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Characterisation of the acoustic impedance of vegetated roofs with a multiple-geometry approach

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A B S T R A C T

Urban vegetation, such as vegetated roofs, is highly important for recovering the ecological balance and for providing visually pleasant environments. Also, it has the potential to reduce urban noise levels. The acoustic surface impedance of vegetated roofs can be determined by an in-situ two-microphone technique. However, different initial estimations of the impedance model parameters can retrieve completely different sets of material properties, but the same impedance, which makes no sense physically. The work presented in this paper investigates the multiple-geometry approach with respect to its uniqueness in the determination of the acoustic impedance model parameters of vegetated roofs. The uniqueness of the new proposed method is first validated for typical porous materials where impedance tube measurements and physical measurements provide reference results. Then, a new proposed measurement system was implemented on three urban vegetated roofs. The results show that the proposed measurement system succeeded in uniquely characterising the acoustic impedance model parameters of vegetated roofs.

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1. Introduction

Urban vegetation, such as vegetated roofs, is highly important for recovering the ecological balance and for providing visually pleasant environments [1–7]. An increase of the urban vegetation cover can alter the air temperature, humidity and wind speed [8,9]. Also, urban vegetation can contribute to significant energy savings and improvement of indoor thermal comfort [10]. Urban air pollution can be mitigated by green walls or green roofs, where the depollution performance of urban vegetation is dependent on building height, vegetation species, vegetation layouts, etc. [11–13]. Moreover, the installation of green roofs is a nature-based solution to mitigate flood generation, extreme rainfall effect, etc. [14]. The agricultural drought can be alleviated by vegetation because the root zone water-loss is slowed down [15]. Apart from that, vegetation promotes restoration by providing a pleasant visual environment, which reduces the burden of environmental noise (previous research indicates that visible green from home can achieve an equivalent noise level reduction in relation to annoyance of up to 10 dBA), and by providing a source of positive natural sounds such as bird songs [16]. Furthermore, the sound absorbing properties of urban vegetation can reduce urban noise levels and promote quite sides [17–29]. Road traffic noise can be reduced by 50 % when minimal roadside vegetation is replaced by medium roadside vegetation [20]. Vegetated roofs can absorb the diffracted sound waves passing over the vegetated roofs [22]. It has been shown that vegetated roofs promote quite courtyards better than vegetated walls [24]. Therefore, it is of high importance to investigate the acoustic benefits of vegetated roofs.

The most important parameter for evaluating the acoustic performance of a vegetated roof is the normalised surface impedance [33]. The normalized surface impedance can be determined by the deduction method from an in-situ measurement [34]. Nocke and Mellert [35], Taherzadeh and Attenborough [36], and Dutilleux et al. [37] have explored the transfer function method to deduce the impedance of a ground surface in-situ. However, few studies have been focused on the impedance characterisation of vegetated roofs with low flow resistivity as the ones investigated in this research [38,39].

The acoustic impedance model parameters can be derived by minimization of the acoustic impedance achieved from in-situ
measurements and impedance model predictions. Uniqueness of the predicted model parameters is one of the main challenges in the impedance characterisation of vegetated roofs. Different sets of initial estimations of the model parameters can lead to completely different sets of predicted model parameters, but to the same impedance, which makes no sense physically. The prediction is considered as non-unique, if the predicted model parameters are affected significantly by alternations of the initial fitting parameters (see subsection 3.4.2 for more details). In previous research, the acoustic impedance and model parameters (flow resistivity, porosity, thickness of vegetation and substrate, roughness value of vegetation) of vegetated roofs were predicted using the simplified modified Nordtest (SMNT) method [40]. The SMNT Method includes a double porous layer with hard backing to represent the vegetated roof (double layer), a locally reacting assumption of the vegetated roof surface, a variable reference surface height of the top surface (variable surface), surface roughness and it relies on the two-parameter Slit Pore (SP) model with two source and microphone configurations. However, the predicted impedance model parameters from the SP model were not unique. Hess et al. [41] and Taherzadeh and Attenborough [36] proposed a multiple-geometry technique to avoid non-unique solutions. The multiple-geometry technique that they proposed was to deduce 3 unknown model parameters (porosity, effective flow resistivity, and tortuosity) with 3 different configurations. However, in the impedance prediction of vegetated roofs, there are 7 (the flow resistivity of the vegetation and the soil, the thickness of the vegetation and the soil, the porosity of the vegetation and the soil and the roughness of the vegetation) model parameters rather than 3, which makes it more difficult to achieve unique solutions in the minimization routine. Therefore, the multiple-geometry technique needs to be further explored to uniquely predict the acoustic impedance of vegetated roofs.

