Determination of the Impedance of Vegetated Roofs with a Double-Layer Miki Model

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Summary

Vegetated roof systems on the top of buildings can act as absorbers for traffic noise mitigation. Recent research explains the properties of vegetated roofs that are important for their sound absorptive and scattering properties. Although it has been identified that the substratum is the major contributor to the acoustic absorption of a vegetated roof, coverage of this substratum by plants may have a significant effect on the acoustic absorption. Short-range acoustic propagation experiments have previously been used for in-situ measurements to determine the acoustic impedance of surfaces as forest floors, grasslands, and gravel. However, it is still less practical to estimate the impedance of a non-locally reacting layer of leaves on substratum using the proposed method. The Miki model provides a satisfactory prediction of the fundamental acoustic properties of soils, plants, and their combinations with the advantage of computational simplicity. Here, the double-layer Miki model is examined based on the short-range acoustic propagation method over substratum (with and without layer of leaves) in the laboratory, and considered through in-situ outdoor measurements over vegetated roofs. In addition, the application of the double-layer Miki model on the prediction of the non-locally reacting surface impedance is evaluated by a comparison with other impedance models.

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1. Introduction

In the urban environment, application of vegetation such as vegetated roofs is highly important for recovering ecological balance and providing visually pleasant environments [1,2]. In addition, the potential of green roof systems to reduce noise outdoors has been identified recently as well [3,4]. Green roofs can also be used to effectively reduce indoor noise levels [5] and increase the sound insulation of light-weight roof structures [6]. As green roofs absorb and scatter the sound in urban environments, they are effective for promoting quiet sides [4]. Although it has been identified that the substratum is the major contributor to the acoustic absorption of a vegetated roof, coverage of this substratum by plants may have a significant effect on the acoustic absorption [7]. However, most studies are either based on laboratory experiments [8] or numerical models [9].

Short-range acoustic propagation experiments have been used for in-situ measurements to determine the acoustic impedance of soils (covered with foliage) [10]. Based on this measurement method, the one parameter impedance model, Delany and Bazley model, is recommended for predicting outdoor ground impedance with the advantage of simplicity [10]. The semi-empirically impedance model proposed by Miki is able to provide a satisfactory prediction of the fundamental acoustic properties of soils, plants, and their combinations with the advantage of computational simplicity [11]. Apart from that, it is possible to estimate with a good degree of accuracy surface impedance of a layer of top soil from the measurements using the two-parameter slit-pore model proposed in [10]. On the other hand, in the case of a low flow resistivity porous layer over another porous layer, such as forest floor [10] and snow layers [12], a double-layer impedance model can lead to a better agreement between predictions and measurement data than using a single layer impedance model.

Therefore, these three impedance models in both single-layer and double-layer versions are examined in this paper on their performance of the determination of the impedance of urban vegetated roofs.

2. Impedance models

The acoustic surface impedance of vegetated roofs is determined using a short range measurement method, which requires one or more impedance models.

The characteristic impedance and propagation constant of the semi-empirical single-parameter model proposed by Delany and Bazley and the identical tortuous slit-pore model can be found in references [10] and [13].

To improve the prediction of the Delany and Bazley model at low frequencies, Miki developed the Delany and Bazley model to a three-parameter model which is the effective flow resistivity (σ_e), tortuosity (q) and porosity (Ω), respectively. It can be written as [11]:

$$Z_c = \frac{q}{\Omega}\left[1 + 0.070\left(\frac{f}{\sigma_e}\right)^{-0.632} + 0.107i\left(\frac{f}{\sigma_e}\right)^{-0.632}\right]; \quad (1)$$

$$k = \frac{\omega q}{c_0}\left[1 + 0.109\left(\frac{f}{\sigma_e}\right)^{-0.618} + 0.16i\left(\frac{f}{\sigma_e}\right)^{-0.618}\right]. \quad (2)$$

with Z_c the normalized surface impedance, f the frequency, ω the angular frequency and c_0 the adiabatic speed of sound. The absorption coefficient for normal incident sound waves for the porous material can be determined by:

$$\alpha = 1 - \left|\frac{Z_c - 1}{Z_c + 1}\right|^2. \quad (3)$$

In some cases, such as a layer of snow or vegetation, the speed of sound in the porous layer is not sufficiently smaller than that in the air, which means that the condition for the index of refraction of ground n_1 »1 ($n_1 = c/c_1$) as used to assume a locally reacting ground surface cannot be satisfied [13]. Therefore, such porous should be treated as extended-reaction surfaces [13]. For a hard-backed layer, the effective admittance is defined as [12, 13]:

$$\beta_e = -is_1\sqrt{n_1^2 - \sin^2\theta}\left(\tan\left(k_0 d_1\sqrt{n_1^2 - \sin^2\theta}\right)\right); \quad (4)$$

and for a double layer with a hard backing, the effective admittance can be written as [12, 13]:

$$\beta_e = -is_1\sqrt{n_1^2 - \sin^2\theta}\left[\frac{\tan\left(k_0 d_1\sqrt{n_1^2 - \sin^2\theta}\right) + g\tan\left(k_0 d_2\sqrt{n_2^2 - \sin^2\theta}\right)}{1 + g\tan\left(k_0 d_1\sqrt{n_1^2 - \sin^2\theta}\right)\tan\left(k_0 d_2\sqrt{n_2^2 - \sin^2\theta}\right)}\right]. \quad (5)$$

where

$$n_j = k_j/k_0; \quad s_j = \rho_0/\rho_j \text{ with } j = 1,2; \quad (6)$$

$$g = \frac{s_2\sqrt{n_2^2 - \sin^2\theta}}{s_1\sqrt{n_1^2 - \sin^2\theta}}; \quad (7)$$

with θ the angle of incidence, d_1,d_2 the thickness of two layers, k ($k = \omega/c$) the wave number, and ρ the density.

3. Measurement technique

The Nordtest method (1999) [14] is adopted in this study, which is used for the in-situ prediction of the normalized specific acoustic impedance of flat outdoor ground surfaces. For this method, 1/3-octave band frequencies from 200 Hz to 2.5k Hz are of interest for accurate results [14]. The sound pressure level is measured at two microphones vertically located above the horizontal ground surface with specified distances between two microphones. The sound pressure level difference measured between the two microphones is used to achieve a best fit to the analytically computed level difference using an impedance model for the ground and the Weyl-Van Der Pol formula for the spherical wave reflection coefficient [12].

The main equipment used in this research consists of a broadband speaker (Visaton - FR 8 WP 8 Ohm) and two omni-directional microphones (Behringer – Type: ECM8000). The internal MLS sound is emitted as the signal for 5.46s for each measurement. The measured sound pressure levels are obtained using DIRAC 6.0 software (Bruël & Kjær /Acoustics Engineering).

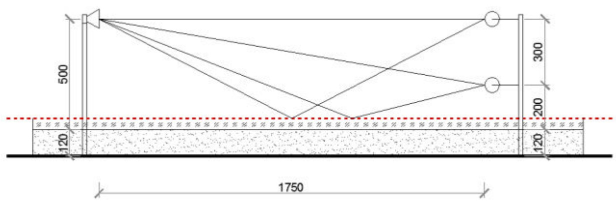


Figure 1. Measurement setup. Dimensions in mm.

The measurement setup is presented in Figure 1 with a distance of 1.75 m between the source and receivers. The height of source is 0.5 m and the two microphones are located at a height of 0.5 m and 0.2 m. The vegetated roofs are considered as a two-layer material with the vegetation layer on the top and substratum at the bottom. Since the vegetated surface is rough, the exact surface position cannot be determined, the effective height of source and two microphones are h_s = (0.5-d) m, h_{r1} = (0.5-d) m and h_{r2} = (0.2-d) m, where d is the thickness of vegetation layer to be fit in the computational calculation.

4. Measurement Sites

Before carrying out the experiment on urban vegetated roofs, the accuracy and reliability of the vegetated roof measurement systems are tested on soils (d_{soil} = 0.12 m) covered with Spirea foliage (950 g per layer) in the laboratory. It is measured in a wooden frame of 1.8 m*1.2 m*0.6 m which is sufficiently larger than the Fresnel zone area from the reflection of sound by the surface for the frequency range of interest [15]. To study the influence of the frame boundary, the measurements are taken at full scale and half scale as shown in Figure 2.

After that, the measurements are taken on three urban vegetated roofs: Cascade Building and MMP Building at the campus of TU/e and one Residential Building located at a former Philips

Figure 2. Measurement Sites. Left top: laboratory conditions (half-size set-up); Right top: Cascade Building (site #1); Left bottom: MMP Building (site #2); Right bottom: Philips Building (site #3);

terrain (Philips Building) as shown in figure 2.

