# Diffusion coefficient of vegetation: measurements and simulation

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This paper reports the initial results of an investigation of the diffuse sound reflection from two typical bedding plants in Europe. It is a part of a larger study of the acoustic properties of vegetation, aiming at reducing noise from urban traffic. Directional diffusion coefficients of the plants have been measured in a semi-anechoic chamber and polar responses that represent sound energy distribution on semicircles surrounding the plants have been obtained. The results show that the plants diffusely reflect sound energy mainly at middle and high frequencies. In parallel, a simulation model based on the finite-element method (FEM) for predicting diffuse reflections from plants has been developed. The model takes into account impedance of foliage and soil measured in an impedance tube, and their geometric characteristics. There is good agreement between prediction and measurement.

# 1 Introduction

Measurement and prediction of surface acoustic diffusion (scattering) [3, 4] properties have mainly been explored in the context of sound fields in enclosed spaces. Research regarding outdoor spaces is scarce, although studies have shown that in the case of urban spaces whose boundaries feature irregularities or vegetation, diffuse (scattering) reflections efficiently affect the sound field.

This paper focuses on diffuse (scattering) properties of vegetation. In this context previous investigations have primarily been in to the global effect of vegetation, e.g. the overall increase of sound level [2,7] caused by vegetation in comparison with empty space. Other recent studies have measured random incident scattering coefficient that characterizes the energy reflected in a non-specular manner compared to the overall (specular plus non-specular) energy of the reflected wave [9]. The purpose of this coefficient is to characterize surface scattering for use in geometrical room modelling programs. Data for scattering coefficients of vegetation would be very useful for more accurate predictions of acoustic performance in an urban space with vegetation. The other essential problem in urban sound field prediction is a possibility to characterize the diffuser (vegetation) performance and the degree of diffusion produced by diffuser in a manner of diffusers used in the indoor spaces. For this purpose a diffusion coefficient that indicates the uniformity of the reflected sound can be a useful measure [3,6]. Similarly, diffusion coefficient can reveal how the scattered energy is spatially distributed from plants. This would be essential for studying the effect of, for example, vegetated barriers or green walls placed on buildings facades with respect to position of the traffic and distance/height to/of the nearby buildings.

The objective of the work in this paper is to investigate diffuse reflections from plants that are typical of those grown on the sides of roads in Europe and to establish a simulation tool for predicting diffusion coefficients for vegetation. This is realized by (1) the free-field measurement procedure of diffuse reflection of two types of bedding plants; (2) developing a computer simulation model using the Finite-Element Method (FEM); (3) comparison between measured and simulated data.

The rest of the paper is organized as follows: Section 2 presents a description of the plants, the methodology of the measurement procedure and of the simulation tool; Section 3 depicts the results of measurements and simulation and also a comparison between them; while Section 4 provides conclusions.

# 2 Method

## 2.1 Description of plants

Two bedding plants have been studied, namely Heather and Pansy in pots with soil as show in Figure 1. Table 1 presents data for height of the plants, height of the pots, average length and area of the leaves.

Figure 1. Samples of Heather (above) and Pansy (below) plants used in measurements.

Table 1: Dimensional properties of plants and pots.

| Plant | Heather | Pansy |
|---|---|---|
| Sample height (mm) | 80 | 35 |
| Pot height (mm) | 7 | 10 |
| Leaf length (mm) | 2 | 25 |
| Leaf area($mm^2$) | 2 | 375 |

## 2.2 Measurement procedure

Free field measurements of diffusion coefficient were performed in a 2D semicircle according to the ISO standard [6] in a semi-anechoic chamber of dimensions 5m x 5m x 3.65m (length, width and height) where the absorptive materials have also been placed on the floor. The measurements were performed in the full-scale. Strictly speaking, the way of evaluating the diffuse reflections depends whether a sample causes scattering in one or more planes [3]. Diffusion coefficients for single-plane surfaces are obtained from semicircular measurements in the plane of maximum diffusion. More complex surfaces may scatter sound in a more diffuse manner. Thus measurements of diffusion coefficient would have to be performed over the surface of a hemisphere. However it needs to be considered if plants can be considered as one-dimensional or multi-dimensional diffusers. Then again, since no regular pattern can be foreseen in the arrangement of leaves and branches it can be argued that the diffusion coefficients obtained using hemispherical and semicircular measurements would be rather similar. Thus a semicircular arch consisting of 16 evenly spaced ½" condenser microphones has been built in the anechoic chamber as shown in Figure 2.

