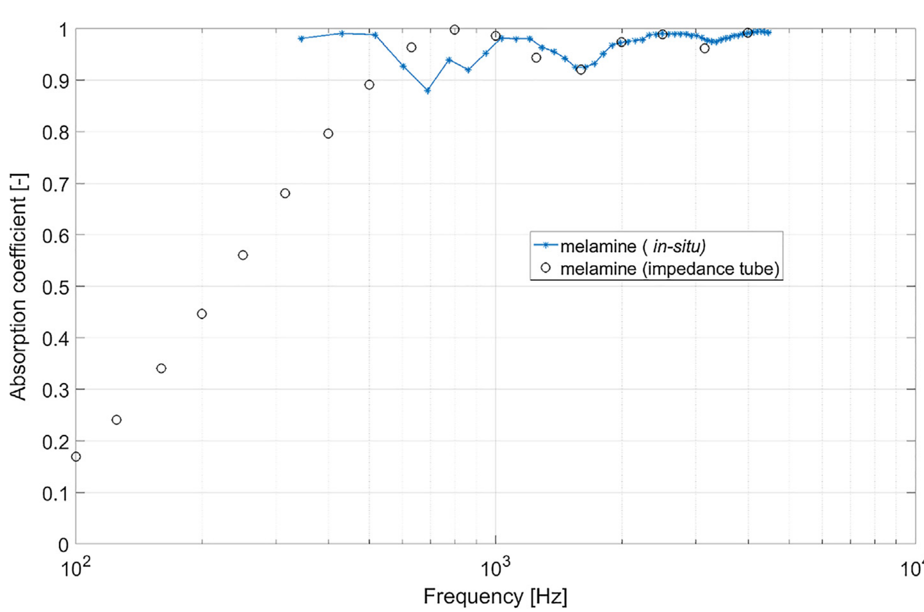

Fig. 10. The absorption coefficient of a 100 mm thick, hard back layer of melamine foam.

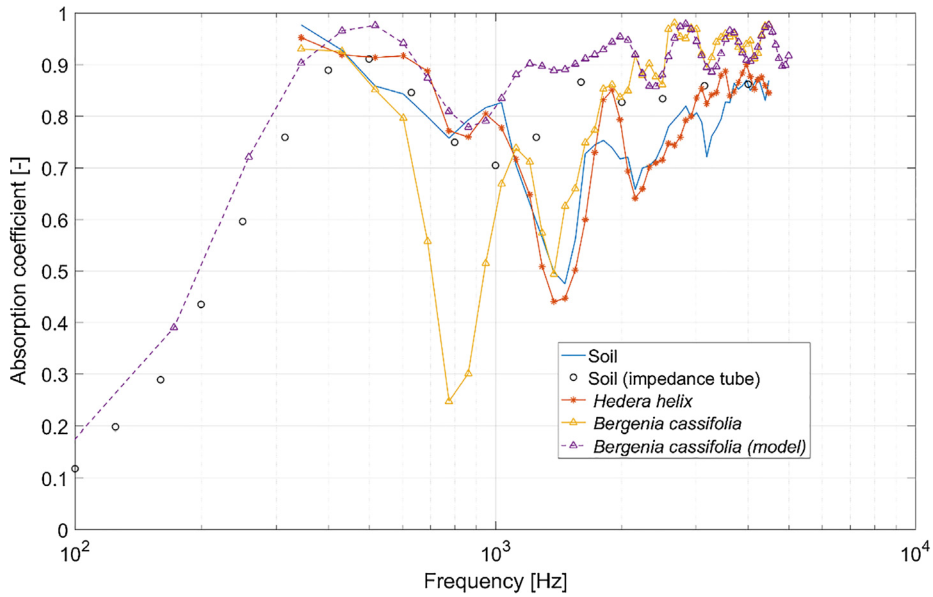

Fig. 11. The absorption coefficient of soil and soil with plants planted in a 2.5 m × 1.8 m green wall system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The summary of the intrinsic parameters used in the 2-layer model [20] to predict the acoustic absorption coefficient of soil with Bergenia cassifolia plant in the green wall.

	Flow resistivity [Pa s m^{-2}]	Porosity [–]	Turtuosity [–]	Standard deviation in pore size [ϕ-units]	Layer thickness [m]
Bergenia cassifolia (top layer)	45	0.98	1.35	0	0.18
Soil (bottom layer)	9170	0.57	1.22	0.77	0.10

individual cells in the green wall. This minimum is not present in the data for the green wall treated with a plant.

The measured absorption coefficient spectrum of the green wall with *Hedera helix* is very similar to that of the green wall with soil only. This is explained by a relatively small effect of the plant which leave area density is relatively small [2]. In the case of the green wall planted with *Bergenia cassifolia* an obvious increase in the absorption coefficient with respect to that of the green wall with soil only can be observed. This increase is particularly pronounced at the frequencies above 1000–2000 Hz and it is predicted within 1–2% by the model. A considerable drop in the measured absorption coefficient for *Bergenia cassifolia* is observed near 800 Hz. This drop is not captured by the model, but can be attributed to coherent scattering of sound by the plant leaves in the direction of the acoustic intensity probe and by the complexity of the arrangement of soil/plant system within the green wall.

5. Conclusions

A new method has been proposed to measure the absorption properties of a Living Green Walls (LGW) *in-situ*. The method has been compared favourably against impedance tube data available for melamine foam and soil, particularly in the frequency range above 500 Hz. The proposed method is less prone to the unwanted ground and edge effects because the adopted loudspeaker and intensity probes are highly directional and enable us to focus the radiated sound on the green wall area primarily. This method is relatively easy to implement, although it requires a relatively large number of measurement positions to capture the complexity of the acoustic fields radiated by the parametric transducer and scattered by the green wall.

The results confirm that the presence of plants with a relatively high leave area density can significantly enhance the absorption properties of a green wall system, particularly in the medium and high frequency range, i.e. above 1000 Hz. The results also show that a compartmentalised green wall system can support acoustic resonances at frequencies which are controlled by the cell dimension and wall thickness. Some of these resonances are reduced or disappear when the wall is treated with a plant with a relatively high leaf area density, e.g. *Bergenia cassifolia*. These resonances deserve a refined numerical modelling to understand better the *in-situ* acoustic performance of a complete Living Green Wall system. There is evidence that in some cases plants can scatter sound coherently resulting in an apparent decrease in the absorption coefficient. These effects need to be accounted for by the refined numerical modelling.

The proposed experimental method needs further improvement. Firstly, it can be suggested that a parametric transducer with better quality can be adopted. This transducer needs to radiate sufficient sound energy in the frequency range below 500 Hz to overcome background noise which inevitably exists *in-situ*. Secondly, the 3-dimensional acoustic radiation patters of the parametric transducer deserves a more detailed analysis. In particular, it is of direct interest to understand the development of the audible sound from the radiated ultrasonic beam, it evolution over the propagated distance and its interaction with the scattering surfaces. Thirdly, it can also be suggested to understand better the scattering patterns of flat and uneven surfaces through more refined mesh of receiver positions. Finally, it is of interest to understand the active and reactive components of the intensity vector in the acoustic field scattered by a real plant. This information may lead to the development of better models for the acoustical properties of living plants which will account for the viscous/inertia absorption, leaf vibration and scattering effects.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2018.09.020.

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