Application of the two-microphone method for in-situ ground impedance measurements

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Abstract

The two-microphone method is a convenient and well- known procedure to measure the surface impedance in-situ. Its proposed implementation in an ANSI standard ("Direct Deduction of Ground Impedance") will contribute to it's wide use. The applicability and adequacy of this method for this purpose is investigated in this article. Measurements of the surface impedance of a number of grounds, which are carried out with the three ANSI S1.18 geometries, are presented. It is shown that the two-microphone method does provide reasonable results on not too hard grounds for frequencies above about 400 Hz, while the performance at lower frequencies and for hard grounds is poor. Practical advise is given on the number of measurements needed and the data pre-processing.

Keywords: Ground impedance; In-situ impedance measurement; ANSI S1.18

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Introduction

For the prediction of the sound propagation, the surface impedance of outdoor grounds is an important parameter together with the meteorological (wind speed profile and temperature)

data. In general, there're two different methods to determine the surface impedance. On the one hand, a number of impedance models are available ranging from simple empirical one-parameter models [1] over microstructural models [2] to sophisticated analytical models [3]. These models, however, do often require parameters which are partly difficult to measure and don't take into account the heterogeneity of the real ground. Therefore, the surface impedance should preferably be determined from acoustical in-situ measurements [4]. The ANSI standard S1.18 [5] describes a procedure for that purpose: The transfer function between two microphone positions is measured and then compared (visually) with pre-calculated transfer functions for the three different proposed measurement geometries and a number of absorber parameter combinations. While this method is easy to use and rather robust, it is restricted to specific impedance models. Currently, a standardisation of the two microphone technique [6, "Iterative Procedure"] is considered (ANSI working group S1/WG 20) so that the impedance can be calculated from the geometry and transfer function without the use of an impedance model.

In the following the adequacy of this method is investigated. Measurements were done for a number of grounds with the three standardised geometries in order to determine the reliability and repeatability of the procedure, the applicable frequency range as well as the influence of the ground impedance and the choice of the test site.

All impedances presented are normalized to the impedance of air and an $\exp(i\omega t)$ time dependence is assumed.

Experimental procedure

Test sites

Measurements of the two-microphone transfer function were done at four different locations:

1. A lawn surrounded by trees and a building on one side. Mostly flat in the centre but somewhat hilly near the borders. Dry condition.
2. A grass covered soccer field of standard size. Dry condition.

3. A flat sand covered area used for long jump training. Upper layer of about 5 cm dry, wet below.

4. An ash covered sports field, about half the size of the soccer field. Slightly wet as it had rained the day before.

The weather was sunny with temperature ranging from 22° - 27°C and wind speeds were lower than 1.5 m/s. The background noise at all locations was low (< 45 dB(A)).

Measurement set-up and procedure

The measurement set-up is shown in fig.1, the following equipment was used:

For test site 1, the sound source consisted of a Philips EJ 1030 compression driver with a 20 cm tube of 2 cm internal diameter. This source had a sound pressure level which did vary less than ± 1.5 dB for frequencies up to 4 kHz (< 45° off axis) and therefore resembles a point source on which the sound field model is based. The test signal was pseudo-random noise.

Because this source did have a rather poor low frequency performance, for test sites 2 – 4 a 10 cm loudspeaker in a (13 cm)³ closed cabinet was chosen and pink filtered pseudo-random noise used as test signal. The sound level at the microphone location was at least 80 dB and thereby well above the background noise.

B&K 4189 microphones (1/2", IEC 651 Type 1) with windscreens were used, the transfer function between them was determined using B&K PULSE (0 – 6400 Hz, Δf = 16 Hz, 400 averages).

Five measurements at different locations on the test sites were done except for site 3 were only one measurement was possible. Additionally, on site 1 nine measurements at the same location were done with the equipment removed and repositioned after each measurement. Three measurement geometries (tab.1) suggested by ANSI S1.18 were used.

Sound field model and impedance deduction

For the calculation of the surface impedance from the two-microphone transfer function, a widespread model for the reflection of spherical waves on a locally reacting impedance planes was used [7].

The velocity potential in the height d above the surface can be described by eq. 1 - 3.

$$\phi(d) = \frac{e^{-ikr_1}}{r_1} + [R_p + (1-R_p)F]\frac{e^{-ikr_2}}{r_2} \tag{1}$$

with

$$F = 1 - i\sqrt{\pi}w \cdot \text{cef}(-w) \tag{2}$$

r_1 and r_2 are the lengths of the direct and reflected path, R_p is the reflection coefficient for plane waves. k denotes the wave number in air, cef the Faddeeva function.