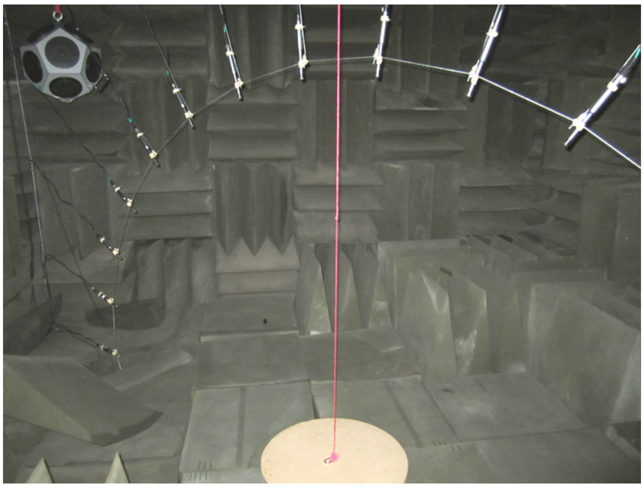


Figure 2. Microphone arch built in the semi-anechoic chamber.

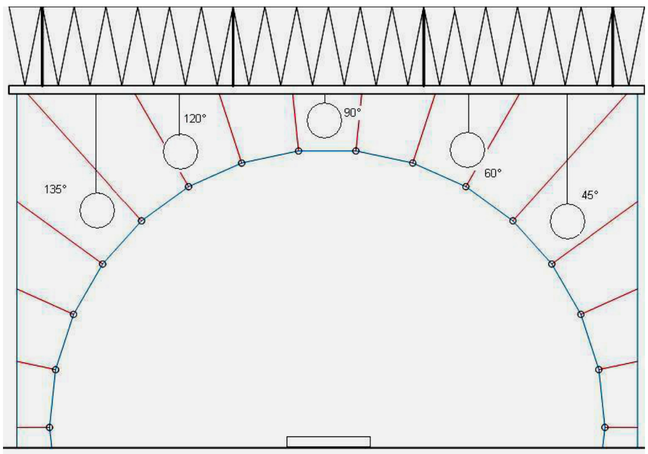



Figure 3. 2D view of the anechoic chamber with microphone and speaker positions.

A 60cm diameter circular plate made from MDF of 20cm thickness was placed on the floor in the middle of the arch and surrounded with absorptive material. The sample must be of sufficient size so that it affects the acoustic waves. On the other hand, if the sample is too large, a scattered wave from the middle of the sample could arrive at the microphone at the same time as a direct reflection from the edge of the sample. Generally, the size of the plate has been chosen considering the rule that 80% of the reflections from the plate/sample should be outside of the specular zone [3] as demonstrated in Figure 4.

Figure 3 shows the three positions of an omnidirectional loudspeaker at angles of incidence of 45°, 60° and 90° used in measurements. The distance from the middle of the plate to the microphones and to the loudspeaker positions was of 1.5m and 2m respectively. These distances were chosen to comply with the conditions that measurements should be made in far-field which can be achieved if at least 80% of the receiver positions are outside the specular zone. These geometries however set limitations to the frequency for which the edge effect would affect the results.

For the measurements the plants were closely arranged and placed on the plate. The diameter of the Heather plants sample was 48cm and size of the Pansy plants sample was 40cm x 58cm. Measurements were performed with WinMLS software using an MLS signal with the upper frequencies of 5kHz.

