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Acoustic absorption of a living green wall - parametric transducer and XYZ gantry measurement method

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ABSTRACT
This work provides evidence of the importance of considering urban green structures and in particular the Living Green Walls (LGW) as sound-scaping instruments. An insight to Living Green Walls sound absorption properties is provided with particular interest of sound absorption coefficient and plant morphology. The work was carried out in-situ in internal and external environment and makes use of parametric transducer and XYZ gantry. Novel method of parametric transducer was previously verified by the use of impedance tube tests benchmarking against porous media material. The proposed XYZ gantry method eliminates the reflection from the ground and averages the discrepancy of the absorbed/reflected sound due to plant morphology over a given area of interest. The new method is an alternative to the ISO354-2003 and CEN/TS 1793-5:2016 standard methods to measure acoustic absorption of materials.

Keywords: urban noise, Living Green Wall (LGW), living plants, green wall, acoustic absorption, acoustic measurement, parametric sound.

1. INTRODUCTION

Soundscape is now recognised as a very important characteristics of the modern, developed civilisation. Soundscape as a term that appeared in 70's and denotes an acoustic environment made of cacophony of sounds as perceived by humans which is different in each given context, urban and non-urban (1). Noise on the other hand is regarded as a loud and unpleasant/unwanted sound that causes disturbance or stress. A new term of noise pollution appears alongside soundscape and is now being used to describe unpleasant soundscapes of urban settings that is dangerous and harmful to both humans and animals (2-3).

In large urban setting as megapolis cities noise pollution is a major problem which is a hindrance to human day-to-day life and that remaining wildlife. With rapid development of economies and work opportunities supported by free mobility of workforce, traffic noise is by far the most harmful noise pollution source, including ground, air and water transportation. America (USA) is the most studied country for noise pollution and it is reported that in general traffic noise accounts for 70% of overall pollution with instantaneous noise values being in excess of 80 dB (4), 1-5 m away from the source, which worryingly are increasing year by year. There are many studies that suggest the harmful effect of noise pollution on human's health (hearing loss, stress, restlessness, nervousness, obesity, heart disease, increased blood pressure, abnormalities in brain reflex, etc.) caused by sharp and short as well as moderate and prolonged noises (5-8). And although cities like London and Tokyo have opted to reduce traffic noise through electric vehicles, the humanity has still a long way to go.

One of the methods to fix the urban soundscapes is to introduce porous materials that can absorb the unwanted noise. Introduction of vegetation is known to help with trapping noise and creating tranquil spaces. Vegetation or plants are able to attenuate sound waves by reflecting and absorbing the acoustic energy of the viscid thermal boundary layer near the surface of the plant. Alternatively, plant internal branches or stems can accommodate vibrating sound that helps to reduce sound energy (9).

In our study we have used the Living Green Walls (LGW) with benchmarks to plywood wall and

