ACOUSTICAL PROPERTIES OF LIVING PLANTS

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1 INTRODUCTION

There is evidence that vegetation can provide an improvement to the acoustic absorption properties of naturally occurring and man-made structures which are usually used in noise control applications (Canevaflor, 2011). However, research on acoustic effects of vegetation has been limited, and work has predominantly centered on the reduction of sound transmission through trees. Some work has also been carried out based on individual plants, especially in terms of the absorption by leaves. It has been shown that factors affecting the absorption include biomass, size and orientation of leaves[1-3]. Tests were made in the anechoic chambers and reverberation boxes, and a laser-Doppler–vibrometer system was used to measure the leaf vibration. However, the studies were not systematic in terms of plant species and the effect of plant leaves on the acoustic absorption coefficient. In the past, relatively little attention was paid to the effects of multiple reflections and interaction between the acoustic field around the plant and in the porous soil from which the plant is grown. This study looks at the influence of leaves on acoustic absorption of plants, porous soil and their combinations. The plants in this study were chosen to cover a range of possible leaf types, leaf sizes and foliage density. The acoustic transmission through a full-size living hedge is also studied in a separate field experiment.

2 EXPERIMENTAL METHODOLOGY

2.1 Acoustic absorption experiment

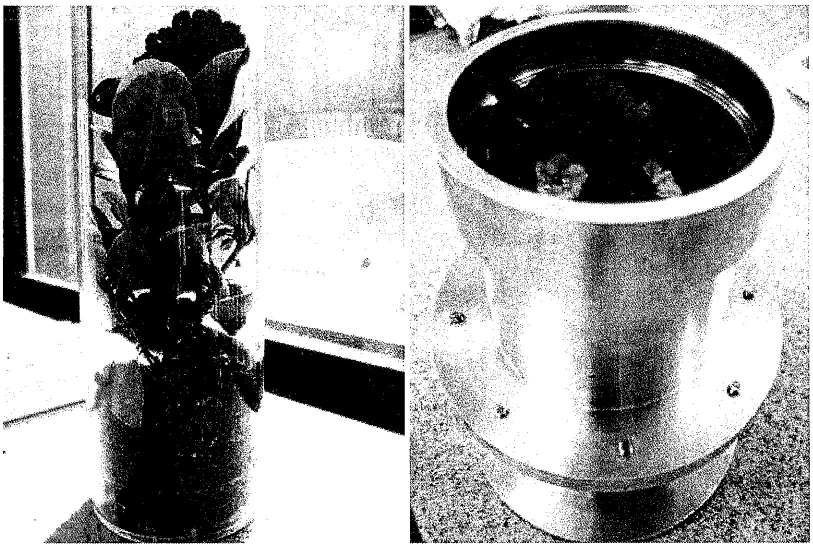
In order to investigate systematically the influence of leaves on the acoustic absorption of soils, species of various plants were acquired from a local garden centre. These plants were grown in a moist soil and presented in pots which were approximately 150mm diameter. The absorption coefficient of the plant specimen was measured in a standard Bruel and Kjaer impedance tube with the internal diameter of 100mm using the method described in ref. [4]. The spacing between the two microphones was 100mm which enabled to determine the acoustic absorption spectra in the frequency range between 50 and 1600 Hz. Because of the random geometry of a living plant specimen it was impossible to determine the exact position of the reference plane from which the distance, x_1 to the microphones can be accurately measured. This is illustrated in Figure 1 (a) which shows the arrangement of a plant specimen in a 100mm transparent sample holder. As a result, it was possible to measure directly only the absolute value of the acoustic reflection coefficient, $|r|$ which is given by[4]

$$r = |r|e^{i\varphi} = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2ik_0 x_1} \quad (1)$$

where H_{12} is the measured transfer function between the two microphones, H_I is the transfer function for the incidence wave, H_R is the transfer function for reflected wave, x_1 is the distance between the sample and the further microphone location and k_0 is the wavenumber. Because of the ambiguity in the position of the reference place it was impossible to determine the term, $i\varphi$, in exp. (1) which is needed to calculate the complex acoustic surface impedance (exp. (19) in ref. [4]) of the plant specimen. Therefore, only acoustic absorption coefficient data are presented in this work which were calculated according to the following expression

$$\alpha = 1 - |r|^2 . \quad (2)$$

The plant specimen was placed in a 200mm long sample holder as shown in Figure 1 (b). In some experiments a 400mm long sample holder was used to allow for longer specimens to be tested. In this arrangement the distance between the top layer of soil and microphone 1 was kept constant and equal (in the case of the 200mm long container) to 250-300mm which was generally sufficient to accommodate the leaves of the studied plant and soil specimens.