The measurement and post-processing procedures have been performed strictly according to ISO 17497-2 [6]. First, the impulse response of the loudspeaker placed on the floor in the middle of the arch was measured. Next, impulse responses from the plate were measured for each loudspeaker position. Finally, impulse responses were measured with each of the plant samples. These measurements were performed twice for each of the above mentioned situations.

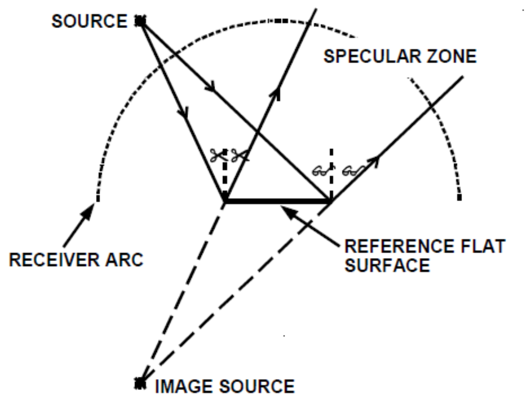



Figure 4. Representation of specular zone (after Cox [3]).

Post processing of the results were done in MATLAB. For each microphone-loudspeaker set the impulse response of the plate was subtracted from the impulse response of the sample and then the impulse response of the loudspeaker was deconvolved from the resulting impulse response and a rectangular windowing applied. Next, the windowed impulse response was Fourier Transformed and the third-octave levels, in decibels, were obtained in each one-third frequency band of interest. The third-octave levels are the power in each frequency band obtained by a numerical integration assuming infinite roll-off filters at the edge of the band. For a fixed source position at angle $\theta$, in each third-octave band, the directional diffusion coefficient $d_\theta$

was calculated from the set of sound pressure levels $L_i$, from the $n$=16 receivers according to the formula:

$$d_\theta = \frac{(\sum_{i=1}^{n} 10^{L_i/10})^2 - \sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}{(n-1)\sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}. \quad (1)$$

Alongside with directional diffusion coefficient a scattered polar response that represents how the scattered energy is spatially distributed was calculated for each angle of incidence and the frequency band of interest. It is worth noting that an ideal diffuser produces a polar response that is invariant to the angle of incidence, the angle of observation and the frequency (within its operational bandwidth) [3].

## 2.3 Simulation procedure

### 2.3.1 Simulation of diffuse reflection

Simulation of diffuse reflections was performed in COMSOL™ using the Finite Element Method. FEM is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as integral equations. This method is good for solving partial differential equations over complicated domains but isn't the obvious choice when it comes to simulating the scatter (diffuse) reflections from a diffuser. A Boundary Element Method (BEM) based on the Helmholtz–Kirchhoff integral equation, has already been introduced as described in [4].

The simulation had to accurately model the effects of acoustic reflections (scattering) both from the plants and the environment inside the semi-anechoic chamber. For this purpose 2D geometrical models of the soil, plants and a semi-anechoic chamber with receivers and sources with geometries the same as in the measurements were constructed. A sample consisting of the plant, soil and a pot was modelled by two layers representing a plant and a soil. The layer that represents a plant has been constructed by a function in MATLAB that consists of four parameters, namely the average area of a single leaf, sample average height, the density of the plant, and sample length. The output of the function is an array of points that must be plotted. These points are then linked to produce a rough surface. The soil layer is simply drawn as a rectangular sub-domain. The depth is the same as the height of the pots and the width is the size of the sample.

The boundary conditions for the semi-anechoic chamber were set to "radiation conditions" with no incoming pressure wave. This property enables the waves to pass the boundary without any reflection. The intention is to match the anechoic chamber conditions with reflections coming from the sample only. As for the two other domains, the outer part of the soil is considered as a hard wall (flower pots and wooden plate) with hard boundary condition. The other boundary conditions are calculated automatically by using the transmission and reflection coefficients that depend on the impedance of the different domains. The complex impedance of plants and soil are imported using data obtained a prior in the measurements using an impedance tube. Loudspeakers with positions the same as in the measurements were simulated by a sub-domain that was simplified to a disk. Furthermore, the loudspeakers boundaries are then configured as "radiation conditions" in which wave with pressure $p = p_I$. By selecting this option, the boundaries will generate the sound wave with pressure $p_I$ - the incident pressure wave.