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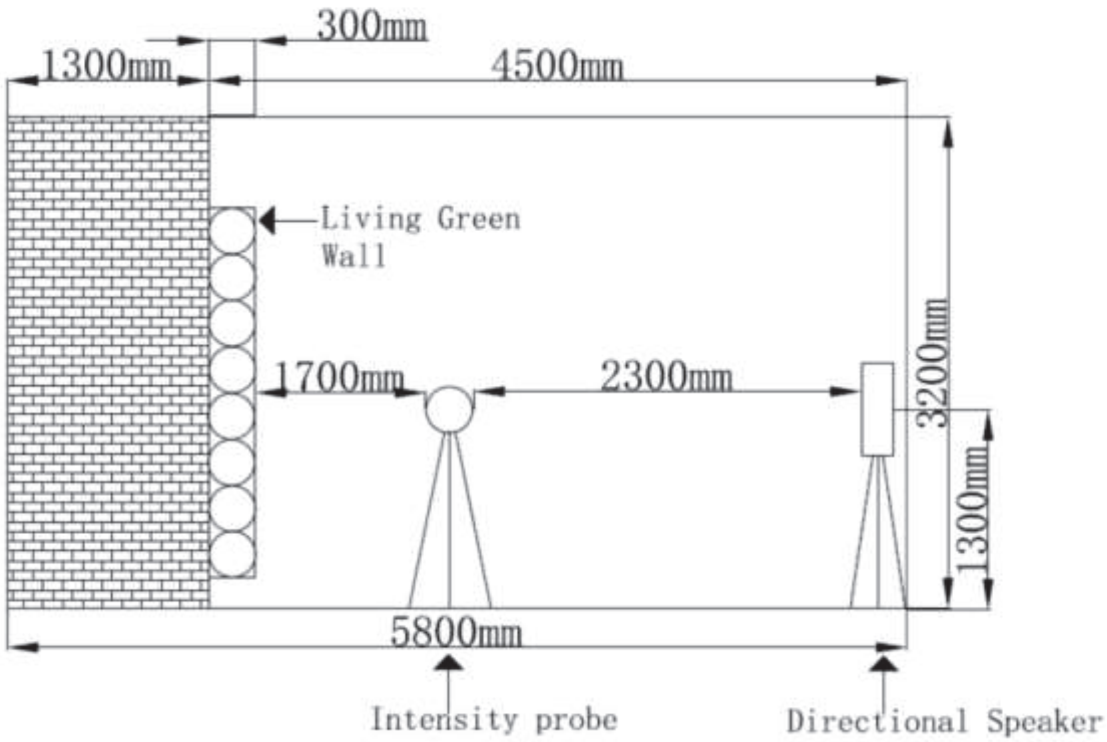
melamine wall to establish how the structures with and without vegetation absorb the sound of different frequencies. To facilitate the measurement with great precision we have constructed a motorised XYZ gantry system that also allows to replicate the experiment over time. The system uses the method of parametric transducer (10) that has feasible benefits over ISO354-2003 and CEN/TS 1793-5:2016 standard methods, as it eliminates the reflection from the ground and edges of the wall.

2. EXPERIMENTAL METHODOLOGY

The acoustic method described in (10) was used, where instrumentation consisted of 'An intensity probe, Brüel & Kjær, type 4197 with Brüel & Kjær NEXUS conditioning amplifier type 2690 and parametric transducer (directional loudspeaker HSS-3000 Emitter) with HSS-3000 amplifier.' The intensity probe was firmly attached to a motorised telescopic X-oriented leg and placed at a height of 0.9 m and 1.7 m away from the measured surface center (corresponding to 0,0,0 mm reference point or C_0). The orientation of the intensity probe with respect to the wall was perpendicular. The directional loudspeaker was also attached to a tripod and it was placed 4 m away from the wall in the same central co-ordinates as per reference point. The line connecting the center point of the directional loudspeaker and the middle of the intensity probe was set perpendicular to the wall. See Figure 1 for the set-up.

2.1 XYZ gantry set-up

The novel motorised XYZ gantry to move the intensity probe in 3-dimensions was built using aluminium profiles with 0.2 mm precision Mclennan motors of type IP57-M1-10 and HepcoMotion moving line attached. The horizontal X-Y axis, allowing movements left-to-right and forward-to-backward have the capacity of 1800 mm spread (the internal space is square). The Z axis allows for 80 mm up-to-down movement. Three of the motors, serving each axis, are connected to the portable SIEMENS TP-Link control unit that is PCB, DAQ and Webserver enabled. This is synchronised with the SIEMENS online application to control the position of the intensity probe in the XYZ axis. This can be repeated with the same precision every time.