This research aims to: 1) validate the uniqueness of the obtained impedance model parameters of porous materials from the multiple-geometry technique where impedance tube measurements and physical measurements provide reference results, 2) uniquely characterise the acoustic impedance of three urban vegetated roofs using the multiple-geometry technique based on the SMNT method as proposed in [40]. Firstly, the multiple-geometry technique is introduced in Section 2. The uniqueness of the predicted impedance model parameters by using the multiple-geometry technique is evaluated in Section 3. Section 4 starts with an introduction to the new measurement system to determine the acoustic impedance of vegetated roofs, using the MSMNT technique, and then details about the measurement setup, experimental procedure, results and discussion are demonstrated. Finally, the conclusions and future work are presented in Section 5.

2. Multiple-geometry technique

The multiple-geometry technique aims to solve the uniqueness problem in the impedance characterisation of vegetated roofs utilizing the SMNT method. The SMNT method is based on a standardized method (Nordtest Method), which is developed to deduce the normalized surface impedance of flat grounds by minimizing the differences between the measured and pre-calculated level differences between two vertically located microphones (as shown in Fig. 4) [40]. In the SMNT method, there are two sets of geometrical configurations, which are two different combinations of the source height, receiver height, and source-receiver distance. This section introduces the implementation of the multiple-geometry technique in the SMNT method by taking into account the same numbers of configurations as the number of model parameters in the impedance model parameter fitting process.

The sound pressure level difference between two fixed microphones in the ith setup is measured (denoted as $\Delta l_{\text{meas},i}$) at 1/3 octave-bands between 200 Hz and 2500 Hz. $\Delta l_{\text{pred},i}$ is the predicted level difference for geometry i, by using the two-parameter SP model with the SP model, the characteristic impedance $Z_{i}$ and propagation constant $k$ of materials with identical tortuous pores can be predicted by the following expressions [33]:

$$Z_{i} = (\rho_{0}c_{0})^{-1} \left[ \left( T/\beta \right)^{2} \rho(\tilde{\lambda})/C(\tilde{\lambda}) \right]^{0.5}$$

$$k = \omega(T\rho(\tilde{\lambda})C(\tilde{\lambda}))^{0.5}$$

where the tortuosity $T$ is computed by porosity $h$ with $T = \sqrt{1/h}$, $\rho_{0}$ is the air density, $c_{0}$ is the adiabatic sound speed, and $\omega$ is the angular frequency. By assuming identical slit-like pores for mathematical convenience, $\rho(\tilde{\lambda})$ and $C(\tilde{\lambda})$ can be given as:

$$\rho(\tilde{\lambda}) = \rho_{0}/G_{v}(\tilde{\lambda})$$

$$C(\tilde{\lambda}) = (\gamma\rho_{0})^{-1} [\gamma - (\gamma - 1)G_{v}(\sqrt{(N_{\text{meq}})})]$$

where

$$G_{v}(\tilde{\lambda}) = 1 - \tanh \left( \frac{\tilde{\lambda}}{\tilde{\lambda}} \right) / \left( \frac{\tilde{\lambda}}{\tilde{\lambda}} \right)$$

and

$$\tilde{\lambda} = \sqrt{\frac{3\rho_{0}\omega T}{\beta \sigma}}$$

where $\rho_{0} = 1.42 \times 10^{5}$ N/m$^2$ is the isothermal bulk modulus in air, $\gamma$=1.4 (for air) is the specific heat ratio, and $N_{\text{meq}}=0.713$ is the Prandtl number.

The initial estimations for the model parameters are the same for each geometrical configuration. The errors between the measurements and predictions for each individual setup $E_{i}$ are computed by the absolute difference of $\Delta l_{\text{meas},i}$ and $\Delta l_{\text{pred},i}$ per 1/3 octave-band (l) (Equation (7)). The average fitting error $E_{av}$ is defined as the average value of the individual geometrical configurations (n) (Equation (8)).

$$E_{i} = \sum_{j=1}^{n} |\Delta l_{\text{meas},j,i} - \Delta l_{\text{pred},j,i}|$$

$$E_{av} = \sum_{i=1}^{n} (E_{i})/n$$

The total fitting error is the sum of $E_{av}$ over all the geometrical configurations. The minimization routine of $\Delta l$ in the multiple-geometry SMNT method (referred to as MSMNT technique) is illustrated in Fig. 1. It was realized by the function ‘fminsearchcon.m’ in Matlab, which returns the local minima using the Nelder-Mead simplex algorithm.

3. Validation of the multiple-geometry technique

In this section, the uniqueness and accuracy of the application of the MSMNT technique for the impedance characterisation of porous materials is evaluated in laboratory conditions. The evaluation consists of two steps. Firstly, the properties of the tested porous materials are extracted using the MSMNT technique, which are then evaluated against the properties measured with physical measurements and extracted from impedance tube measurements. The porous materials studied are two single-layer materials (material A, and material B) and one double-layer material, which is represented by two different materials placed on top of each other (material A with low flow resistivity on top of material B with high flow resistivity on the bottom). The materials are placed on a hard
ground surface (similar to vegetated roofs on rigid backed surfaces). Secondly, the uniqueness of the impedance characterisation of the single-layer materials and the two-layer material are investigated based on the MSMNT technique.