Mesh generation is also an important consideration. In order to perform the finite element analysis, the domain (i.e. semi-anechoic chamber, plate and samples) had to be decomposed into small elements connected to a mesh. As the model had no particular geometric orientation, the type of elements used was kept at the default setting (Lagrange Quadratic). It was considered that the largest element size must be smaller than 1/5 of the smaller wavelength. Generally, the simulation will never exceed 2000Hz, so this will give an element size of approximately 0.04m. Unfortunately, due to limitations of the computation resources a slightly bigger element size has been selected for elements of the mesh in the semi-anechoic environment with a smaller mesh size around the important points (boundaries and measurement points).

For calculation of acoustic pressure distribution in the chamber, the general wave partial differential equation (PDE) was reduced to Helmholtz equation [8]:

$$\nabla \cdot \left( -\frac{1}{\rho_0} \nabla p \right) - \frac{\varpi^2 p}{\rho_0 c_0^2} = 0, \qquad (2)$$

where $\varpi = 2\pi f$ is angular frequency, $\rho_0$ is the density of fluid (air).

The solving option for the pressure was set to 'parametric time harmonic' with frequency as a changing parameter. The optimum step of 2Hz has been found considering the trade-off between the computation resources and accuracy of the results. Once the solving is performed, the data are exported to MATLAB for post-processing. The data represent the scattered sound pressure level collected in a semi-circle of 1.5m radius around the sample obtained for a particular angle of incidence and between 200Hz and 1kHz. Points are placed at every degree of reflection. The simulations are solved twice: once with the sample and once without (i.e. plate only). Using a specially built function in MATLAB the comparison between these two simulations provides the specular scattered level at a specific incident angle. These values are integrated over 1/3 octave frequency bands and scattered pressure levels $L_i$ representing the amount of sound energy that is scattered (disused) by the sample toward the angle $i$ are then calculated.

### 2.3.2 Graphic User Interface (GUI)

The whole MATLAB processing (post-processing of the measurements and simulations) is gathered in a unique Graphical User Interface (GUI), as shown in Figure 5. In the GUI for post processing the measurement results it is possible to select the number of channels, sampling frequency and distances to the microphones and speakers. The user also selects a folder with impulse responses obtained at the measurements for a particular speaker position. For the simulation results a selection of files with scattered sound pressure level from a plate and a sample is possible. The user can also modify the starting frequency and the frequency step. For the results from measurements and simulations the polar plots of scattered sound pressure levels are plotted for a selected 1/3 frequency band and diffusion coefficients are calculated.

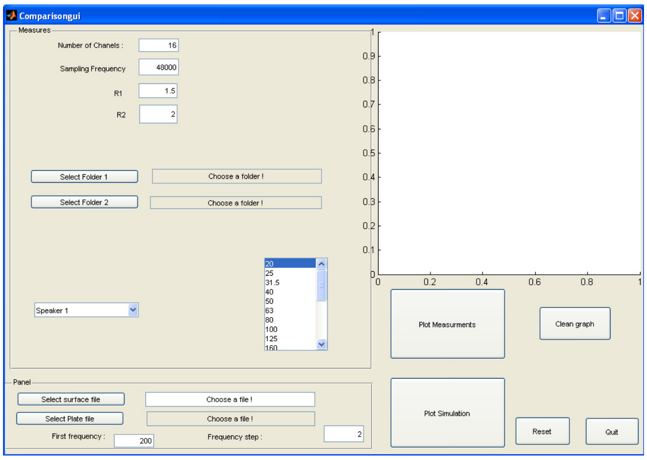



Figure 5. GUI for post-processing the measurements and simulations results.

