LABORATORY MEASUREMENT OF THE ACOUSTIC ABSORPTION COEFFICIENT OF LIVING PLANTS VIA MODAL DISPERSION

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This paper presents a new method to obtain the complex reflection and absorption coefficients of living plants above the first cut-on frequency using a large impedance tube. The novelty of this method is that it allows the modal reflection and absorption coefficients to be recovered with a single microphone which is traversed in the tube. In this way, large plant specimens can be tested with the proposed method in the frequency range that extends above the first cut-on frequency of the tube. The method is based on sound pressure measurements at several locations along the axial direction of the tube. These frequency data are Fourier transformed into the wavenumber space and then the modal amplitudes and phases of incident and reflected waves are obtained by minimising the difference between the measured spectra and theoretical predictions. The recovered modal reflection coefficients can then be used to calculate the modal absorption coefficients for a range of angles of incidence and the total proportion of the sound energy absorbed by the plant. The method has been successfully tested on Geranium plant specimens.

1. Introduction

Porous media reflection and absorption using the impedance tube measurements has been extensively used in the past. The impedance tube measurement procedure to determine the plane wave absorption coefficient is described in ISO 10534-2 [1]. The high frequency limit for the plane wave regime which needs to be ensured in this experiment is determined by the cross-sectional dimension of the impedance tube. The high frequency limit which can be attained with this setup is inversely proportional to the diameter of the tube so that there is a conflict between the maximum size of the material specimen which can be tested in a given frequency range and the diameter of the tube which can be used to ensure that this frequency range can be attained.

There have been a number of works which attempted to address this limitation (e.g. [3, 2, 4]). In these works the acoustical properties of discontinuities in a duct ([3]) or porous materials ([2, 4]) were studied. The aim of the present work is to apply an alternative method ([10]) to measure the acoustical properties of a living plant in an extended the frequency range and at a range of angles
of incidence. This work is inspired by recent findings [9] which suggest that a properly selected living plant can exhibit very high values of the absorption coefficient in a broad frequency range. The novelty of this work is that the acoustical properties of a representatively large plant specimen are studied for the first time using a new method which is based on modal dispersion. This method enables to extend the maximum frequency limit of the ISO 10534-2 [1] method by a factor of 3 and determine the acoustical properties of a plant at angles other than normal.

2. Experimental methodology

2.1 Acoustic setup

The experiments described in this work were carried out using the large impedance tube which is available at the Laboratoire d’Acoustique de l’Université du Maine (LAUM). A sketch of an experimental setup is presented in Fig. 1. It consists of a square waveguide which is 4.15 m long and of 300 x 300 mm cross-section. One end of the waveguide is terminated with a 30 mm thick metal lid. At the opposite end three loudspeakers are installed in parallel and the coordinates of their centres are (50 mm, 50 mm), (50 mm, 150 mm) and (150 mm, 150 mm). The step-by-step sine sweep ranging from 50 to 1800 Hz is used for sound field excitation. The sound pressure in the tube is recorded by a single 1/4” B&K microphone which is traversed to simulate an axial microphone array. The use of a single microphone enables us to avoid amplitude and phase mismatch problems. In our experiment the microphone was placed in the corner of the tube at $x_m = 5$ mm, $y_m = 5$ mm, where the amplitude of all the propagating modes was maximum. The robotic arm controlled the movement of the microphone, resulting in pressure readings being taken at 52 axial positions, distributed with a 40 mm step. The data were acquired by a Stanford Research Systems SR785 signal analyser which provided the sound pressure signals in the frequency domain and stored the pressure spectra in the text file format.

![Figure 1.](image)

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

2.2 Data processing

The full procedure for the experimental data post-processing is detailed in [10] but the main theoretical basis for data analysis and interpretation is provided below. The sound pressure in a square waveguide which is terminated by an acoustically absorbing layer can be expressed as a superposition of an infinite number of normal modes which travel in the waveguide at a range of angles of incidence. The spatial Fourier transform of the sound pressure in this waveguide is:
\[
p(\mathbf{K}, \omega) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \cos \frac{m\pi}{a} x \cos \frac{n\pi}{a} y \times \cdots \\
\cdot \cdot \cdot \left[ A_{m,n} e^{i(K-k_{m,n})\frac{2z_2+z_1}{2}} (z_2-z_1) \text{sinc} \left( (K-k_{m,n})\frac{z_2-z_1}{2} \right) \right] + \cdots \\
\cdot \cdot \cdot A_{m,n} R_{m,n} e^{i(K+k_{m,n})\frac{2z_2-z_1}{2}} (z_2-z_1) \text{sinc} \left( (K+k_{m,n})\frac{z_2-z_1}{2} \right),
\]

