The frequency and angular dependence of the absorption coefficient of common types of living plants

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ABSTRACT

The frequency and angular dependence of the absorption coefficient of specimens of several types of plants used in living walls and noise barriers is investigated. The reported data are obtained by placing the specimens in a large impedance tube which frequency range has been extended significantly beyond the frequency of the plane wave regime. The multi-modal sound pressure field in the tube is measured with a microphone array. A theoretical model is adopted to determine the reflection coefficients for the individual modes. This information is used to estimate the frequency and angular dependent absorption coefficient for the plant specimens. The absorption coefficient data are compared against the predictions made with an equivalent fluid model which is based on the leaf area density and dominant angle of leaf orientation.

Keywords: Absorption, living plants, impedance tube I-INCE Classification of Subjects Number(s): 35.2, 72.7, 26.1.

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 frequency range (e.g. below 100-200 Hz) the thermal dissipation mechanisms are important [5]. 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 [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 representatively 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. The difficulty in measuring the absorption of plants in the laboratory is that the standard ISO 354 test [7] requires 10 m^2 area of living plant specimen which is difficult and expensive to resource. The alternative, ISO 10534-2 test [8] does not allow for a large enough living plant specimen to be tested. The difficulty of measuring the absorption

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of 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 aim of this work is to apply a new laboratory method which is able to measure the acoustic absorption by large enough living plant specimens in a broad enough frequency range which is representative of the spectrum of noise emitted by traffic. This laboratory method has recently been developed to measure the absorption of large material specimens as it enables us to extend the frequency range of the standard impedance tube method by a factor of 3 [9].

Table 1. The morphological characteristics of the two plants.

	Geranium	**Begonia**
Mean leaf weight (g)	0.7004	1.01
Mean leaf thickness (mm)	0.572	0.4608
Mean leaf area (m)	0.00213	0.00317
Number of plants present in tube	4	5
Mean orientation angle (degrees)	31.97	35.89
Mean plant height (m)	0.35	0.18
Plant volume (m^3)	0.007875	0.003241
Number of leaves	182	193
Foliage area (m^2)	0.0969	0.1224
Foliage volume (m^3)	$5.5435\ 10^{-5}$	$5.6384\ 10^{-5}$
Leaf area density (m^{-1})	12.307	37.766
Porosity	0.993	0.983
Tortuosity	1.512	1.568

2. EXPERIMENTAL PROCEDURE

2.1 Impedance tube setup

The reported experiments were carried out using the 4.15 m long impedance tube in the LAUM laboratory at the l’Universit´e du Maine (France). The impedance tube is a square cross-section of 300 mm x 300 mm constructed from 38 mm thick panels of medium density fibreboard which are varnished to ensure that the walls are perfectly reflective so that they do not contribute noticeably to the level of air attenuation expected for this tube. Figure 1 shows schematically the impedance tube setup. The unique feature of the experimental setup is that the measurement procedure is based on traversing a roving microphone and taking sound pressure measurements at 51 axial positions in the frequency range of 50 – 1800 Hz, effectively extending the maximum frequency recommended in the ISO 10534-2 [8] by a factor of 3. The sound pressure spectra measured at these 51 positions are used in the spatial Fourier transform the results of which enable us to determine the complex frequency and angular dependent reflection coefficients for the first 5 normal modes which were excited in the tube. The full details of the experimental method and data analysis can be found in ref. [9].