5. Results And Discussion

5.1 Indoor Measurement

In the laboratory experiment, the acoustic surface impedance of soil covered with 1 to 6 layers of foliage are examined using the proposed measurement system with the two-layer hard-backing extended-reaction Miki model. The results are presented in Figures 3 and 4. It is shown that the half-size set-up can obtain a slightly better fit than that of full-size set-up with a total fit error (total difference between measured and predicted level differences in all 1/3 octave band frequencies) of 6.8dB with thickness 1 and 7.2dB with thickness 6 (half-size set-up), respectively. Even though, in general, the predictions in laboratory condition are acceptable according to the Nordtest method, the fitting not very good in frequency range between 400-800 Hz and at around 2k Hz. The possible reason for the poor fitting is the reflection from the wooden frame and room boundaries. Therefore, this measurement system needs to be tested in the open space on real urban vegetated roofs.

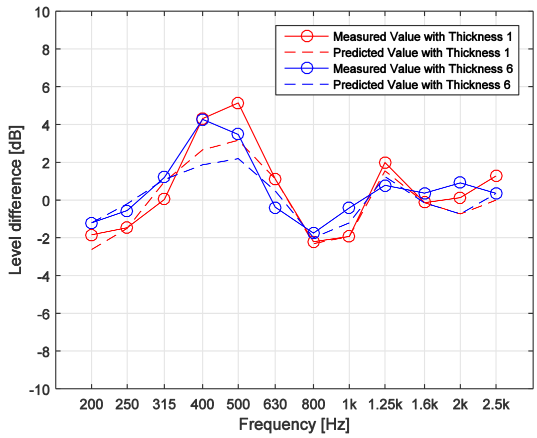


Figure 3. Level differences obtained in full-size set-up in laboratory. Thickness 1: 950g foliage; Thickness 6: 950*6=5710g foliage.

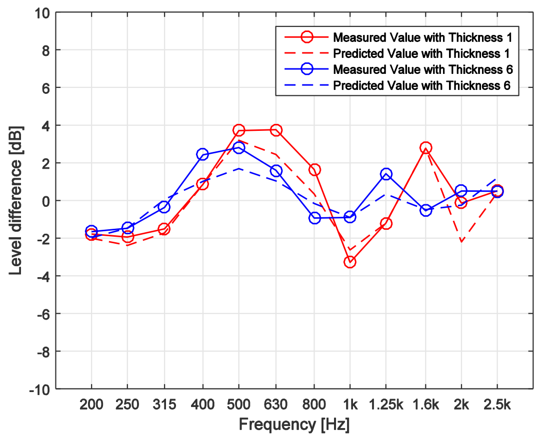
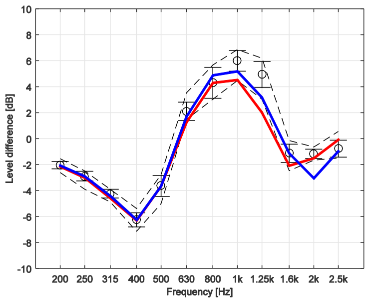
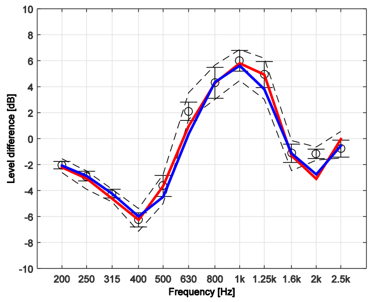


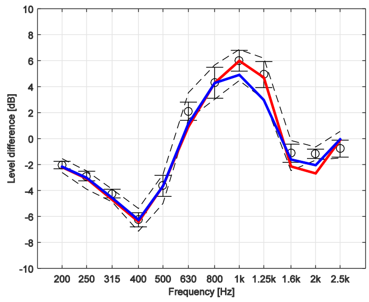
Figure 4. Level differences obtained in half-size set-up in laboratory. Thickness 1: 950g foliage; Thickness 6: 950*6=5710g foliage.



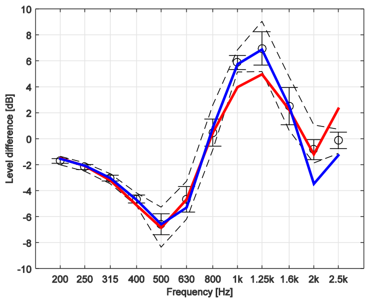
Prediction with Delany-Bazley Model on Cascade Building (site #1)



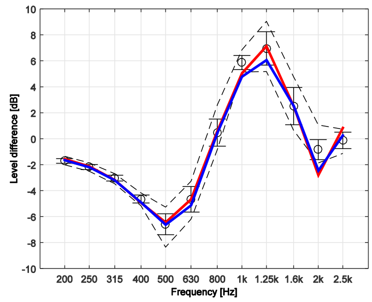
Prediction with Slit Pore Model on Cascade Building (site #1)