3.1. Test materials

Laboratory measurements were taken for two commonly used porous materials: sound absorbing panels manufactured by Caruso (material A) and baffle panels by Ecophon (material B) as shown in Fig. 2.

These materials belong to the class of fibrous materials and are widely used for acoustic absorption. Material A is made of 100% polyester fibers. Material B is made of high-density glass wool and is coated with a layer of paint. The sizes of material A and material B are 0.11 m (thickness) x 1.20 m (length) x 0.60 m (width), and 0.04 m (thickness) x 1.20 m (length) x 0.30 m (width), respectively.

3.2. Physical measurements

The physical measurements in this section include the measurements of the static airflow resistivity and open porosity of the test materials, which are two of the most important parameters for the characterisation of porous materials.

The static airflow resistivity $\sigma$ is determined by measuring the air velocity and pressure difference when a steady and laminar flow of air passes through the material sample [42]. The measurements were conducted in the Laboratory for Acoustics and Thermal Physics at the Katholieke Universiteit Leuven (KU Leuven) and the international standard ISO 9053 [42] was followed. Two samples were cut from material A with 100 mm diameter, and thickness of $D = 58$ mm and 60 mm. The airflow resistivity was averaged over 10 measurements on each sample. The airflow resistivity of material B was taken from N. Hoekstra [43].

3.3. Impedance tube measurements

The acoustic impedance and other properties (such as flow resistivity and porosity) of porous materials can be determined by impedance tube measurements based on ISO 10534-2 [44].

Material A was characterised in the impedance tube (shown in Fig. 3) at TU/e. The sound source (Dynaudio D-54 AF) was mounted on the one end of the tube, and the sample of 40 mm in diameter was mounted on the other end backed by a solid piston. A microphone (Endevco 8510B) was placed at six different receiver positions to increase the measurement accuracy [45,46].

The surface impedance $Zm$ was directly computed from the impedance tube measurements. Afterwards, the flow resistivity $\sigma$ and porosity $h$ of the test materials were predicted by fitting the predicted impedance $Zp_f$ to the measurement data using the two-parameter (flow resistivity and porosity) SP model [33]. The fitting error $E_{tube}$ in the logarithmically spaced frequency range $f = 200$ Hz–2500 Hz is defined as:

$$E_{tube} = \sum_f \left( |\text{real}(Z_{mf} - Z_{pf})|^2 + |\text{imag}(Z_{mf} - Z_{pf})|^2 \right)$$

(9)
where \( Z_{nf} \) is the surface impedance directly achieved from the impedance tube measurements, and \( Z_{pf} \) is the predicted impedance from the impedance model.

3.4. MSMNT technique

The multiple-geometry technique was applied to the impedance model parameter deduction of the test materials. The technique was first studied on the single-layer material (material A) and then on the two-layer setup (material A + B), which was used to mimic the vegetated roofs. Measurements based on the MSMNT technique were carried out inside the building acoustics transmission suite of the TU/e Echo building with concrete room surfaces. The dimensions of the measurement room are around 6 m × 4 m × 3 m. To avoid undesirable reflections from surrounding surfaces, each impulse response was multiplied by a time window. The length of this time window was computed according to the time between the arrival of the direct sound wave path and the first unwanted reflection (0.01 s in this case). The measurements were carried out using a broadband speaker (Visaton – Type FR 8 WP 8 Ohm), an omni-directional microphone (Behringer – Type ECM800), a one-channel USB audio interface with sample frequency of 192 kHz (E-MU – Type 0202 USB2.0), a power amplifier (Brüel & Kjær - Type 2706), a Phantom Power Supply (Superlux – Type PS-2B) and the DIRAC 6.0 software (Bruel & Kjær /Acoustics Engineering). The microphone was calibrated with a class 1 pistonphone emitting a single sound frequency of 1 kHz at 94 dB (Brüel & Kjær, Type 4231).

3.4.1. Geometrical configurations

The geometry of a typical setup based on the MSMNT technique, which was used in this research, is shown in Fig. 4. It consists of a broadband speaker and an omni-directional microphone at two receiver positions. The sound produced from the speaker has a directional character. To minimize the effect of directivity, the following approach was taken. For both receiver positions, the sound source was directed towards the ground right below the microphones (red arrow in Fig. 4), as the difference between the two angles, the first being the angle between the normal to the membrane of the sound source and the direct sound wave from the source to the receiver (angle A) and the second the angle between the normal to the membrane of the sound source and the sound waves reaching the receiver via the ground reflection (angle B), was minimized as such.