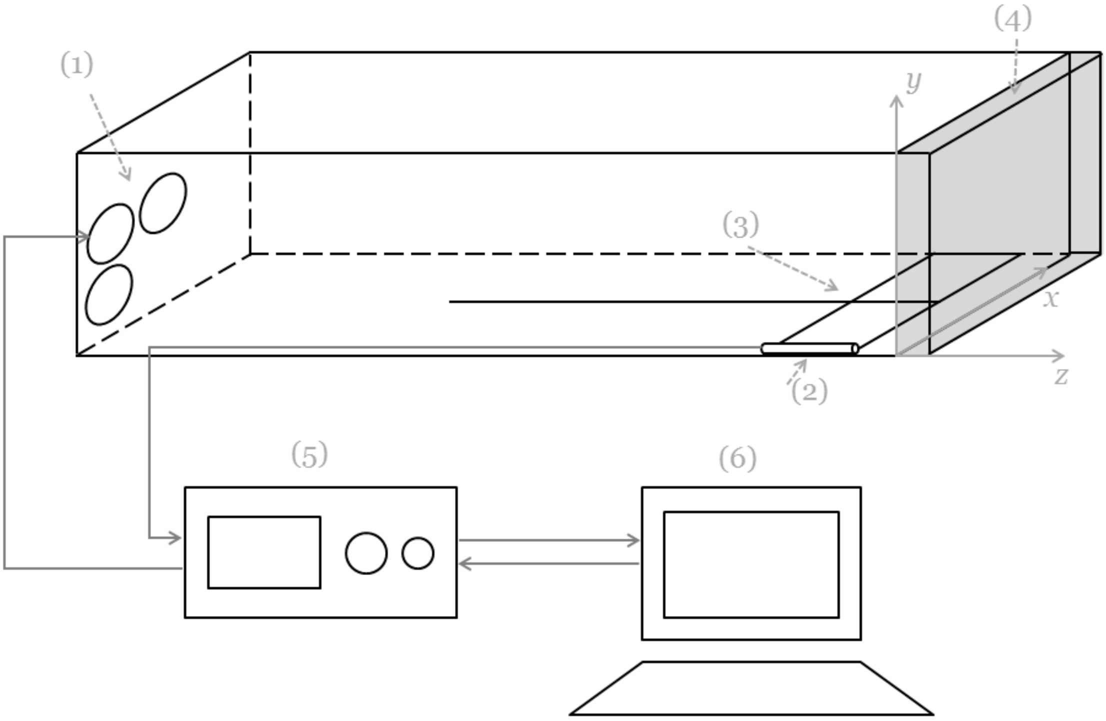

Figure 1. A schematic illustration of the impedance tube setup: (1) loudspeakers; (2) microphone; (3) microphone frame designed to maintain the microphone's position in a corner of tube; (4) living plant specimen; (5) signal analyser; (6) PC.

2.2 Living plant characteristics

Two types of plants were tested in the impedance tube: begonia (*Begonia semperflorens*) and geranium (*Pelargonium hortorum*). Photographs of these plants are shown in Figure 2. Table 1 lists the values of key morphological properties of these two plants and related non-acoustical properties needed in the modelling process. These characteristics were estimated from the image analysis as detailed in ref. [2].

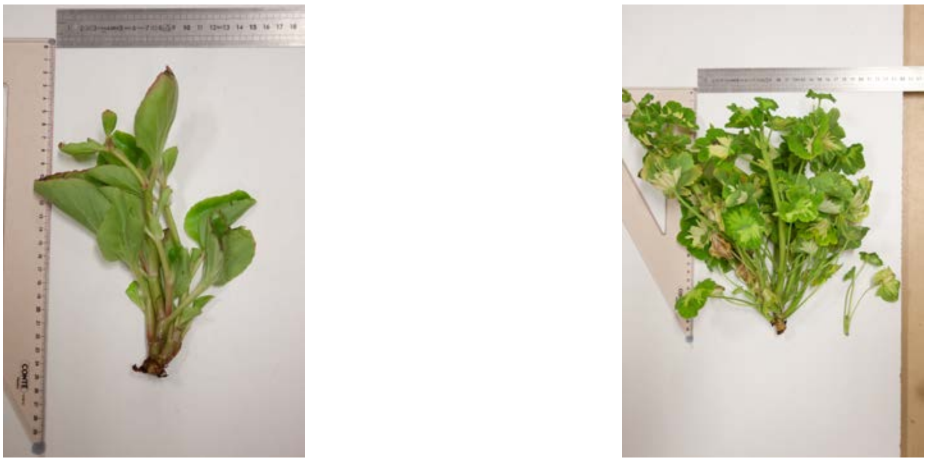

Figure 2. Photographs of *Begonia semperflorens* (left) and *Pelargonium hortorum* (right) plants used in the impedance tube experiments.