# 3 Results

## 3.1 Measurement results

Figures 6 - 9 present polar responses of scattered energy (in dB) for Heather plants for 45° and 90° speaker incident angles obtained for various 1/3 octave bands. Data of the directional diffusion coefficient averaged over two measurement repetitions of Heather and Pansy plants are presented in Table 2.

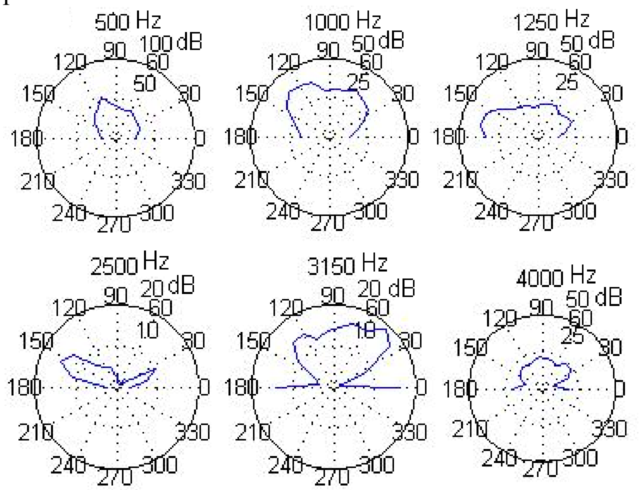
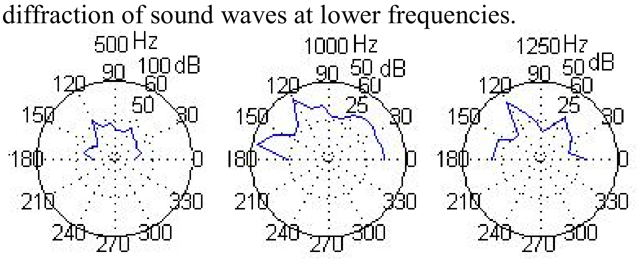



Figure 6. Polar responses of scattered energy (in dB) for Heather plants for 45° speaker incident angle.

The blue lines represent scattered energy obtained by interpolating data obtained from 16 microphones. The circular lines show the relative scattered levels in dB. The polar plots have been plotted for frequency bands starting from 500Hz based on the size of the sample which causes diffraction of sound waves at lower frequencies.



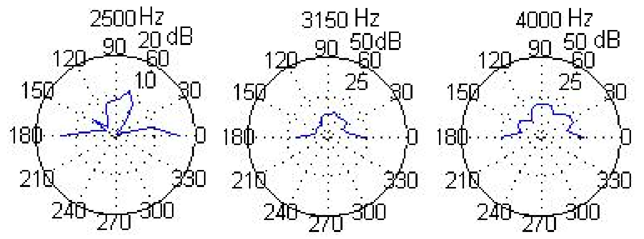




Figure 7. Polar responses of scattered energy (in dB) for Heather plants for 90° speaker incident angle.

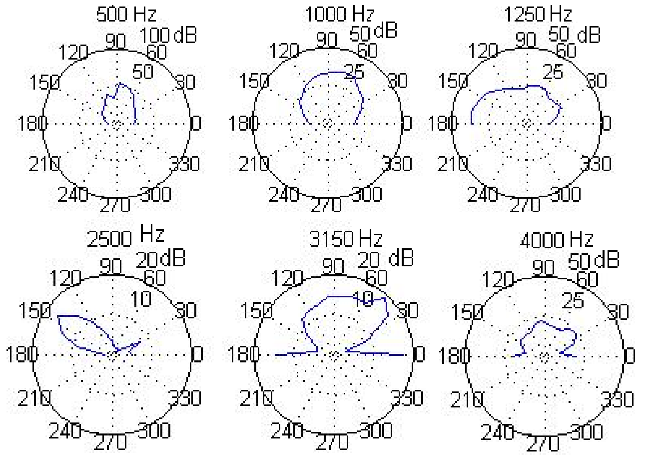



Figure 8. Polar responses of scattered energy (in dB) for Pansy plants for 45° speaker incident angle.