The numerical distance w is defined in eq.3 representing a common simplification of the definition by [8]. It is a function of the angle of incidence θ and the normalized surface admittance β.

$$w = \sqrt{-\tfrac{1}{2}ikr_2}\,(\sin(\theta) + \beta) \tag{3}$$

The transfer function T is defined as the ratio of the velocity potential at the upper microphone position divided by the potential at the lower microphone position (eq.4).

$$T = \frac{\phi(d,upper)}{\phi(d,lower)} \tag{4}$$

The surface impedance Z was calculated from the measured transfer function T and geometry by the Newton-Raphson algorithm which finds the zero of the function (predicted T-observed T) and therefore gains the surface impedance Z which minimizes the difference between the observed transfer function and the transfer function predicted by the model. This

very efficient method has been described in [9]. For all calculations, Matlab R2006b was used. The Matlab code can be found on the authors webpage[1].

The sound field model assumes a point reacting ground which is completely described by the angle independent surface impedance. Some grounds (e.g. snow, forest floors) can feature a low flow resistivity and may therefore be considered to be extended reacting. In this case, the estimated surface impedance will be the effective impedance / admittance β_e. An approximate solutions for a semi-infinite ground is given by eq. 5, for a hard-backed layer by eq.6 [10]: An extended reacting ground needs to be described by at least two parameters and has an angle dependent surface impedance.

$$\beta_e = m_1 \sqrt{k_1^2 - \cos^2 \theta} \tag{5}$$

$$\beta_e = -i \cdot m_1 \sqrt{k_1^2 - \cos^2 \theta} \tan(kL \sqrt{k_1^2 - \cos^2 \theta}) \tag{6}$$

with k_1 the normalized wave number of the ground, L the thickness of the layer and m_1 the ratio of the density of air ρ_0 by the complex density of the ground ρ_1.

Impedance model

For the assessment of the estimated surface impedances, the one-parameter Delany Bazley model (eq.7,8) was fitted to the impedance in the frequency range from 250 – 3000 Hz (averaged over 1/3rd octave bands) to obtain estimates of the effective flow resistivity σ_{eff}.

$$\mathrm{Re}(Z_0 / \rho_0 c_0) = 1 + 9.08 (\frac{1000 f}{\sigma_{eff}})^{-0.75} \tag{7}$$

$$\mathrm{Im}(Z_0 / \rho_0 c_0) = -11.9 (\frac{1000 f}{\sigma_{eff}})^{-0.73} \tag{8}$$

These estimates were compared with data for different grounds tabulated in the standard and given in [4] and [11]. Furthermore, the flow resistivity was determined by visually comparing the transfer function with the templates from ANSI S1.18 paying particular attention to the position of the first minimum as suggested by [12].

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[1] http://www.physik.uni-oldenburg.de/aku/

Results

The results for the nine measurements on test site 1 (lawn) at the same location are shown in fig.2 for geometry B. The repeatability of the measurement is rather high, only slight variations occur between the nine measurements even though the equipment was removed and repositioned after each measurement. The general course of the impedance does agree with models for porous absorbers for frequencies above about 300 Hz, but the decline in impedance towards lower frequencies is not expected. Furthermore, the course of the impedance is not very smooth.

Measurements with the geometries A and C, though largely comparable, show significant higher differences between the nine repetitions and also show higher fluctuations in the frequency dependence of the impedance.

In fig.3, the result of the measurement at five different locations of the lawn is shown for geometry B. In comparison with fig.2, the differences between the measurements are much larger, esp. in the low frequency range. The mean impedance is higher at these five locations and the unexpected decline in impedance with decreasing frequency starts at about 400 Hz. On the other hand, the course of the impedance is slightly more smooth.

In fig.4, the estimated surface impedance of test site 2, the soccer field, is presented for all three geometries. While the average course of the impedance does agree - for the three geometries - with know data for grass covered ground [13], geometry B shows the least fluctuations with frequency and geometry C by far the highest.

The results for test site 3, the sand area, are shown in fig.5. They generally agree with the results on the soccer field, but the low frequency performance is slightly better as the impedance does increase down to 300 Hz. The course of the impedance is smoother for geometry B, and geometry A shows an unexpected behaviour above 3 kHz.

In contrast to these two grounds of medium impedance, the measurements on the ash sports field with its compacted ground exhibit a very poor performance (fig.6). For all three geometries, the course of the impedance is very erratic and the results do not agree well.

Even if one would severely smooth the data, the decrease in impedance for frequencies lower than about 500 Hz is still unreasonable.

In fig.4 - 6, the transfer functions of the five measurements were averaged and then the impedance was calculated. Another possibility would be to calculate the impedances first and average them afterwards. For geometry A and test site 4, the two results are compared in fig.7. For high frequencies, there is only a minor difference between the two results. For frequencies below 500 Hz, averaging of the transfer functions does result in a much smoother course of the impedance though the expected increase with decreasing frequency is still not observed. Furthermore, it can be seen that the differences between the five measurements at different locations are high in this frequency range.