3. MODELLING OF THE ABSORPTION BY PLANTS

The study reported in ref. [2] suggests that the absorption coefficient of a plant can be predicted using an equivalent fluid model developed for sound propagation in porous media. It can be shown that the equivalent flow resistivity in this model relates to the leaf area density, A_v, e.g. [2]

$$\log_{10}\sigma = 0.067A_v + 0.746 \tag{1}$$

whereas the tortuosity relates to the difference between the sound wave incidence angle and dominant angle of leaf orientation, φ, e.g. [2]

$$\alpha_\infty = \cos\varphi/2 + 2\sin\varphi/2\,. \tag{2}$$

The porosity, effective flow resistivity and tortuosity can be used to predict the angular-dependent acoustic reflection coefficient for each of the normal mode excited in the tube using the model proposed by Miki [10]. The equation for the modal reflection coefficient is

$$R_{mn}(\omega) = \frac{Z_s(\omega)\cos\theta_{mn} - \rho_0 c_0}{Z_s(\omega)\cos\theta_{mn} + \rho_0 c_0} \tag{3}$$

where $Z_s(\omega)$ is the frequency and angular dependent surface impedance of the equivalent layer occupied by the plant, θ_{mn} is the angle at which the normal mode (*mn*) is incident on the plant specimen in the tube, ρ_0 is the air density and c_0 is the sound speed in air. The total absorption coefficient is calculated from the following equation

$$\alpha_{total} = 1 - \frac{\sum\limits_{m,n} \frac{\mathrm{Re}(k_{mn})}{\gamma_m\gamma_n}\left|A_{mn}R_{mn}\right|^2}{\sum\limits_{m,n} \frac{\mathrm{Re}(k_{mn})}{\gamma_m\gamma_n}\left|A_{mn}\right|^2} \tag{4}$$

where k_{mn} are the modal wavenumbers, $\gamma_m = 1$ if $m = 0$ and $\gamma_m = 2$ if $m > 0$, and A_{mn} are the modal excitation coefficients.

4. RESULTS

The measured and predicted absolute values of the modal reflection coefficient for the two plants as a function of the frequency and angle are shown in Figure 3. Figure 4 shows the measured and predicted total absorption coefficients for these two plants. The mean error, ε, between the measured and predicted data is shown on each of these graphs.

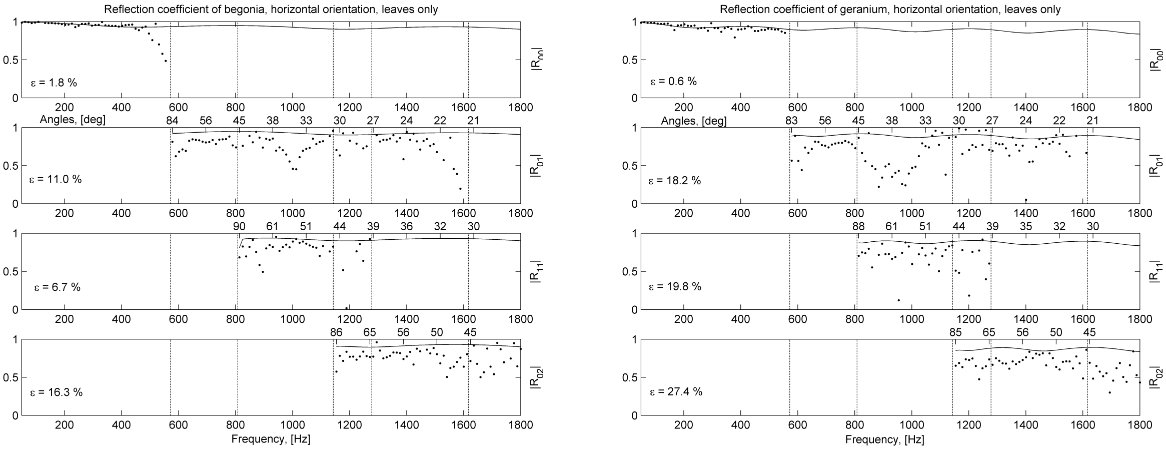

Figure 3. The modal reflection coefficients of *Begonia semperflorens* (left) and *Pelargonium hortorum* (right) as a function of the frequency and angle of incidence.