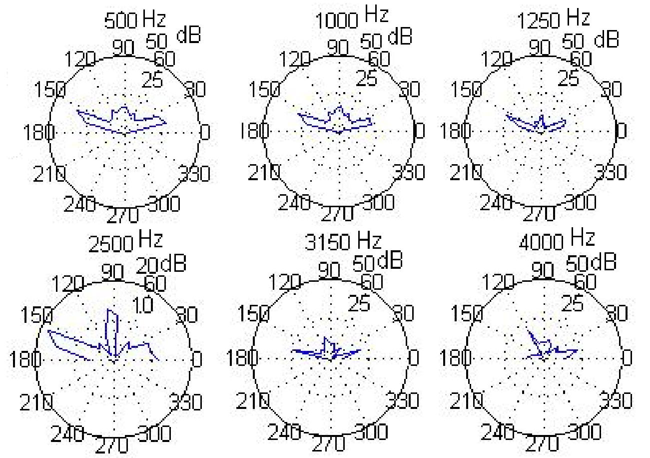



Figure 9. Polar responses of scattered energy for Pansy plants for 90° speaker incident angle.

It can be seen that polar responses differ between two plants, among the frequency bands and are dependent on the angle of incidence. Generally, the higher scattering pattern can be observed for higher frequencies (above 1kHz) as expected. It can be noted that for the 45° angle of incidence the scattering plots for Heather and Pansy samples are very similar which may be explained by the fact that scattering is caused mainly by the edges of the samples rather than the leaves. However for normal incidence (90°) the patterns of scattered plots are different. Polar plots for Heather plants seem to be less dependent on angle of observation compared to the Pansy sample. This might be due to a scattering effect from the branches of the Heather sample [1]. Moreover, the larger sized Pansy leaves may behave as membranes at higher frequencies and thus absorb more sound energy compared to Heather. This can be confirmed by lower values of the scattered energy in Figure 9 compared to Figure 7. It can be also confirmed by higher diffusion coefficient values obtained for normal incidence for Heather plants compared to Pansy plants (Table 2).

Table 2: Directional diffusion coefficient for Heather and Pansy samples.

| Angle of incidence: 45° | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Sample* | *500* | *1k* | *1.25k* | *2k* | *2.5k* | *3.15* | *4k* |
| Heather | 0.14 | 0.33 | 0.35 | 0.29 | 0.47 | 0.55 | 0.63 |
| Pansy | 0.16 | 0.33 | 0.27 | 0.23 | 0.22 | 0.32 | 0.35 |
| **Angle of incidence: 60°** | | | | | | | |
| Heather | 0.23 | 0.16 | 0.31 | 0.32 | 0.28 | 0.26 | 0.27 |
| Pansy | 0.06 | 0.26 | 0.29 | 0.39 | 0.31 | 0.34 | 0.37 |
| **Angle of incidence: 90°** | | | | | | | |
| Heather | 0.51 | 0.48 | 0.48 | 0.50 | 0.35 | 0.40 | 0.54 |
| Pansy | 0.41 | 0.36 | 0.30 | 0.39 | 0.31 | 0.35 | 0.36 |

## 3.2 Simulation results

In Figure 10 polar plots of scattered energy (in dB) obtained for the Pansy sample and a 45° angle of incidence are shown (red lines). The plots also show results obtained from measurements (blue lines). It can be seen that generally there is agreement between results obtained from simulations and measurements in terms of tendency of distribution of the scattered energy. However, it can be seen that the information given by the simulation is much more detailed than that obtained from the measured results. This is mainly due to the small number of receivers used in the measurements and thus a large step in the polar response (12°) compared to the simulations (1°).