The effective flow resistivity σ_{eff} obtained by fitting the Delany Bazley model to the surface impedances from measurements with geometry A and B are presented in tab.2.

For test sites 1- 3, the estimated effective flow resistivities are in the range of 400 kPas/m², the predicted flow resistivity of the ash sports field is about 1700 kPas/m². In comparison, the results obtained by visually comparing the transfer functions with the templates from ANSI S1.18 are very similar for test sites 3 and 4, for the soccer field and especially the lawn the template method indicates a higher flow resistivity than the impedance fit. The results for the sand area and the ash field are in the range of flow resistivities reported in the literature for such types of grounds. On the other hand, the estimated flow resistivities for the lawn and the soccer field are higher than the maximum of 300 kPas/m² reported for institutional grass, lawn and grass covered fields.

Discussion

Concerning the reproducibility of the two microphone method, the nine measurements at the same location showed that the reproducibility is high, only small differences occur between subsequent measurements at the same location. This also indicates that small errors in the measurement geometry, which are likely to occur when repositioning the set-up, do not have a large effect on the predicted surface impedance.

On the other hand, the measurements at different locations of the same ground did show much larger deviations, esp. in the low frequency range. Therefore, for obtaining a good estimator of the "real" ground impedance measurements at different locations are necessary. Furthermore, comparing the measurement at one location with the mean of the five measurements at different locations shows that a single measurement can indeed be misleading because the impedance at the first location was well below the average impedance of test site 1.

In general, for all test sites except site 4 the course of the impedance does agree well even with simple impedance models [1] which predict a monotonous decrease of the impedance with frequency. The fluctuation of the impedance above 1 kHz (fig.3) is reasonable because such a behaviour is predicted by more advanced impedance models [3] for layers of low flow resistance on a harder backing.

The main cutback of the two-microphone method – at least with the three predefined geometries for ANSI S1.18 – is the poor performance at low frequencies and especially for hard grounds. The observed decrease of the impedance for frequencies below about 400 Hz is not expected and may result from either small errors in the measured transfer function or the actual (inhomogeneous) structure of the investigated ground not accounted for in the sound field model (eq.1).

Comparing the three used geometries, geometry B seemed to provide the best results for the investigated grounds, while geometry C did not appear to be suited for them. This does agree with the fact that the ANSI standard does recommend geometry C only for very soft grounds not included in this investigation.

Regard the question of data pre-processing, the results in fig.7 indicate that it is better to average the transfer functions and then derive the impedance than to average the impedances. While the difference between these two approaches is small for "good" measurements on softer ground, the advantage for more critical (hard) grounds is evident.

It may well be assumed that the differences between the results obtained by the two approaches are the outcome of the highly nonlinear relationship between the transfer

function and the surface impedance at low frequencies. Therefore, even small errors in the transfer function can lead to high errors in the predicated surface impedance [14] which may not be reducible by averaging the impedances. Averaging the transfer functions, however, should lead to an average transfer function not much different from the "true" transfer function and thereby leading to a surface impedance with a not so large error.

In this context it may be advisable to look for outliers by first calculating the impedance from the single transfer functions and rejecting the ones leading to an obviously wrong result. Finally, the results of the flow resistivity estimation underline the general adequacy of the two microphone method for the determination of ground impedances. In particular, the results for the sand area and the ash sports field do match the results of the template method and the values from the literature. The predicted flow resistivity of the soccer field, though higher than the maximum of 300 kPas/m² reported in the literature, appears to be reasonable as, by its use, a sports area will be more compacted than a typical lawn or other grass covered ground. Even the lawn with its flow resistivity of 365 kPas/m² does not exceed the reported values by such an extent that this result would appear to be unreasonable.

Conclusion

The two microphone method is a convenient and well known method for the in-situ determination of surface impedances. It has shown to provide a reasonable reliability and repeatability for surfaces of not too high impedance for frequencies above about 400 Hz. Under these circumstances, a good estimator for the "true" surface impedance can be found by making measurements at different locations of the area and averaging the transfer functions before calculating the impedance.

Unfortunately, the performance for lower frequencies and hard surfaces is rather poor, at least when using the three predefined geometries from the ANSI standard. Except from changes in the method itself like the use of other geometries [14], it may be recommended to fit one of the (empirical) impedance models from ANSI S1.18 to the data in the valid

frequency range to obtain an estimate on how the impedance may look like at lower frequencies [4]. This procedure resulted in reasonable estimates of the effective flow resistivity. While these estimates were sometimes higher than values reported in the literature this finding does not raise doubts about the method in general but should be considered as a warning that even grounds which appear to be visually similar may have largely different acoustical properties.