(a) (b)

Figure 1. Plant arrangement in sample holders (a) transparent (100mm diameter) showing random geometry, (b) plant inside impedance tube holder (100mm diameter).

In order to understand better the relationship between an apparent change in the absorption coefficient spectrum of soil which can be caused by the presence of foliage we examined four plant species with a relatively broad range of leaf characteristics and common enough to be found in gardens and on living walls. These plants are: (a) Pieris Japonica, (b) Green Ivy, (c) Primrose, and (d) Geranium. The following plant leaf characteristics were determined: (i) mean thickness of a single leaf; (ii) mean weight of a single leaf; (iii) mean area of a single leaf; (iv) number of leaves on the plant; (v) height of the plant; (vi) equivalent volume occupied by the plant. These characteristics were then used to calculate: (i) the total area of leaves on the plant; (ii) surface density of a leaf; (iii) total weight of leaves on the plant; (iv) leaf area per unit volume. These characteristics are summarised in Table 1.

In these experiments the absorption coefficient of a plant was measured in the absence and presence of soil so that the effect of the acoustic interaction between the plant and soil could be quantified. The soil specimen used in this experiment was a 100mm thick, hard backed layer composed of ordinary, clay-based soil with approximately 1660 kg/m^3 density. The acoustical properties of this soil were predicted using the model detailed in ref. [5] in which the following non-acoustical parameters were assumed: flow resistivity σ = 200 kPa s m^{-2}, porosity ϕ=0.23, tortuosity α_∞=1.0 and standard deviation in the pore size $\partial\phi$=0.01. The results of these experiments are shown in Figure 2 which presents the absorption coefficient spectra of the plant without the soil specimen, soil specimen with the plant and soil specimen without the plant. The shaded regions in these graphs show the range of the reproducibility of these experiments. The data presented in this figure suggest that different plant species have markedly different effect on the absorption coefficient of soils. This effect needs to be quantified and the data shown in Figure 2 were used to calculate the mean change in the absorption coefficient caused by the presence of foliage above the soil specimen. The mean change in the absorption coefficient was calculated from the following equation

$$\langle\alpha\rangle = \sum_{n=1}^{N} \frac{\alpha_p(f_n) - \alpha_s(f_n)}{N}, \qquad (3)$$

where $\alpha_p(f_n)$ is the absorption coefficient of the plant with soil, $\alpha_s(f_n)$ is the absorption coefficient of soil without the plant, f_n is the n-th frequency in the absorption coefficient spectra and N is the total number of frequency points in the adopted frequency range. The maximum change in the absorption coefficient and the frequency at which this change has occurred were also determined.

Plant species	**Average thickness of single leaf (mm)**	**Average weight of single leaf (g)**	**Average area of single leaf (m^2)**	**Number of leaves on plant**	**Total area of leaves on plant (m^2)**	**Leaf surface density (kg/m^2)**	**Height of plant from surface of soil (m)**	**Equivalent volume occupied by plant (m^3)**
Pieris Japonica	0.42	0.26	0.00068	272	0.185	0.38	0.26	0.002
Green Ivy	0.26	0.12	0.00062	115	0.071	0.19	0.08	0.0006
Primrose	0.49	2.88	0.006	33	0.198	0.48	0.18	0.0014
Geranium	0.68	1.04	0.0023	42	0.097	0.45	0.13	0.001

Table 1. Parameters of plant leaf specimens used in the acoustic absorption experiment.