The geometrical configurations for the single-layer medium A and double-layer medium A + B are presented in Appendix A. For a single layer medium using the SP impedance model, a unique prediction requires at least three different geometrical configurations for the three unknown parameters mathematically. These parameters are the flow resistivity, porosity and thickness of the material. For the double layered medium model A+B, for a unique prediction six geometries for six unknown parameters were adopted. These are the flow resistivity, porosity, and thickness of each of the two media.

The transducers’ locations for these geometrical configurations in this research ensured the following: 1) the estimated interference peak frequencies of the predicted \( \Delta f \) between the two receivers were in the frequency range of interest (200 Hz–2500 Hz); and 2) the sound propagates in a far field and in grazing incidence,
which means the conditions of \( k_1R_1 \gg 1 \) and \( \cos \theta \ll 1 \) were fulfilled, where \( k_1 \) is the wave number in the ground medium, and \( R_1 \) is the path length of the direct sound wave. After pilot tests, the locations of each transducer were extracted [47].

### 3.4.2. Experimental procedures

The procedure of the MSMNT technique can be divided into two steps: 1) Prediction of the acoustic impedance; 2) Analysis of the uniqueness of impedance prediction.

1) Prediction of the acoustic impedance.

The acoustic impedance and material properties were predicted using the MSMNT technique introduced in Section 2. An extended reacting assumption was used in the impedance prediction of material A and material B, since the extended reaction assumption is preferred regardless of the computational complexity. The extended reacting surface can be modelled in the expression for the spherical wave reflection coefficient as in the authors’ previous paper [40].

A prediction of the flow resistivity and porosity is considered as physically reasonable when the predicted properties are within the same range as the properties of a similar type of material computed in previous studies in the literature. Therefore, boundary limitations were set in the fitting process to guarantee physically reasonable predictions for the flow resistivity, porosity and thickness, which are summarized in Table 1.

2) Analysis of the uniqueness of impedance prediction.

To investigate the uniqueness of the impedance prediction, a range of initial values within the boundary limitations were selected, as shown in Table 1. The best guess initial values according to physical measurements are marked in bold. Based on the best guess initial values, another two sets of initial values for flow resistivity, porosity and thickness were selected, therefore, 7 sets of initial values for single material in total (as shown in the first column of Table 2). The uniqueness of the impedance model parameters was investigated by computing the relative standard deviation (RSD) of the predicted material properties, which is the ratio of the standard deviation to the mean [48]. Based on previous research [48–50] the prediction of the material properties was considered here as unique when the RSD was no larger than 10%.

### 3.5. Results and discussion

First, the uniqueness of the prediction of material properties of single material (material A) and the two-layer material (A+B), which was used to mimic a vegetated roof, was evaluated and is presented in Subsection 3.5.1. Detailed results on impedance characterisation of the single material and the two-layer material are presented in Table 2 and Appendix B. Next, the absorption coefficients and material properties based on physical measurements, impedance tube measurements and in-situ measurements using the MSMNT technique are presented (in Subsection 3.5.2).

#### 3.5.1. Uniqueness using multiple configuration

The RSD (expressed in %) is calculated from the ratio of the standard deviation and the averaged values over seven predictions under different initial estimations. The RSD for the predicted flow resistivity and porosity is presented in Table 2. The RSD for the predicted thickness is presented in Table 3.

![Measurement geometry in the MSMNT technique.](image-url)

**Fig. 4.** Measurement geometry in the MSMNT technique.

#### Table 1

<table>
<thead>
<tr>
<th>Boundary limitations</th>
<th>Flow resistivity [kPa·s/m²]</th>
<th>Porosity [-]</th>
<th>Thickness [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material A</td>
<td>(1,1000)</td>
<td>(0.05,1)</td>
<td>(0.09,0.15)</td>
</tr>
<tr>
<td>Material B</td>
<td>(1,1000)</td>
<td>(0.05,1)</td>
<td>(0.01,0.06)</td>
</tr>
</tbody>
</table>

The best guess initial values are marked in bold.

#### Table 2

<table>
<thead>
<tr>
<th>Initial Values</th>
<th>Flow resistivity [kPa·s/m²]</th>
<th>Porosity [-]</th>
<th>Thickness [m]</th>
<th>Error [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10; 0.80; 0.11)</td>
<td>2.2</td>
<td>0.87</td>
<td>0.12</td>
<td>5.04</td>
</tr>
<tr>
<td>(2; 0.80; 0.11)</td>
<td>2.2</td>
<td>0.87</td>
<td>0.12</td>
<td>5.04</td>
</tr>
<tr>
<td>(500; 0.80; 0.11)</td>
<td>2.2</td>
<td>0.87</td>
<td>0.12</td>
<td>5.04</td>
</tr>
<tr>
<td>(10; 0.10; 0.11)</td>
<td>2.2</td>
<td>0.87</td>
<td>0.13</td>
<td>5.07</td>
</tr>
<tr>
<td>(10; 0.90; 0.11)</td>
<td>2.3</td>
<td>0.87</td>
<td>0.12</td>
<td>5.04</td>
</tr>
<tr>
<td>(10; 0.80; 0.08)</td>
<td>2.2</td>
<td>0.87</td>
<td>0.12</td>
<td>5.04</td>
</tr>
<tr>
<td>(10; 0.80; 0.14)</td>
<td>2.2</td>
<td>0.87</td>
<td>0.12</td>
<td>5.04</td>
</tr>
</tbody>
</table>
resistivity, porosity and thickness of material A over predictions with 3 geometrical configurations for various initial estimates are only 3 %, 0 % and 1 % respectively, which shows that the prediction is unique. This result shows that unique predictions of single-layer material A (three unknown parameters) can be achieved with the MSMNT technique.