The results shown in Figure 3 suggest that the model predicts very accurately the reflection coefficient for the fundamental (00) mode which is incident on the plant at the normal angle of incidence. The model generally underpredicts the reflection coefficient of the plant above the first cross-sectional resonance of 572 Hz. Above this frequency the behavior of the modal reflection coefficients is much more complex than that predicted by the model. The is an apparent decrease in the value of the absolute reflection coefficient R_{01} near the angle of incidence $33 < \theta_{01} < 38$ in the case of begonia and $33 < \theta_{01} < 45$ in the case of geranium plant. This effect can relate to the apparent increase in the effective value of the plant tortuosity which is given by equation (2).

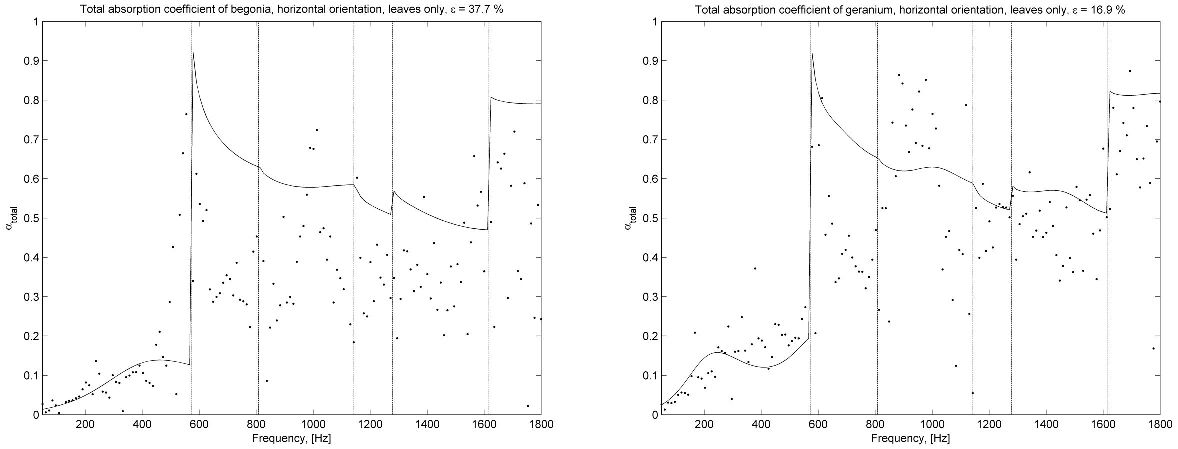

Figure 4. The total absorption coefficient of *Begonia semperflorens* (left) and *Pelargonium hortorum* (right).

Figure 4 shows that there is a strong scattering in the total absorption coefficient data for the two plants beyond the frequency of the first cross-sectional resonance. The model predicts accurately the measured spectrum of the total absorption coefficient up to this frequency. Beyond this frequency the model overestimates consistently the absorption coefficient spectrum except in the 800 – 1000 Hz range which is dominated by the behavior of the (01) mode which seems to be strongly absorbed (see Figure 3).

5. CONCLUSIONS

This work has been concerned with a new laboratory method to measure the acoustical properties of relatively large specimens of low growing plants. For this purpose, the maximum frequency of a large 300 mm x 300 mm impedance tube has been extended using the method detailed in ref. [9]. It has been shown that this method is capable of measuring the angular-dependent acoustic reflection coefficient spectra of two types of plant over the frequency range which extends 3 fold beyond that suggested in ref. [8]. It has been shown that the equivalent fluid model can be used to predict accurately the reflection coefficient spectra below the frequency of the first cross-sectional resonance. This model is based on the measured data for the leaf area density and dominant angle of leaf orientation. Above this frequency the model consistently underpredicts the measured reflection coefficient spectra. It can be suggested that the model needs refinement to include the multiple scattering phenomena as suggested in ref. [3]

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