where \( x, y \) and \( z \) are the coordinates of the microphone, \( m, n \) are the indices of the modes propagating in the tube, \( a \) is the width of the tube cross-section, \( k_{m,n} \) is the modal wavenumber, \( k_{m,n} = \sqrt{k^2 - \left( \frac{m\pi}{a} \right)^2 - \left( \frac{n\pi}{a} \right)^2} \), \( k = 2\pi f/c \) and \( A_{m,n} \) are the modal excitation coefficient in the incident sound wave and \( R_{m,n} \) are the unknown modal reflection coefficients which depend on the frequency, on the angle of incidence of the mode and on the acoustical properties of sound-absorbing material and \( \text{sinc} z = \frac{\sin z}{z} \). The modal amplitude and the modal reflection coefficient can be presented in the following form:

\[
A_{m,n} = a_{m,n} e^{i\phi_{m,n}}, \quad A_{m,n} R_{m,n} = b_{m,n} e^{i\psi_{m,n}},
\]

where \( a_{m,n}, b_{m,n} \) are the absolute values of the incident and reflected waves, whereas \( \phi_{m,n} \) and \( \psi_{m,n} \) are their phases. These quantities are real numbers which can be recovered using an optimisation procedure in which the difference between the measured and predicted sound pressures (see Eq. (1)) is minimised. Subsequently, the modal amplitude and phase can be used to calculate the complex modal reflection coefficients and, hence, the absorption coefficients of the porous media layer at the end of the impedance tube at a particular frequency and/or at a given angle of incidence. Therefore, the modal reflection coefficient and the plane wave absorption coefficient are:

\[
R_{m,n} = \frac{b_{m,n} e^{i\psi_{m,n}}}{a_{m,n} e^{i\phi_{m,n}}}, \quad \alpha_{00} = 1 - |R_{00}|^2.
\]

### 2.3 Plant analysis

For the experiments described in this paper, garden geranium plants (*Pelargonium hortorum*) were acquired from a local garden center. Plant stems with foliage were cut off and placed in the waveguide with two orientations - stems parallel (horizontal plant orientation) and perpendicular (vertical plant orientation) to the direction of sound propagation. For the experiments described in this paper, only plant greenery was tested without any soil present. Twenty-five leaves from the geranium plants were randomly chosen to determine the key non-acoustical characteristics of this type of plant. The following plant characteristics 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 \( (\theta_f) \). The values of these characteristics are presented in Table 1. These characteristics were then used to derive the following quantities: equivalent volume occupied by the plant \( (V_p) \), leaf area per unit volume \( (A_v) \), total area of leaves on a plant \( (s_p) \), total weight of leaves/stems \( (w_p) \), and volume of plant foliage \( (V_f) \). These values are presented in Table 2.

| Table 1. Measured characteristics of geranium |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( w_f, \text{ (g)} \) | \( h_f, \text{ (mm)} \) | \( s_f, \text{ (m}^2\) | \( n_f \) | \( h_p, \text{ (m)} \) | \( \theta_f, \text{ (degrees)} \) |
| 0.794 | 0.383 | 0.0020 | 41 | 0.20 | 42.6 |

It has been suggested in Ref. [9] that the acoustical properties of living plants can be approximated with an equivalent fluid model. This model enables us to account for the viscous losses and...
Table 2. Derived characteristics of geranium

<table>
<thead>
<tr>
<th>$V_p$ (m$^3$)</th>
<th>$A_v$ (m$^{-1}$)</th>
<th>$s_p$ (m$^2$)</th>
<th>$w_p$ (kg)</th>
<th>$V_f$ (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0036</td>
<td>23.12</td>
<td>0.083</td>
<td>0.0326</td>
<td>0.000032</td>
</tr>
</tbody>
</table>

Thermal dissipation of the sound wave as it propagates through the plant foliage and through the layer of porous soil. It is believed that these mechanisms can explain the acoustic absorption coefficient spectra observed in the impedance tube experiments with the plants.

The plant characteristics listed in Tables 1 and 2 were used to estimate the porosity, tortuosity and flow resistivity of this plant. The porosity was estimated directly from:

$$\phi = 1 - \frac{V_f}{V_p}. \quad (4)$$

The tortuosity of the plant $\alpha_{\infty}$ was estimated from the dominant angle of leaf orientation data for geranium and expression (13) from Ref. [9]:

$$\alpha_{\infty} = \cos \frac{\theta}{2} + 2 \sin \frac{\theta}{2}. \quad (5)$$

The flow resistivity $\sigma$ was estimated using the leaf area density data for geranium and expression (15) from Ref. [9]:

$$\log_{10} \sigma = 0.0067 A_v + 0.746. \quad (6)$$

The above non-acoustical parameters were used in the Miki [11] equivalent fluid model to calculate the characteristic impedance $z_c$ and complex wavenumber $k_c$ for this plant. These acoustical properties were then used to determine the normalised acoustic surface impedance and the modal reflection coefficient which are given by the following expressions:

$$z_{sn} = \frac{z_c}{\cos(\theta_{\text{in}})} \coth(-i k_c \cos(\theta_{\text{in}})) d, \quad R_{mn} = \frac{z_{sn} \cos(\theta_{\text{in}}) - 1}{z_{sn} \cos(\theta_{\text{in}}) + 1}, \quad (7)$$

where $\theta_{\text{in}}$ is the modal angle of incidence, $\theta_{\text{in}}$ is the modal angle of refraction and $d$ is the equivalent height of the plant. The plane wave absorption coefficient was calculated using the following formula:

$$\alpha_{00} = 1 - |R_{00}|^2. \quad (8)$$

3. Results and discussion

Fig. 2 presents the modal reflection coefficients as a function of the frequency and the incidence angle. This figure is for geranium plants with horizontal (left) and vertical (right) orientation in the impedance tube. It was obtained from the analysis of the spatial-frequency spectra which present the amplitudes of incident and reflected pressure waves as a function of frequency and wavenumber. The experimental results are shown with square markers whereas the solid line corresponds to the numerical predictions which were obtained using expression 7 and the Miki model based on the plant data listed in Tables 1 and 2.

For the plane wave, the results are presented for the frequency range below the first cut-on frequency at 572 Hz. The mean squared error between the experimental and predicted results for the mode (00) reflection coefficient is very low, ranging from 1.47% in case of vertical orientation to 2.66% in case of horizontal orientation. In case of higher order modes there are greater discrepancies between the experimental and numerical data, which can be caused by several reasons. Firstly, the adopted speaker arrangement and the positioning of the microphone was particularly favourable for excitation of the (01) and (02) modes particularly in the vicinity of their cut-on frequencies. As a
result, the signal-to-noise ratio was low for some modes and frequencies which made the recovered reflection coefficient data less accurate. It is likely that a different speaker setup would enhance the quality of the experimentally obtained data. Secondly, the equivalent fluid model for plants [9] was originally developed for plane wave regime and at normal incidence in the frequency range below 1200 Hz. This model may need further development to take into account the high-frequency scattering effects and attenuation of those waves are incident at angles other than normal.

Fig. 3 presents the total absorption coefficient data for both adopted experimental setups in a frequency range of 500-1800 Hz. The errors for the plant species / orientation combinations are 16.9% for the geranium plant in horizontal orientation and 20.4% for the geranium plant in vertical orientation. The discrepancy between the measured and predicted data is relatively small in case of the plane wave regime. After the first cut-on frequency of 572 Hz the general trend in the data follows closely the predictions, but the difference between the experimental data and model become more significant. The fluctuations are especially visible each time when the frequency of sound approaches a cross-sectional resonance when the incident angle for the normal mode becomes relatively large.

4. Conclusions

A method to measure the reflection and absorption coefficients of living plants in an impedance tube which lateral dimensions are much larger than the acoustic wavelength is proposed in this paper. The method is based on measuring the sound pressure spectra with a horizontal microphone array and then applying the spatial Fourier transform to these data to separate the waves incident on plants specimen and the waves reflected from them. It has been shown that in this way the high frequency limit of a rectangular impedance tube can be extended by a factor of three. This enables us to measure the acoustical properties of much larger material specimens well beyond the high frequency limit for the tube which is currently set in the standard[1]. The method also enables us to determine the acoustical properties of large plant specimens in the laboratory at a range of angles of incidence.
The geranium plants have been used to test the proposed method and obtain the complex reflection coefficients and the absorption coefficients. The plants were characterised using the Miki model [11] and the standard optimisation algorithm. A good match between the measured and the predicted data has been achieved. The measured and predicted modal reflection coefficient frequency spectra agree within 5\% in case of a plane wave, whereas the total absorption coefficient spectra agree within 15-25\% along the whole frequency range. The reflection coefficients of higher order modes exhibit a less close agreement because not all the modes are equally excited in the tube. The agreement between the measured and predicted absorption coefficient spectra is particularly close in the plane wave regime below the frequency of the first cross-sectional resonance. In the vicinity of a cross-sectional resonance this agreement can deteriorate because some cross-sectional modes begin to dominate whereas the others are not excited strongly enough to be resolved with the proposed modal analysis method. A poor signal to noise ratio affects the accuracy with which the modal reflection coefficients can be derived using the optimisation algorithm. This issue can be addressed by either adopting a phased speaker array or by repeating the measurements with the same microphone array moved to an alternative cross-sectional position in the impedance tube.

REFERENCES