The impedance prediction of a single-layer medium contains only three unknown parameters. Further studies on the uniqueness and accuracy of impedance predictions were carried out on the double-layered medium, which has 6 unknown parameters.

In general, there is a small deviation between the predicted model parameters for different initial estimations, with the RSD being 4.1 %, 1.0 % and 5.4 % for the flow resistivity, porosity and thickness of material A, and 26.4 %, 0.0 %, and 20.2 % for material B respectively. If the difference between any of the model parameters and the average value of that parameter for all the initial estimations is over two times its standard deviation that specific result is considered as an outlier (see 3rd, 4th, 6th and 7th initial estimations in Table B1). After excluding these outliers, the RSD becomes 1.7 %, 0.4 %, 1.3 %, 9.1 %, 0.0 %, and 6.5 % for the six model parameters respectively. Thus, the prediction can be considered as unique.

3.5.2. Physical, impedance tube and MSMNT technique

Fig. 5 shows the measured acoustic impedance and normalized absorption coefficient for normal sound wave incidence of Material A measured with the impedance tube in red and with the MSMNT technique in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The material property values obtained by physical, impedance tube, and MSMNT technique are presented in Table 3. For single-layer material A, the predicted flow resistivity and porosity from the MSMNT technique are slightly smaller than obtained from the tube and physical measurements: 3.8 kPa · s/m² (flow resistivity) and 0.97 (porosity) from the impedance tube measurements, 2.4 kPa · s/m² (flow resistivity) and 0.98 (porosity) from the physical measurements, versus 2.2 kPa · s/m² (flow resistivity) and 0.87 (porosity) from the MSMNT technique. The deviation between the MSMNT technique, and the tube and physical measurement could be due to the inhomogeneous material properties.

The impedance prediction of a double-layer medium was evaluated with the multiple-geometry technique under six geometries.
different geometrical configurations for six unknown model parameters. A unique prediction was obtained by fitting six model parameters with six geometrical configurations. The predicted flow resistivity and porosity of material B were in good agreement with the physical measurements. Although the predicted porosity of material A using the MSMNT technique matches with tube measurements, the flow resistivity deviates slightly.

![Measurement on Cascade building (a), Park building (b) and Educatorium building (c).](image)
4. Impedance prediction of vegetated roofs

A new measurement system to determine the acoustic impedance of vegetated roofs, using the MSMNT technique, was developed and applied on three urban vegetated roofs in-situ. The details of the measurement system, measurement roofs, experimental procedure, and the measurement results are presented in this section.

4.1. Proposed measurement system

The precision of the adopted transducers’ locations is important for the impedance prediction of porous materials using the MSMNT technique [51–53]. Due to the roughness of the vegetation, it is difficult to determine the exact height of the source and receivers. In the research presented in this paper, a measurement system that integrates the multi-geometry technique is proposed, in order to achieve a unique prediction on the acoustic properties of vegetated roofs. The benefits of this new system are the following: 1) it is easy to measure different geometrical configurations with one setup; and 2) the locations of the speaker and microphones are fixed for each geometrical configuration during measurements on different materials; 3) the exact locations of speaker and microphones can be determined inside the laboratory [50].

The new measurement system, which is shown in Fig. 6, was constructed with a trilateral frame (F1, F2, and F3 shown in black). The two sub-beams (U1 and U2 shown in dark grey) are suspended on the horizontal bar F1 and can move freely along it. Moreover, the speaker (S) and microphone (M1 and M2) are connected to beams U1 and U2, and can also move along them. Scales are carved on the beams F1, U1 and U2 so that it is convenient to read the positions of the speaker and microphone. Different geometrical configurations can be realized by moving the source and receiver along the beams F1, U1 and U2. Since sound propagation is influenced by the surfaces of the metal beams, especially at high frequencies, sound absorbing foam (30 mm thick) was attached to the beams U1, U2, F2 and F3 to minimize the effect of reflections. According to pilot tests, the working frequency range of the measurement system is limited to below 1600 Hz, above this frequency the effect of the beam reflections is noticeable. Moreover, since the original NT method has a low frequency limit of 200 Hz (the NT method is applicable for the frequency range between 200 Hz and 2500 Hz), the working frequency range of the system is between 200 Hz and 1600 Hz. All the other measurement equipment (source, microphone etc.) is the same as the one used in the laboratory measurements introduced in Section 3.4.