The obtained results enable us to draw several conclusions. Firstly, there is a clear dependence of the frequency at which the maximum change in the absorption coefficient takes place on the mean leaf area. This finding implies that the leaves in a plant vibrate and/or scatter sound stronger at specific frequencies. At these frequencies sound scattering and damping effects must be sufficiently pronounced to explain the observed maximum increase in the absorption coefficient spectra. Secondly, there is a weak, but consistent dependence of the mean change in the absorption coefficient on the number of leaves present on a plant. Apparently, the more leaves are on the plant, the stronger are the scattering and vibration damping effects contributing to the observed increase in the acoustic absorption coefficient. Thirdly, there is a weak dependence of the change in the absorption coefficient on the leaf area. Here we observe a general trend whereby the mean change in the absorption coefficient is greater for those plants which appear to have a larger leaf area (primrose plant). This change can be approximated with the following empirical equation

$$<\alpha> = 0.20\ln s + 1.49, \qquad (4)$$

where s is the mean leaf area in m^2. Fourthly, the mean change in the absorption coefficient can be negative for plants with lighter leaves and smaller surface area signifying the fact that the presence of foliage in some cases can decreases the overall performance of the plant soil system.

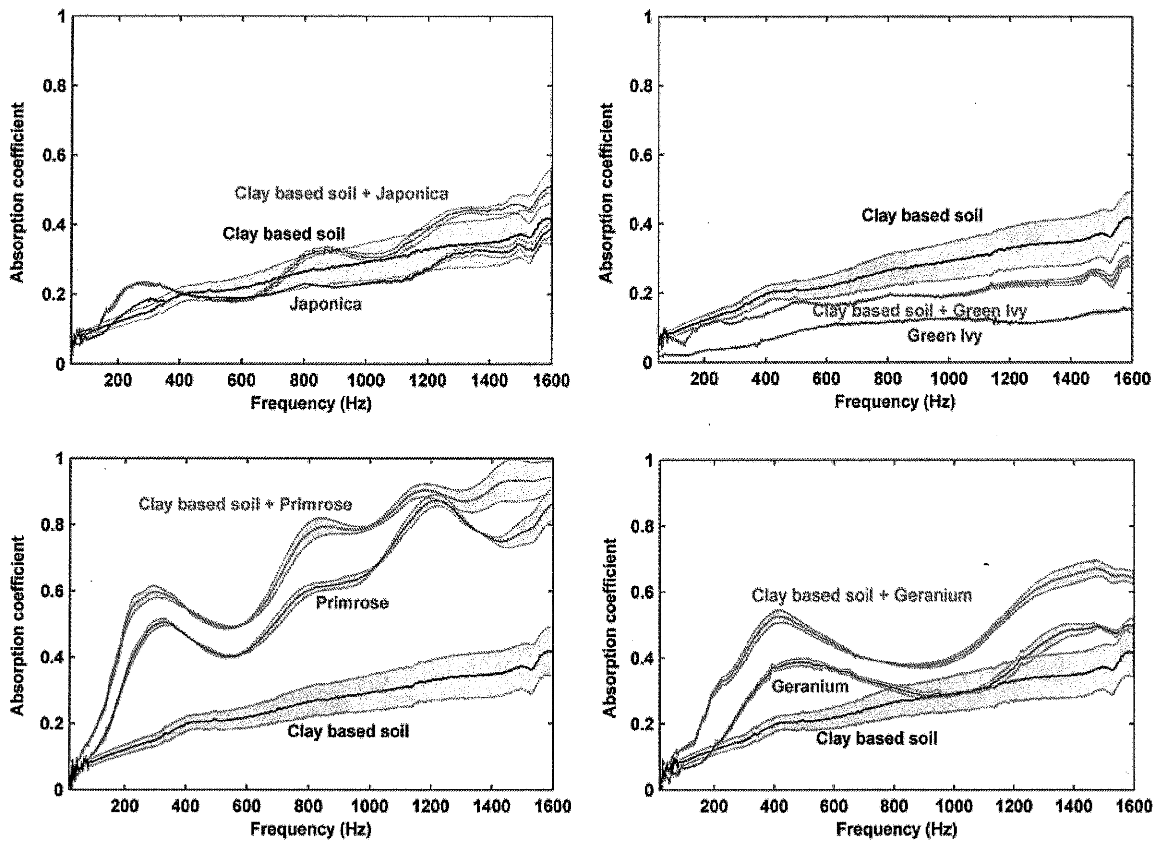


Figure 2. Comparison of absorption coefficient of the four plants in presence and absence of soil.