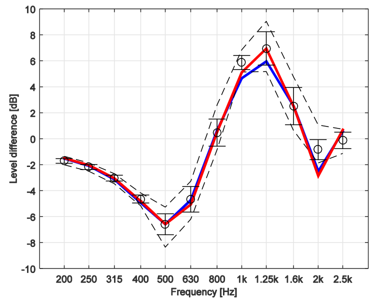
Prediction with Miki Model on Cascade Building (site #1)



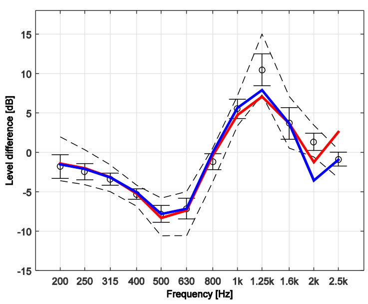
Prediction with Delany-Bazley Model on MMP Building (site #2)



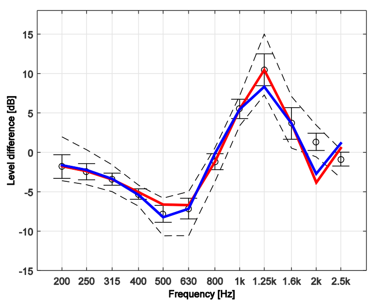
Prediction with Slit Pore Model on MMP Building (site #2)



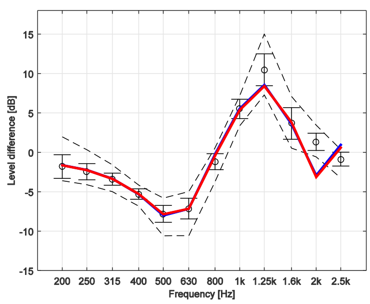
Prediction with Miki Model on MMP Building (site #2)



Prediction with Delany-Bazley Model on Philips Building (site #3)



Prediction with Slit Pore Model on Philips Building (site #3)



Prediction with Miki Model on Philips Building (site #3)

Figure 5. Comparison of level difference predictions using two-layer (red lines) and one-layer versions (blue lines) of Delany-Bazley Model, Slit Pore Model and Miki Model with measured data (open circles). The dashed lines show the maximum and minimum measured data from the various measurement locations.

5.2 Green Roofs

Figure 5 contains level difference predictions using the hard-backed one-layer and two-layer versions of impedance models with the measured data at these three urban vegetated roofs. For each vegetated roof, the measurement locations (4 on Cascade Building; 12 on MMP Building and 14 on Philips Building) are distributed evenly over the roof with different orientations. The measured sound pressure level differences are averaged with a standard deviation less than 4dB. In general, in the low frequency range (below 800 Hz), both the two-layer and one-layer versions of these three impedance models can obtain reasonable fits in all the cases. However, for the whole 1/3 octave band frequency range, the total error using the one-parameter double-layer Delany-Bazley model are relatively large with 7.8 dB, 8.2 dB and 12.9 dB in the three cases, respectively. Even though, the total error using the Delany-Bazley model can be reduced to 5.9 dB, 5.4 dB and 10.0 dB with a single-layer approach. However, the parameters derived from the fit are not physically reasonable in some cases as marked in Table 1. Furthermore, it is clear that two-layer form of Slit-pore and Miki models results in a better fit than the one-layer form, especially in the frequency range between 1k-1.6 kHz, implying that the agreement between the predicted and measured level differences can be improved by using hard-backed two-layer impedance models compared with hard-backed one-layer versions. Therefore, the best-fit model parameter values for level difference data using double-layer version impedance models from 3 sites are compared in Table 1. Although, the total error predicted with double-layer Miki model can compare with that with double-layer

Table 1 Comparative best-fit model parameter values for level difference data from 3 sites