4.2. Information of experimental vegetated roofs

The measurements were carried out at the vegetated roofs of the following three buildings: an office building located at a theme park (referred to as Park Building) in the Netherlands on 2018/08/22, and two educational buildings: one is located at the campus of TU/e (Cascade Building) on 2018/06/08, and the other one at the campus of Utrecht University (Educatorium Building) on 2018/09/28. Photos from the measurements on the three vegetated roofs are shown in Fig. 7.

The measurement conditions on the three urban vegetated roofs and main information of their structures are summarized in Table 4.

4.3. Geometrical configurations

According to the multi-geometry technique, seven geometrical configurations should be taken into account in order to predict the following seven properties of the vegetated roofs: flow resistivity (\(\sigma_{\text{reg}}, \sigma_{\text{air}}\)), porosity (\(h_{\text{reg}}, h_{\text{air}}\)), thickness (\(d_{\text{reg}}, d_{\text{air}}\)) and roughness of vegetation (\(\sigma_{r}\)). The configurations of the setups are based on the original NT method. The designated configurations require the interference peak frequencies of the predicted \(\Delta L\) between two receivers to occur within the frequency range of interest (200 Hz–1600 Hz). Due to the assembling and disassembling of the measurement system, the configurations of the three vegetated roofs were not exactly the same. The configurations that were used in the Park Building, Educatorium Building, and Cascade Building are given in Appendix A.

4.4. Experimental procedures

During the measurements on the vegetated roof, the posts F1, F2 and F3 (see Fig. 6) were fixed. For each configuration, five measurements were repeated to suppress individual deviations. \(\Delta L_{\text{meas}}\) for each geometrical configuration is achieved by the subtraction of energetically averaged sound pressure levels over the five measurements at the two receiver positions. \(\Delta L_{\text{pred}}\) is calculated using a hard-backed double-layered SP model with a locally reacting...
assumption as in the SMNT method [40]. The material properties are determined by the minimization (Equation (8)) of the $\Delta L$ between measurements and predictions. The boundary conditions of these 7 parameters, which were set for the error fitting function to guarantee physical reasonable predictions, are summarized in Table 5. The uniqueness of the impedance prediction of the in-situ vegetated roofs was investigated with 15 different initial estimations on the seven model parameters. These initial estimations can be found in Table 5.

Afterwards, the predictions that did not satisfy the inequalities of Equation (10) were excluded,

$$\sigma_{\text{veg}} - \sigma_{\text{soil}} < 0 \text{ kPa} \cdot \text{s/m}^2, \quad h_{\text{veg}} - h_{\text{soil}} > 0$$

(10)

4.5. Results and discussion

The uniqueness of the impedance prediction of the three vegetated roofs using the MSMNT technique is discussed in the following paragraphs based on the RSD of the fitted parameters. The predictions that did not satisfy the criteria of Equation (10) were excluded from the following analysis. Furthermore, predictions with initial estimations that produced extreme values even for one parameter were also excluded. A value of a parameter was again considered extreme if its difference from the average value predicted from all the initial estimations was greater than two times its standard deviation.

For the Cascade roof case, the variation of the predicted flow resistivity, porosity, thickness of vegetation and soil, and the surface roughness values among the remaining estimations after excluding the outliers are plotted in Fig. 8. The RSD values of seven parameters were 5% and 3% for the flow resistivity of vegetation and soil, 3% and 1% for the porosity, 6% and 1% for the thickness and 2% for the roughness. Thus, the impedance prediction of the Cascade roof was unique with the MSMNT technique.

The flow resistivity, porosity, thickness of vegetation and soil, and the surface roughness values were determined by averaging the predicted values over the remaining data under 10 initial estimations (summarized in Table 6).

![Fig. 8](image-url)

**Table 6**

Best-fit model parameter values obtained with the MSMNT technique for the Cascade, Park and Educatorium roof.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Substratum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetated roof</td>
<td>Flow resistivity [kPa \cdot s/m²]</td>
</tr>
<tr>
<td>Cascade</td>
<td>2.3</td>
</tr>
<tr>
<td>Park</td>
<td>5.3</td>
</tr>
<tr>
<td>Educatorium</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Fig. 9. As Fig. 8, but for the Park roof.