Primrose can be singled out as the best acoustic absorber out of all the plants studied in this work. Primrose plant on top of clay based soil shows a 48% increase in acoustic absorption averaged over the whole frequency range. Since primrose displays substantial surface per unit of soil area, losses due to viscous and thermal mechanisms become more important. Certainly, some of the energy incident on a leaf is reflected and some is transmitted, with the relative amounts of each depending primarily on the angle of incidence of the sound wave to the leaf and the surface area density of the leaf. Plants with small leaf area for example Pieris Japonica and Green Ivy (see Table 1) can have rather negative effect on the overall acoustic absorption of soil. This can be related to shielding of soil from the incident sound and not contributing enough to the acoustic absorption because of their relatively small scattering cross section and relatively high frequency at which the leaf resonates.

2.2 Acoustic transmission loss experiment

This section presents experimental evidence that a hedge with large leaves can exhibit a high transmission loss which is comparable to that expected from a man-made noise barrier. In order to illustrate that relatively thin, but dense plants are able to provide a considerable degree of acoustic attenuation an experiment was carried out on a laurel hedge with the leaf area per unit volume of 15 m^{-1}. The hedge had approximately 320 leaves per m^3 and the average leaf area was around 0.006 m^2. The average length of the leaves was approximately 160mm and the average width was 60mm. Figure 3 illustrates the setup used in this experiment.

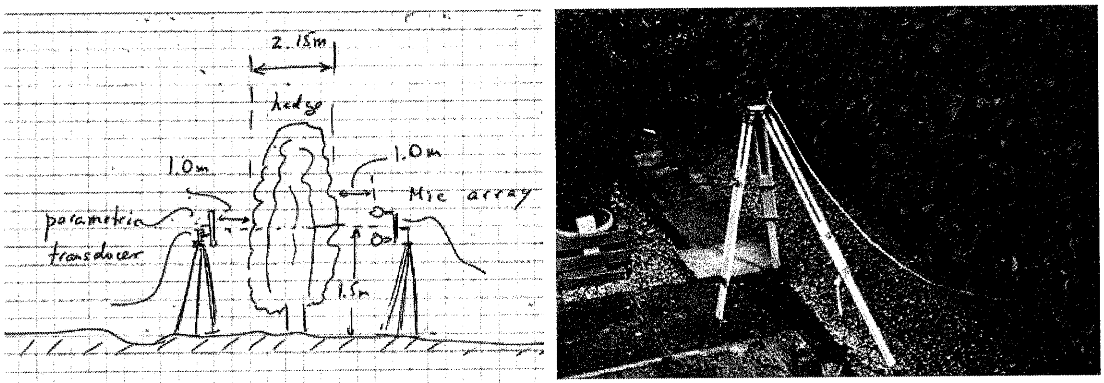


Figure 3. Schematic presentation of the hedge transmission experiment (left) and photograph of the parametric speaker used in the experiment (right).