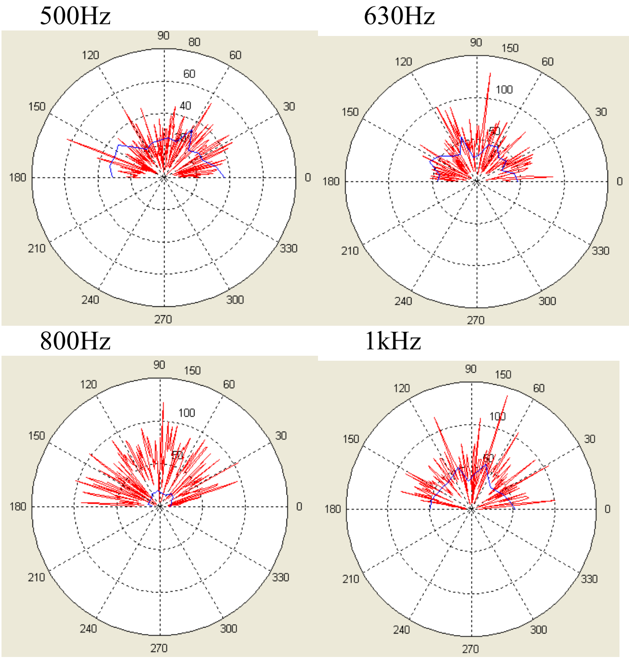



Figure 10. Polar plots of scattered sound energy (in dB) for the Pansy sample and 45°of angle of incidence. (—) simulation results, (—) measurements result.

## 3.3 Parametric study on simulation accuracy

In order to find out how the step size on polar responses influences the accuracy in agreement between simulated and measured results adjustments in post-processing of the simulation results were made as follows. First, a step of 12° was applied and results for 500Hz and 800Hz and 45°of angle of incidence are displayed in Figure 11.

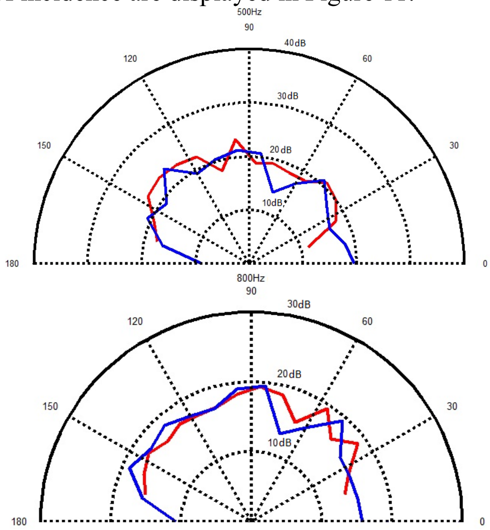



Figure 11. Polar plot of scattered energy (in dB) obtained from simulation (—) and measurements (—) with a 12° step for 500 and 800Hz and 45°of angle of incidence.

This figure shows some differences between measured and simulated results. These could be caused by the ground effect from around the sample that has not been considered in the simulations. Indeed, the foam placed on the floor of the anechoic chamber may act differently than the input in the simulation (total absorption).

In order to examine the above differences the Relative Percentage Difference (RPD) has been calculated between two sets of data (simulations and measurements) as follows:

$$\%RPD = \left( \frac{|X_1 - X_2|}{\overline{X}} \right) \times 100\%, \quad (3)$$

where $X_1$ and $X_2$ are the values obtained, respectively, for simulations and measurements for a particular angle on the polar plot and $\overline{X}$ is the mean between $X_1$ and $X_2$. Generally values of RPD below 20% are considered as acceptable [10]. The RPD values are shown in Figure 12.

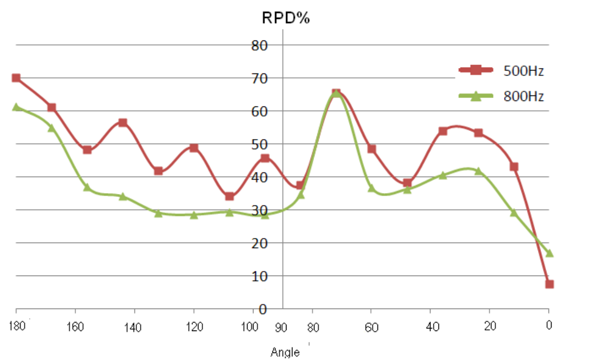



Figure 12. RPD (%) between simulated and measured results with 12° of step for 500Hz and 800Hz.