Fig. 10. As Fig. 8, but for the Educatorium roof.
The same process was also implemented on the other two vegetated roofs. Fig. 9 and Fig. 10 show the variation of seven model parameters of the Park roof and Educatorium roof for different initial estimations. In Fig. 9, no significant fluctuation can be detected on the predicted porosity and thickness of vegetation and substrate under 13 different initial estimations. The RSD values are just 2 % and 1 % for the porosity of vegetation and substrate, and 0 % for their thickness. The predicted flow resistivity of the substrate on the Park roof levels is around 13 kPa·s/m², with a RSD of only 1 %. Since the Park roof was measured during a very dry period, especially for Dutch weather standards, the vegetation had dried considerably, which partly explains why the predicted roughness remained at 0 m. However, there is still some noticeable roughness on several parts of the roof.

In Fig. 10, the flow resistivity of vegetation varies between 2.7 and 3.0 kPa·s/m² with a RSD value of 4 %. The disparity between the predicted substrate flow resistivity (varies between 395 and 465 kPa·s/m²) and the average value (418 kPa·s/m²) is less than 50 kPa·s/m², and the RSD value is 6 %. The RSD values of the other model parameters are 1 % and 6 % for the porosity, 1 % and 5 % for the thickness and 4 % for the roughness.

4.5.1. Predicted impedance of vegetated roofs

The post-processed predicted model parameter values are presented in Table 6. The normalized impedance and absorption coefficient for normal incidence of these three vegetated roofs, and the simulated roof (Material A on top of Material B) are plotted in Fig. 11. Since the Park roof was measured during a very dry period, with the temperature as high as 30.6 °C and with only 6 mm of rainfall in total from 2018 to 06-08 to 2018–08-07, its absorption coefficient reached a very high value of 0.8 at 500 Hz and 630 Hz. The measurement on the Educatorium roof (a new-built roof) was carried out under wet conditions, which could explain the high flow resistivity (418 kpa·s/m²) and low porosity (0.30) predicted using the MSMNT technique.

5. Conclusions

This research investigated a multiple-geometry technique based on the SMNT method to predict the impedance of in-situ vegetated roofs uniquely. This method was first explored in laboratory measurements against impedance tube and physical measurements. Next, the uniqueness of the impedance predictions on three vegetated roofs was assessed using a newly proposed measurement system. Laboratory measurements confirmed that a unique prediction of porous materials can be achieved by multiple configurations, using as many configurations as unknown material parameters. Moreover, after excluding the outliers in the predicted material properties, a unique prediction of the remaining properties of the vegetated roofs could be achieved. The new proposed measurement system and MSMNT technique is based on the Nordtest Method, and is limited to the impedance prediction of vegetated roofs at frequencies 200 Hz to 1600 Hz. This system can be further extended and applied to in-situ impedance measurements of other soft outdoor ground surfaces. Future work can be done on the validation of the multiple-geometry technique on other in-situ measurement methods.

CRediT authorship contribution statement

Chang Liu: Conceptualization, Methodology, Writing – original draft. Fotis Georgiou: Writing – review & editing. Maarten Hornikx: Conceptualization, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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Appendix A. Geometrical configurations for measurements

The geometrical configurations for the single-layer media A, double-layer medium A + B, and three urban vegetated roofs are presented in Table A1 and Table A2.

Appendix B. Impedance characterisation results for material A + B

Table B1 shows the best-fit model parameter values for ΔL on the double-layered medium A+B for various initial estimations.
References


Table A1
Geometrical configurations for Material A and Material A + B.

<table>
<thead>
<tr>
<th></th>
<th>( h_1 ) [m]</th>
<th>( h_{11} ) [m]</th>
<th>( h_{22} ) [m]</th>
<th>( d_4 ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Configuration 1</td>
<td>0.496</td>
<td>0.500</td>
<td>0.200</td>
<td>1.733</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>0.603</td>
<td>0.600</td>
<td>0.350</td>
<td>1.223</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>0.333</td>
<td>0.300</td>
<td>0.150</td>
<td>1.788</td>
</tr>
<tr>
<td>Material A + B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Configuration 1</td>
<td>0.523</td>
<td>0.500</td>
<td>0.200</td>
<td>1.737</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>0.623</td>
<td>0.651</td>
<td>0.300</td>
<td>1.772</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>0.603</td>
<td>0.599</td>
<td>0.351</td>
<td>1.180</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>0.520</td>
<td>0.500</td>
<td>0.200</td>
<td>1.423</td>
</tr>
<tr>
<td>Configuration 5</td>
<td>0.466</td>
<td>0.466</td>
<td>0.350</td>
<td>1.163</td>
</tr>
<tr>
<td>Configuration 6</td>
<td>0.308</td>
<td>0.300</td>
<td>0.200</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Table A2
Geometrical configurations for measurements.