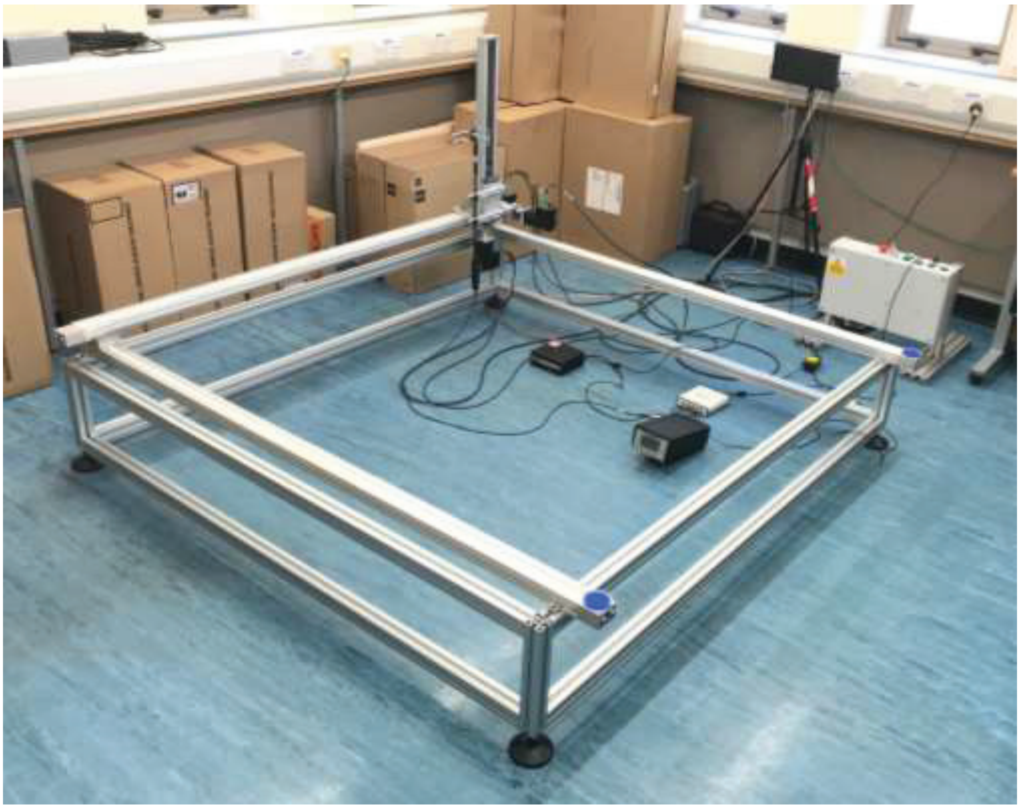


Figure 1 - Laboratory side view schematics (top) and XYZ gantry picture (bottom)

In these experiment sinusoidal chirp sound of 20 Hz - 20 kHz was emitted. As per (10) '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.'

2.2 LGW and benchmarks

The LGW can be constructed from different materials and in our case the 2 m wide and 1.8 m tall wall donated by ANS Global Ltd (see Figure 2 and 3) is assembled from HDPE modules, growth medium (soil & fertilisers) and pipeline with pump based irrigation system that is hidden behind the modules together with water membrane and wood hinges.

Figure 2 - Living Green Wall schematics (11), left-to-right: single empty module, module with soil, module with plants, attached module to the LGW construction wall

Figure 3 - Plywood and melamine foam (left), green wall vegetation (right)

In this study 3 sets of experiments have been performed: (i) 100mm melamine foam, (ii) 18 mm plywood wall, (iii) LGW with selection of four random plants and 10% moisture content. In each cases the test area was 2 m by 1.8 m, where the intensity probe was moved in the following XYZ positions:

H_{-15}	H_{-7}	H_0	H_{-7}	H_{-15}
C_{-15}	C_{-7}	C_0	C_{-7}	C_{-15}
L_{-15}	L_{-7}	L_0	L_{-7}	L_{-15}

Figure 4 - Intensity probe XYZ positions, for center (C_0) and 7 cm or 15 cm shift from high (H) to low (L) and left to right

Although the plant species selection was mostly random, it was ensured that the chosen morphology of each of the group of plants would differ. The morphology parameters included: leaf and stem length and width to give leaf area, leaf thickness, number of leafs / flowers per 10 cm^2 to calculate density and plant height as distance from the module until the plant edge to give volume.

3. DATA ANALYSIS

3.1 Acoustic Analysis

The signal used with the described experimental setup was a 10 sec sinusoidal sweep in the frequency range of 20 Hz - 20 kHz, but only100 - 5000 Hz used on reflection. 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 (10). The recorded signals were processed with Matlab® to obtain the acoustic instantaneous intensity using the same deconvolution method as detailed in Chapter 5 of (12). The application to deconvolution enabled 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

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

where $\Delta = 12$ mm and is the microphone separation in the intensity probe and ρ_0 is the equilibrium density of air. Intensity spectra of the sound waves were used to calculate the absorption coefficient which was determined as the following ratio

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

where $I_a(\omega)$ is the intensity spectrum reflected from an absorbing layer (e.g. melamine), $I_r(\omega)$ is the intensity spectrum reflected from the 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 wall is a perfectly reflecting surface, i.e.