It can be noticed that RPDs are large but the relationship is relatively constant. However, the deviance is too large to consider that the apparent accuracy is trustworthy.

As a way of improving the observation without changing the simulation, the top semi-circle of the polar response has been divided into 8 equal parts. The average of the simulated values located in each part has been calculated and plotted in the centre of the area as demonstrated in Figure 13 and RPD has been also calculated (Figure 14).

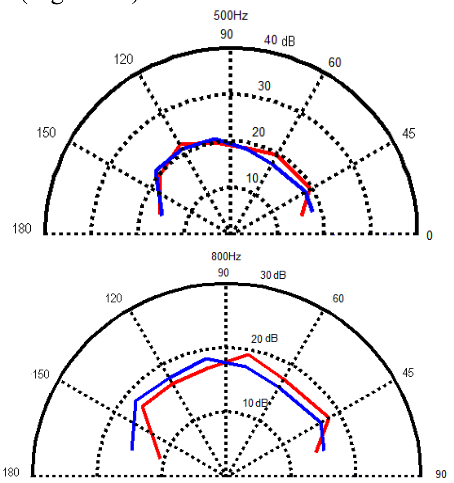



Figure 13 Polar plot of scattered energy (in dB) obtained from simulation (—) and measurements (—) with 22.5° of step for 500Hz and 800Hz and 45°of angle of incidence.

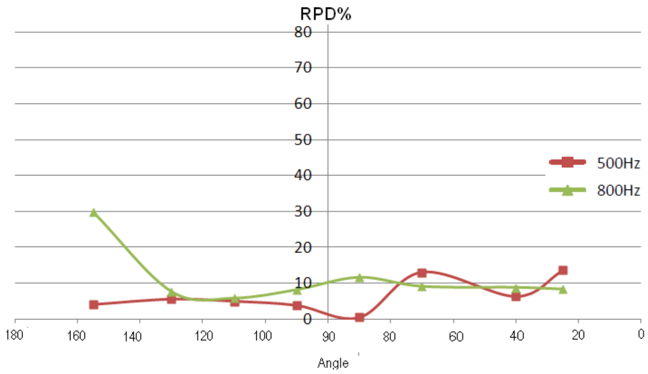



Figure 14. RPD (%) between simulated and measured results with 22° of step for 500Hz and 800Hz.

The polar graphs contain less information but the difference between results is smaller as the relative percentage difference is much smaller especially for higher frequencies.

The other ways of improving agreement between results obtained from the measurements and simulations may be as follows: 1) more detailed simulation of the plant's geometry; 2) modelling of the soil based on, e.g. four soil parameters, porosity, flow resistivity, tortuosity, and the standard deviation of the pore size, as it has been described in [5]. This could improve the reliability of the simulation especially in the low frequency range; 3) adding more microphones in the measurements to the semi-circle in the anechoic chamber would reduce the step size between each of them and thus improve the accuracy.

# 4 Conclusions

This paper reported some initial results of an investigation on the diffuse reflection from two typical bedding plants grown on roadsides in Europe. Results obtained from measurements have shown that the plants diffusely reflect sound energy mainly at middle and high frequencies, as expected. Leaf size and the presence of stems seem to be important for diffusive properties of plants confirming findings reported in the literature. It was also noticed that scattering from the plants is dependent on the angle of incidence of the incoming sound.

Comparing measurements with simulations agreement in the general pattern of polar plots were demonstrated. Also noted was step size in polar responses is a major consideration. Regarding the accuracy of simulation, the predicted diffusion pattern from plants may depend on accuracy of modelling the plant geometry and the model used to describe soil properties.

# Acknowledgments

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