On the Park Building and Educatorium Building

<table>
<thead>
<tr>
<th></th>
<th>( h_1 ) [m]</th>
<th>( h_{11} ) [m]</th>
<th>( h_{22} ) [m]</th>
<th>( d_4 ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>0.533</td>
<td>0.496</td>
<td>0.196</td>
<td>1.776</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>0.616</td>
<td>0.596</td>
<td>0.296</td>
<td>1.200</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>0.537</td>
<td>0.496</td>
<td>0.196</td>
<td>1.547</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>0.495</td>
<td>0.456</td>
<td>0.346</td>
<td>1.260</td>
</tr>
<tr>
<td>Configuration 5</td>
<td>0.688</td>
<td>0.646</td>
<td>0.296</td>
<td>1.800</td>
</tr>
<tr>
<td>Configuration 6</td>
<td>0.383</td>
<td>0.346</td>
<td>0.196</td>
<td>1.049</td>
</tr>
<tr>
<td>Configuration 7</td>
<td>0.477</td>
<td>0.456</td>
<td>0.246</td>
<td>1.005</td>
</tr>
</tbody>
</table>

On the Cascade Building

<table>
<thead>
<tr>
<th></th>
<th>( h_1 ) [m]</th>
<th>( h_{11} ) [m]</th>
<th>( h_{22} ) [m]</th>
<th>( d_4 ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>0.513</td>
<td>0.500</td>
<td>0.200</td>
<td>1.768</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>0.602</td>
<td>0.500</td>
<td>0.300</td>
<td>1.206</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>0.565</td>
<td>0.500</td>
<td>0.200</td>
<td>1.508</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>0.466</td>
<td>0.456</td>
<td>0.350</td>
<td>1.206</td>
</tr>
<tr>
<td>Configuration 5</td>
<td>0.651</td>
<td>0.650</td>
<td>0.300</td>
<td>1.751</td>
</tr>
<tr>
<td>Configuration 6</td>
<td>0.352</td>
<td>0.350</td>
<td>0.200</td>
<td>0.604</td>
</tr>
<tr>
<td>Configuration 7</td>
<td>0.400</td>
<td>0.400</td>
<td>0.250</td>
<td>0.607</td>
</tr>
</tbody>
</table>

Table B1
Best-fit model parameter values for \( \Delta L \) on material A+B for 13 different fitting runs with various initial estimations. Data to be excluded are printed in bold. The outliers are shown in bold.

<table>
<thead>
<tr>
<th>No. of initial estimations</th>
<th>Initial values</th>
<th>Best-fit model parameter values for Material A</th>
<th>Best-fit model parameter values for Material B</th>
<th>Error [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[10;0.8;0.11]</td>
<td>( \sigma_A ) = 7.9 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.18</td>
</tr>
<tr>
<td>2</td>
<td>[10;0.8;0.04]</td>
<td>( \sigma_A ) = 8.2 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.90 ( \text{[m]} )</td>
<td>6.23</td>
</tr>
<tr>
<td>3</td>
<td>[2;0.8;0.11]</td>
<td>( \sigma_A ) = 7.4 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.87 ( \text{[m]} )</td>
<td>6.21</td>
</tr>
<tr>
<td>4</td>
<td>[10;0.8;0.04]</td>
<td>( \sigma_A ) = 8.2 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.90 ( \text{[m]} )</td>
<td>6.22</td>
</tr>
<tr>
<td>5</td>
<td>[10;0.9;0.11]</td>
<td>( \sigma_A ) = 7.8 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.17</td>
</tr>
<tr>
<td>6</td>
<td>[10;0.8;0.10]</td>
<td>( \sigma_A ) = 8.6 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.39</td>
</tr>
<tr>
<td>7</td>
<td>[10;0.8;0.04]</td>
<td>( \sigma_A ) = 7.9 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.18</td>
</tr>
<tr>
<td>8</td>
<td>[10;0.8;0.01]</td>
<td>( \sigma_A ) = 8.2 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.18</td>
</tr>
<tr>
<td>9</td>
<td>[500;0.8;0.04]</td>
<td>( \sigma_A ) = 7.9 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.18</td>
</tr>
<tr>
<td>10</td>
<td>[10;0.8;0.10]</td>
<td>( \sigma_A ) = 8.2 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.18</td>
</tr>
<tr>
<td>11</td>
<td>[10;0.8;0.04]</td>
<td>( \sigma_A ) = 7.9 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.18</td>
</tr>
<tr>
<td>12</td>
<td>[10;0.8;0.02]</td>
<td>( \sigma_A ) = 8.2 ( \text{[kPa s/m}^2])</td>
<td>( h_A ) = 0.89 ( \text{[m]} )</td>
<td>6.18</td>
</tr>
</tbody>
</table>

* \( \sigma_A \) —— flow resistivity of Material A, in [kPa s/m²]; \( h_A \) —— porosity of Material A; \( d_A \) —— thickness of Material A, in [m]; 
\( \sigma_B \) —— flow resistivity of Material B, in [kPa s/m²]; 
\( h_B \) —— porosity of Material B; \( d_B \) —— thickness of Material B, in [m];


[37] Hoekstra N. Sound absorption of periodically spaced baffles. Eindhoven University of Technology; 2014.


Further Reading