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

in the case of the wall. In this calculation the intensity spectrum reflected from the 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.

3.2 Initial Experimental Results

The instantaneous intensity (Equation 1) recorded in the presence of the wall and in the presence of the 100 mm layer of melamine is presented in Figure 5. The presented wave samples are numerous repetitions of the same experiments before averaging. The reflective wave for the wall is 10 fold higher than for the melamine sample as expected.

Figure 6 demonstrates the reflected intensity spectrum (Equation 3) over 0 - 2000 Hz for the wall sample, *hedera helix* (ivy) and 100 mm melamine sample. The performance of ivy plant with 10% of moisture content is placed between the wall and melamine results which yield promising results as sound absorbent medium.

Figure 7 shows absorbtion coefficient (Equation 4) for melamine sample and four different plant type based LGW's. To remind, each plant type exhibited unique values in the morphological analysis. When examining these parameters all together and separately it was established that the leaf area density has a direct correlation with the obtained acoustic coefficient. The leaf area density for each of the plant types is also identified in Figure 7 and shows that the absorbtion coefficient improves as the leaf are density increases. In the case of *bergennia crassifolia* the acoustic absorbtion coefficient in the range of 1100 - 1600 Hz is very similar to the performance of the melamine foam.

4. DISCUSSION AND IMPROVEMENTS

The current XYZ method proved to be reliable at performing high quality repetitive measurements and could be set up at any location to perform the in-house or in-situ experiments under the conditions that would be comparable. It should be noted that the equipment should be placed as indicated in geometrical arrangement in Figure 1 (top). To further advance the set-up either laser or GPS system can be used to establish on-site repetitive co-ordinates in correlation to the wall of interest.

The presented experiments demonstrate the data from 15 intensity probe locations and in the future more co-ordinates will be examined. It is proposed to look at 50 - 150 mm steps in X and Y directions expanding to 1 m and 600 mm in Z direction to provide an understanding of the sound field that can be modelled.

To further prove the validity of the method and provide a range of data to inform the modelling exercise it is proposed to carry out systematic experiments with a large variety of plants and LGW systems.

