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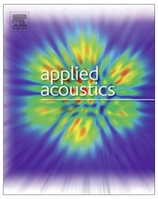

An application of normal mode decomposition to measure the acoustical properties of low growing plants in a broad frequency range

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ABSTRACT

This paper presents a new application of the normal mode decomposition to measure the reflection and absorption coefficients of a low growing living plant in a large 300 × 300 mm impedance tube. In this way the higher frequency limit can be extended by a factor of 3 in comparison to that suggested by the standard ISO 10534-2 method for this type of an impedance tube. The adopted method (Prisutova et al., 2014) is based on minimising the difference between the spatial Fourier transform of the measured sound pressure at a range of closely spaced positions along the impedance tube and the predicted transform arising from the normal mode decomposition method. The angular and frequency dependent complex reflection coefficients for the first 5 normal modes are recovered. The acoustical properties of three plants specimen, *Pelargonium hortorum*, *Begonia benariensis* and *Hedera helix*, are measured with the adopted method. These properties are related to the plant morphology through an equivalent fluid model. It is shown that in some cases the predicted and measured data are in close agreement. However, there are cases when the agreement between these data is poor. The possible reasons for this discrepancy are proposed and discussed. This work paves the way for a better understanding of the relations between the plant morphology and its acoustical properties.

1. Introduction

Impedance tubes are used widely to determine the ability of materials to absorb sound. The standard procedure for the determination of the absorption coefficient of materials is detailed in the ISO 10534-2 [1]. Porous media are a mostly well understood class of acoustic materials and the relations between the porous microstructure and its acoustical properties are generally well known [2]. However, the acoustical properties of living plants are poorly understood. This information is desirable as 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, which makes them attractive for use in noise control elements [3].

The fact that living plants have useful acoustical properties has been known for a while. The original work by Aylor [4] based on field experiments suggested that the ability of crops to attenuate sound waves relates to its leaf area density. Wong et al. [5] conducted the experiments with different vertical greenery systems, both in field conditions and a reverberation room. They concluded that vertical greenery positively affects the absorption of sound, but more experiments needed to be done on actual building facades for a better understanding of green acoustic insulations. A more recent laboratory work [6] showed that the acoustical properties of low growing plants can be predicted by an equivalent fluid model which is typically used to describe the acoustic behaviour of porous media at low frequencies. In this model the effective flow resistivity was related directly to the leaf area density whereas the tortuosity was related to the dominant angle of leaf orientation [6].

The evidence assembled so far suggests that three main mechanisms are responsible for the absorption of sound by living plants. In the lower frequency range (e.g. below 100–200 Hz) the thermal dissipation mechanisms are important [2]. In the low and medium frequency (e.g. below 1–2 kHz) where the acoustic wavelength is still much larger that the characteristic leaf dimension (e.g. 15–250 mm for typical plants [7]) the viscous dissipation is the prime absorption mechanism [6,4]. 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

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leaf vibration and multiple scattering begin to contribute to the dissipation of the energy in the incident sound wave [7,4].

There are several reasons by which it is difficult to generalise the results of previous studies to a wider range of low growing plants. A main 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 representatively range of acoustic frequencies and angles of incidence. In the field and reverberation chamber experiments which have been reported so far it was difficult if not impossible to deconvolve the acoustic ground effect from the effect of the plant biomass. The reverberation chamber experiments on plants reported so far presented data on the random incident absorption coefficient. Testing large samples of living plants in a laboratory in accordance with the standard ISO 354 method [8] is expensive. It is difficult or impossible to develop from ISO 354 data a general theoretical model for plant absorption which takes into account some morphological characteristics of plants, acoustic frequency and angle of sound wave incidence. Finally, published laboratory work on plants (e.g. by [6]) obtained through a controlled experiment in a standard impedance tube presents data for the normal incidence plane wave absorption coefficient determined for a relative small sample area and in a rather limited frequency range.

In this sense, an impedance tube experiment is very attractive. It offers the opportunity to measure the acoustical properties of a plant with great degree of control. However, plants occupy a volume which is greater than that permitted by the cross-section of a standard impedance tube. Therefore, it is of direct interest to be able to measure the acoustical properties of a plant specimen with representative dimensions. This paper attempts to address this issue through the application of an alternative impedance tube method [9] to measure the acoustic absorption of a representatively large specimen of a living plant in a relatively large impedance tube. In this way, the acoustical reflection and absorption coefficient of this plant can be measured in the frequency range well beyond the first cross-sectional resonance and a range of angles of incidence, as these depend on frequency for higher order modes. An equivalent fluid model is then used together with the independently measured plant morphological data to explain the observed absorption behaviour.