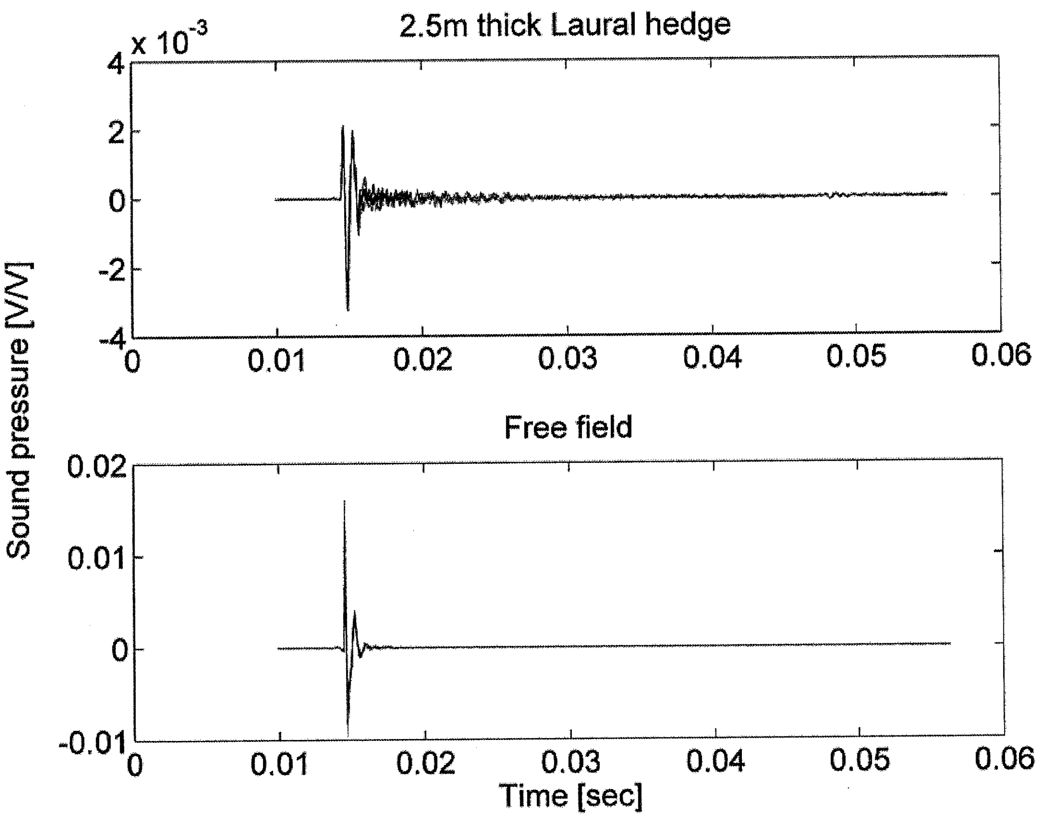


Figure 4. Examples of the impulse response recorded on the 4-microphone array in the presence of the laural hedge (top) and in the free field(bottom).

The dimensions of the hedge were: 3m high, 2.15m deep and 25m long. The heights of the source and receiver were fixed at 1.5m. The source of sound used in this experiment was a sine sweep produced from a directional, parametric speaker of type HSS 3000 the directivity of which was ± 10°. This type of speaker was selected to reduce the effect of ground reflections and the diffraction effect on the hedge top. The signal used in this experiment was a 50 – 16000 Hz sinusoidal sweep which was amplified using a HSS 3000 amplifier. The speaker was situated on one side of the hedge, 1.5m away from the hedge face and perpendicular to it. An L-shape array of four 1/2" Bruel and Kjear microphones (type 4188) which was installed on a tripod on the other side of the hedge. The microphones were spaced at 100mm to allow for the uncertainties in the microphone positoning. The sine sweep was generated and amplified signals were captured using a Marc-8 sound card installed in a PC. WinMLS software was used to record the measurements and to obtain the impulse response via the deconvolution theorem. The microphone array was moved within a 1m x 1m plane to take into account the fine directivity of source and scattering effects by the hedge. The microphone signals were then Fourier transformed and combined in terms of the acoustic intensity spectra to obtain the mean sound pressure level spectrum. The same experiment was repeated in the free field conditions to obtain the reference sound pressure level spectrum. The attenuation caused by the hedge was calculated as

$$A(f) = 10\log_{10}\left\{\sum_{n=1}^{N} 10^{L_n^{(F)}/10} - \sum_{n=1}^{N} 10^{L_n^{(H)}/10}\right\} \qquad (5)$$

where $L_n^{(F)}$ is the sound pressure level spectra measured in the free field, $L_n^{(H)}$ is the sound pressure level spectra measured in the presence of the hedge and N is the total number of signals recorded though the 4-microphone array and at all the positions to which the microphone array was moved.