		Vegetation				Soil				
		Flow Resistivity	Tortuosity	Porosity	Thickness	Flow Resistivity	Tortuosity	Porosity	Thickness	Total Fit Error
		[kPa s m^{-2}]	[-]	[-]	[m]	[kPa s m^{-2}]	[-]	[-]	[m]	[dB]
Site 1 Cascade Building	Initial Value	5,00	1,50	0,80	0,010	40,00	1,50	0,40	0,050	-
	2 Layer MK Model	4,02	1,17	**1,13**	0,007	14,28	1,10	0,35	0,079	5,57
	2 Layer SP Model	4,37		0,65	0,010	46,30		0,39	0,073	4,90
	2 Layer DB Model	5,35			**-0,003**	64,40			0,044	7,83
Site 2 MMP Building	Initial Value	5,00	1,50	0,80	0,010	40,00	1,50	0,40	0,200	-
	2 Layer MK Model	1,53	**0,77**	0,76	0,009	7,17	2,61	0,33	0,342	4,61
	2 Layer SP Model	4,75		0,98	0,004	40,60		0,25	0,398	4,83
	2 Layer DB Model	14,87			**-0,008**	80,23			**1,659**	8,18
Site 3 Philips Building	Initial Value	5,00	1,50	0,80	0,010	40,00	1,50	0,40	0,070	-
	2 Layer MK Model	4,24	**0,59**	0,38	0,015	17,54	2,28	0,27	0,066	9,51
	2 Layer SP Model	0,79		0,76	0,010	57,30		0,21	0,098	8,61
	2 Layer DB Model	5,65			**-0,012**	98,19			0,106	12,85

Slit Pore model with less than 1dB in difference, non-physically reasonable values as marked in Table 1 can be detected in the prediction with double-layer Miki model. Apart from that, there are only 6 parameters to be fit using double-layer Split Pore model during the computation comparing with 8 parameters using double-layer Miki model. For the prediction of the acoustic impedance of urban vegetated roofs, the hard-backed double-layer Slit Pore model is preferred based on these results. At last, the predicted acoustic impedance and absorption coefficient for normal incident sound waves for these three urban vegetated roofs using the optimized hard-backed double-layer Slit Pore model are presented in Figures 6 and 7. The absorption coefficients of three vegetated roofs level at between 0.4-0.6 for frequency range between 800Hz and 2.5kHz.

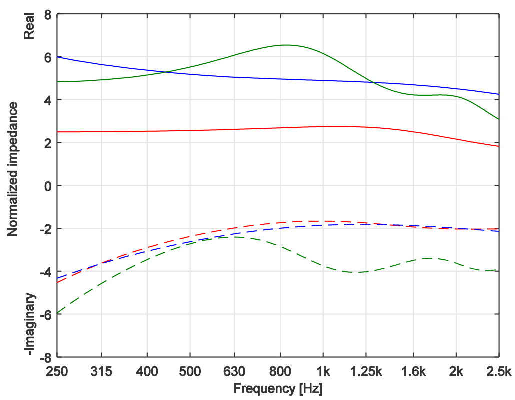


Figure 6. Predicted acoustic impedance of three vegetated roofs on Cascade Building (red lines), MMP Building (blue lines) and Philips Building (green lines) using hard-backed double-layer Slit Pore model.

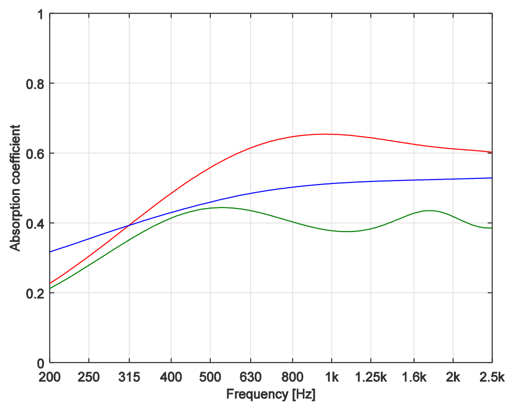


Figure 7. Predicted absorption coefficient for normal incident sound waves of three vegetated roofs on Cascade Building (red lines), MMP Building (blue lines) and Philips Building (green lines) using hard-backed double-layer Slit Pore model.

6. Conclusions

The performance of single-layer and double-layer versions of Miki surface impedance model are compared with Delany-Bazley model and Slit Pore model regarding the prediction of acoustic impedance of urban vegetated roofs. Although the hard-backed single-layer Delany-Bazley model has generally provided a relatively accurate fit between predicted and measured level differences, it fails to give a physically reasonable value for the acoustic properties of vegetation and soil. By using a double-layer version of impedance models, both Slit Pore model and Miki model have been proved successful for predicting the acoustic impedance of vegetated roofs. However, the hard-backed double-layer Slit Pore model is computationally convenient since it requires less parameters to be fit and produces less non-physically reasonable predicted parameters. Therefore, it is recommended for the further research on vegetated roofs. In further work, the non-physically reasonable values are to be improved by defining the constraint boundary for each parameter. In addition, the fit in the frequency range around 2kHz is not completely satisfied, possibly due to the loss of coherence between direct and reflected wave. This will be explored in further which is in progress as well.

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