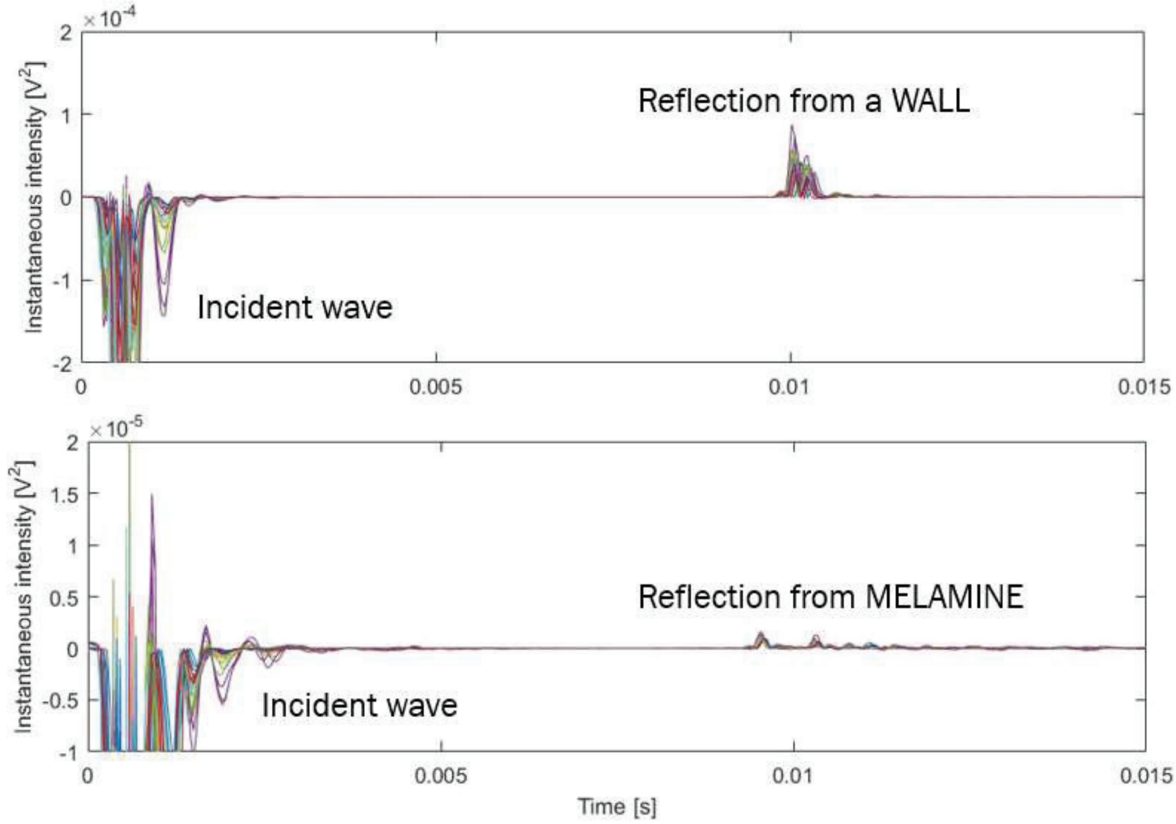


Figure 5 - The time histories for the instantaneous intensity recorded in the presence of the wall (top) and in the presence of the 100 mm layer of melamine (bottom)

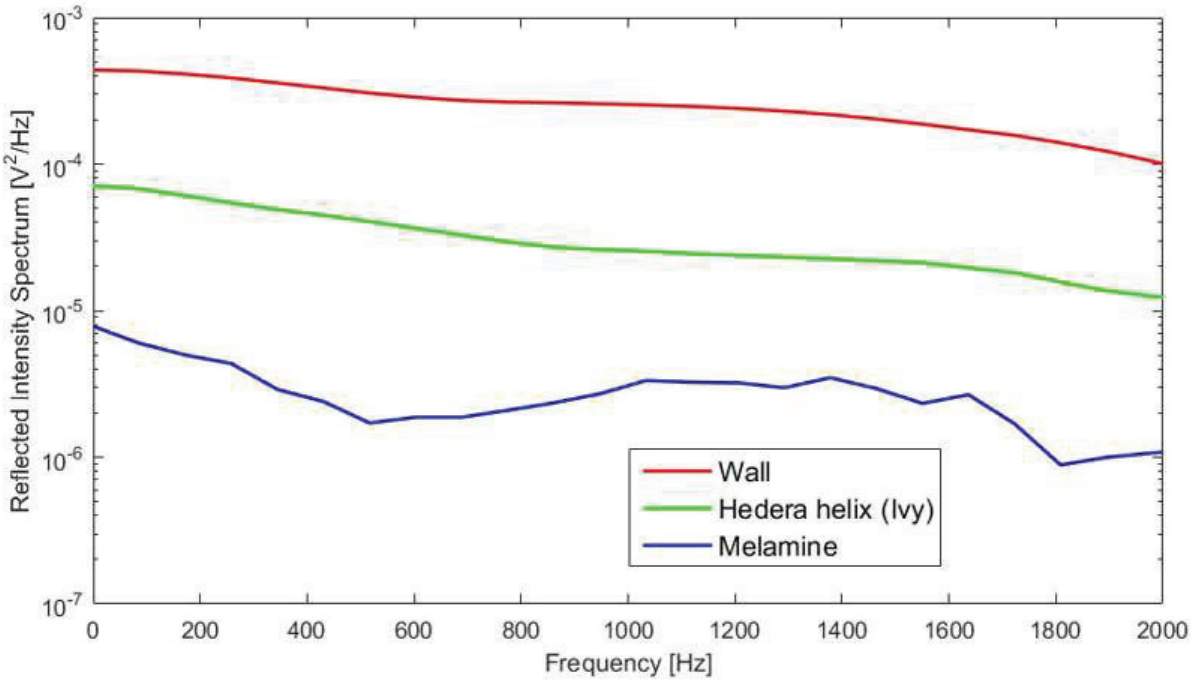


Figure 6 - Reflected intensity spectrum for the wall sample, ivy and melamine sample