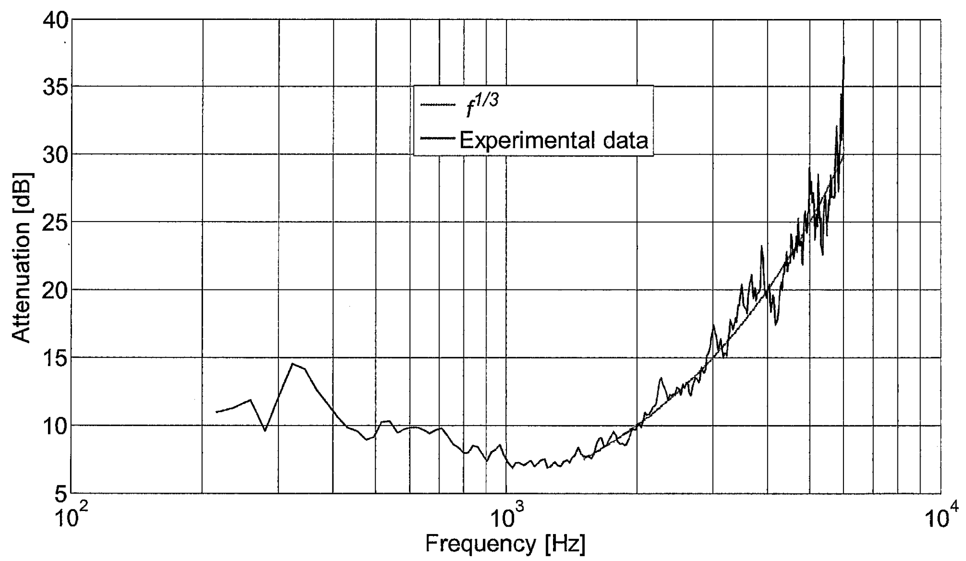


Figure 5. The acoustic attenuation caused by the presence of a 2.15m thick laurel hedge.

Figure 4 presents an example of the impulse response recorded on the 4-microphone array in the presence and absence of the hedge. The presence of the hedge causes a noticeable reduction in the maximum amplitude of the impulse response and scattering. The latter is clearly visible in the prolonged tail of the impulse response of the signal propagated through the hedge (top of Figure 4).

The measured acoustic attenuation is shown in Figure 5. Aylor[6] suggested that when the length of vegetative canopy is much greater than the wavelength, then the attenuation can be approximated with the $A(f) \sim \sqrt{f}$ dependence. The result obtained in this work demonstrates that at the frequency around350 Hz the attenuation caused by the hedge can reach approximately 14 dB and it decreases to approximately 7 dB as the frequency of sound increases to 1000 Hz. Beyond this frequency the wavelength becomes comparable with the size of the leaf and the frequency behaviour of the attenuation obeys the following law

$$A(f) \sim \sqrt[3]{f}\text{, dB.} \qquad (6)$$

This cubic root of frequency behaviour was observed by Shamanaeva[7] and Pan[8] in the case of sound propagation through coherent turbulent structures. This enables a theory based on the concept of a spatial sinusoidal diffraction grating to be adopted and developed to explain the attenuation spectrum obseved in the hedge experiment.

3 CONCLUSIONS

The results obtained from this work show that absorption coefficient of plants can be considerable and it is affected by the presence of soil. Specifically: (i) there is a clear dependence of the frequency at which the maximum change in the absorption coefficient takes place on the mean leaf area; (ii) there is consistent dependence of the absorption coefficient on the mean leaf area; (iii) the mean change in the absorption coefficient can be negative for plants with lighter leaves and smaller surface area signifying the fact that the presence of foliage in some cases can decreases the overall performance of the plant soil system.

This work also reported the results of outdoor measurements which were carried out using a highly directional parametric acoustic transducer and a 2-D array of microphones. The purpose of these measurements was to determine the frequency and angular dependence of the acoustic attenuation caused by a hedge. The experimental setup and procedure used in this work enabled us to simulate an approximately plane wave propagation regime and to reduce considerably the effect of ground on the recorded transmission loss data. The results show that a 2.15m thick hedge can provide a considerable (up to 20 dB) transmission loss which is comparable to that expected from an artificial noise barrier structure. It is shown that the attenuation obeys the $A(f) \sim \sqrt[3]{f}$ at the frquencies at which the wavelengths becomes comparable or smaller than the characteristic size of the leaf.

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