2. Experimental methodology

The reported experiments were carried out using the large impedance tube facilities available at the Laboratoire d'Acoustique de l'Université du Maine (LAUM). A sketch of an experimental setup is presented in Fig. 1. It consisted of a square tube which is 4.15 m long and of 300 × 300 mm cross-section at the end of which a plant specimen was installed. The walls of the tube were constructed from 38 mm thick fibreboard panels which were varnished to ensure that they are reflective. One end of the tube was terminated with a 30 mm thick metal lid and at the opposite end three loudspeakers were installed and operated in parallel. The coordinates of their centres were (50 mm, 50 mm), (50 mm, 150 mm) and (150 mm, 150 mm). Such distribution enabled us to excite the maximum number of propagating modes in the adopted frequency range. The signal generated by the three speakers was recorded by a single 1/4" B&K microphone which simulated the axial microphone array in order to avoid amplitude and phase mismatch problems. The movement of the microphone was controlled by a robotic arm. The microphone was placed in the corner of the pipe's cross-Section 5 mm away from the wall where the amplitude of all the propagating modes was maximum. The pressure readings were taken at 52 axial positions, distributed with a 40 mm step, with the first reading taken at the interface between a plant and air. As living plants have an uneven surface, the interface was assumed to be at the edge of a leaf farthest from the roots. The data were acquired by a Stanford Research Systems SR785 signal analyser which Fourier transformed the sound pressure signals and stored the pressure spectra in the text file format. According to the ISO 10534-2 [1] the maximum frequency of this tube at $T = 20\,^{\circ}\mathrm{C}$ is $f_u = 0.5c/d = 572$ Hz, where c is the sound speed in air and $d = 0.3$ m is the tube dimension. In our work we extended this range to 1800 Hz by using a step-by-step 50–1800 Hz sine sweep and the method detailed in [9]. We recalled this method in Appendix A for the sake of completeness. In accordance with this method the modal reflection coefficients were determined by solving the optimisation problem (Eq. (A.4)). The absorption coefficients were then calculated either using the energy ratio (Eq. (A.7)) or discrete sound intensity data (Eq. (A.8)) which were determined with the array of equidistantly spaced microphones. The two methods we used to calculate the absorption coefficient are essentially the same. The only difference is that the former method is continuous, whereas the latter is discrete so that the intensity fit better because of a more accurate determination of the cut-off frequency.

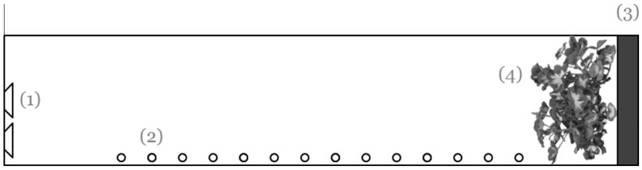

Fig. 1. A schematic illustration of the experimental setup: (1) loudspeakers, (2) simulated horizontal microphone array, (3) metal lid, (4) plant specimen.

3. Plant analysis

For the experiments described in this paper, three plant species were used: garden geranium (*Pelargonium hortorum*), begonia (*Begonia benariensis*) and ivy (*Hedera helix*). These plants were purchased from a local garden centre in Le Mans (France). Fig. 2 shows the photographs of these plants in the pots whereas Fig. 3 illustrates the shape and dimensions of their leaves. For the reported experiments plant stems with the foliage were cut off from their roots and placed in the impedance tube with stems parallel (horizontal plant orientation) to the direction of sound propagation. The following morphological characteristics of these plants were measured: mean weight of a single leaf (w_f), mean thickness of a single leaf (h_f), mean area of a single leaf (s_f), number of leaves on a plant (n_f), estimated height of a plant (h_p), and dominant angle of leaf orientation (θ_f). Their values are presented in Table 1. Twenty-five leaves from the geranium plants and twenty leaves from the ficus plants were randomly chosen for the determination of plant characteristics. The weight of leaves was measured using electronic scales the precision of which was ±0.005 g. The thickness was estimated with the electronic caliper which is capable of measuring distance to ±0.01 mm. For the leaf area estimation, a picture of a leaf framed by rulers was taken as shown in Fig. 3. Then the picture was imported to Adobe Photoshop software and the amount of pixels in the leaf was determined. Subsequently the leaf area was calculated using the following formula:

$$s_f = p_f p_s^{-1} s_s \tag{1}$$

where p_f is the number of pixels in a single leaf, p_s is the number of pixels in a reference square and s_s is the area of a reference square. The leaf orientation angles were also estimated using digital images of plants and the screen protractor tool. The above described

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