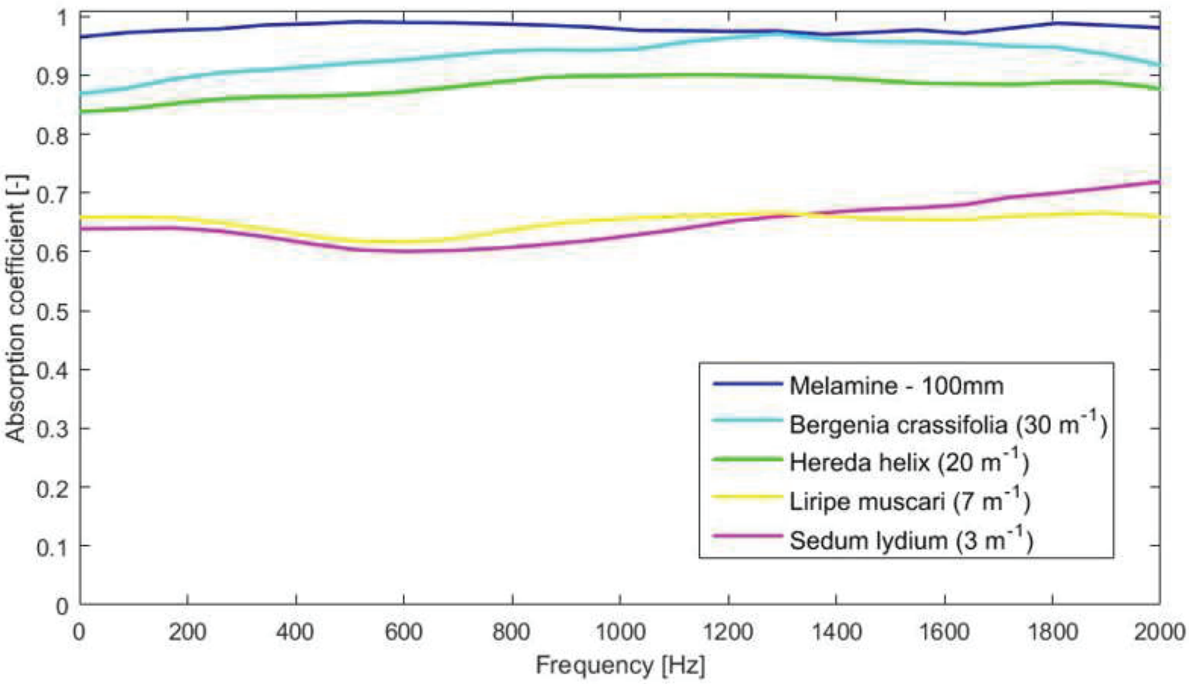


Figure 7 - Absorbtion coefficient for melamine sample and four LGW based on different plant types with indication of leaf area density

5. CONCLUSIONS

The newly proposed method is less prone to the unwanted ground and edge effects compared to standard methods (ISO354-2003 and CEN/TS 1793-5:2016) 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 and replicate. Automated XYZ instrumentation allows to easily perform a large number of measurements to capture the complexity of the acoustic field in space radiated by the parametric transducer and scattered by the green wall or other walls of interest.

The results confirm that the presence of plants with a relatively high leave area density can significantly enhance the absorption properties of a Living Green Wall system, particularly in the medium and high frequency range, i.e. above 1000 Hz.

The results also show that a compartmentalised Living 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. These resonances deserve a refined numerical modelling to understand better the in-situ acoustic performance of a complete Living Green Wall system.

There is also evidence that in some cases plants can scatter sound coherently resulting in an apparent decrease in the absorption coefficient. Refined numerical modelling of such phenomenon would be highly beneficial for future development of the theory.

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