However, it must be acknowledged that fitting an impedance model to the data does to some extent void the advantage of the direct deduction of the ground impedance over the ANSI S1.18 template method.

Acknowledgement

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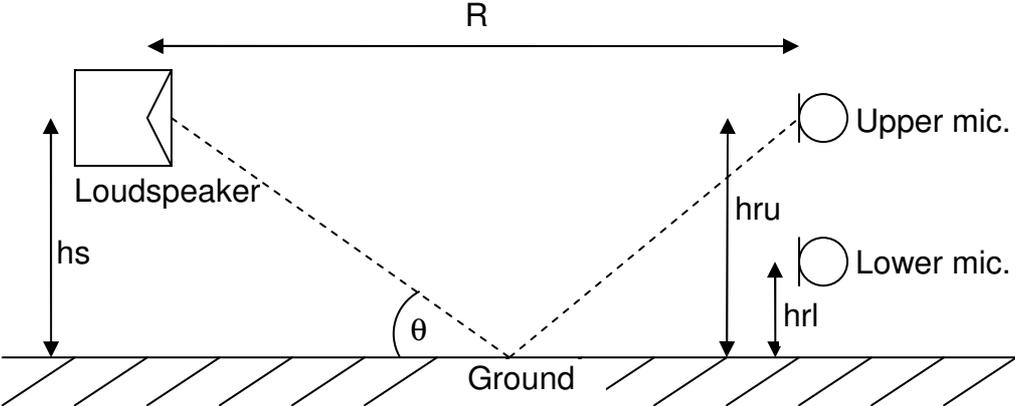
Figures

Fig. 1: Measurement set-up for the transfer function method. Values for the geometry are given in table 1.
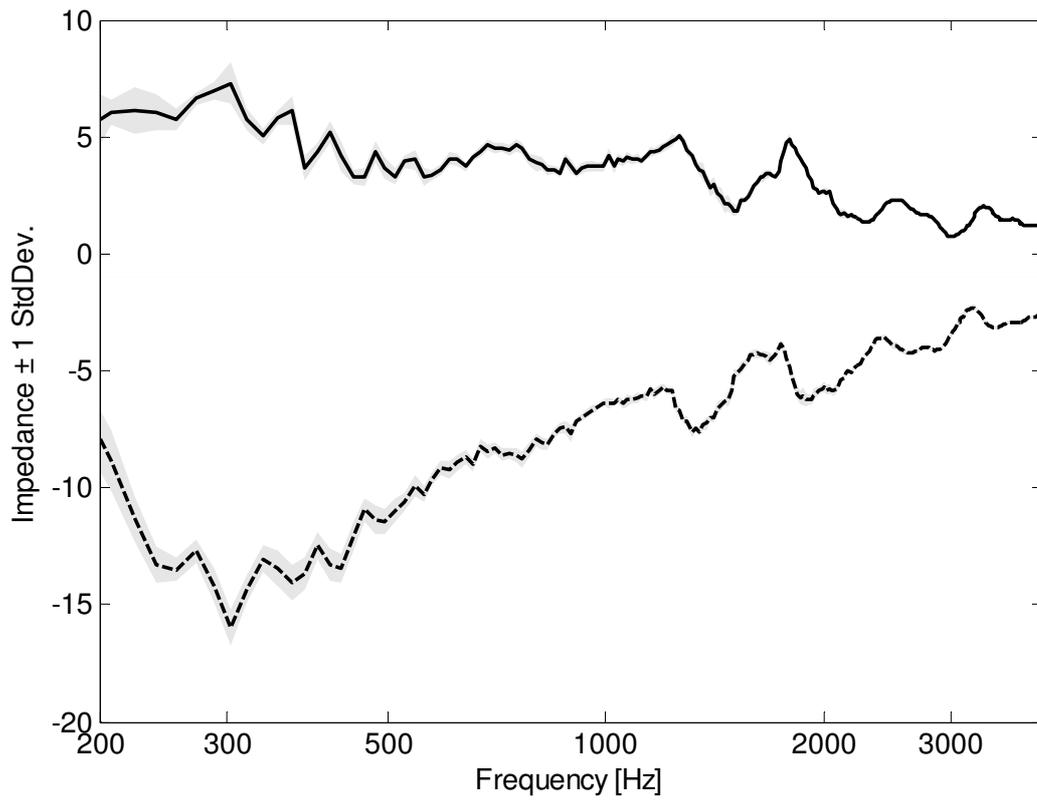
Fig. 2: Predicted surface impedance of a lawn. Mean and standard deviation of nine measurements at the same location. Real part (———), imaginary part (— —)
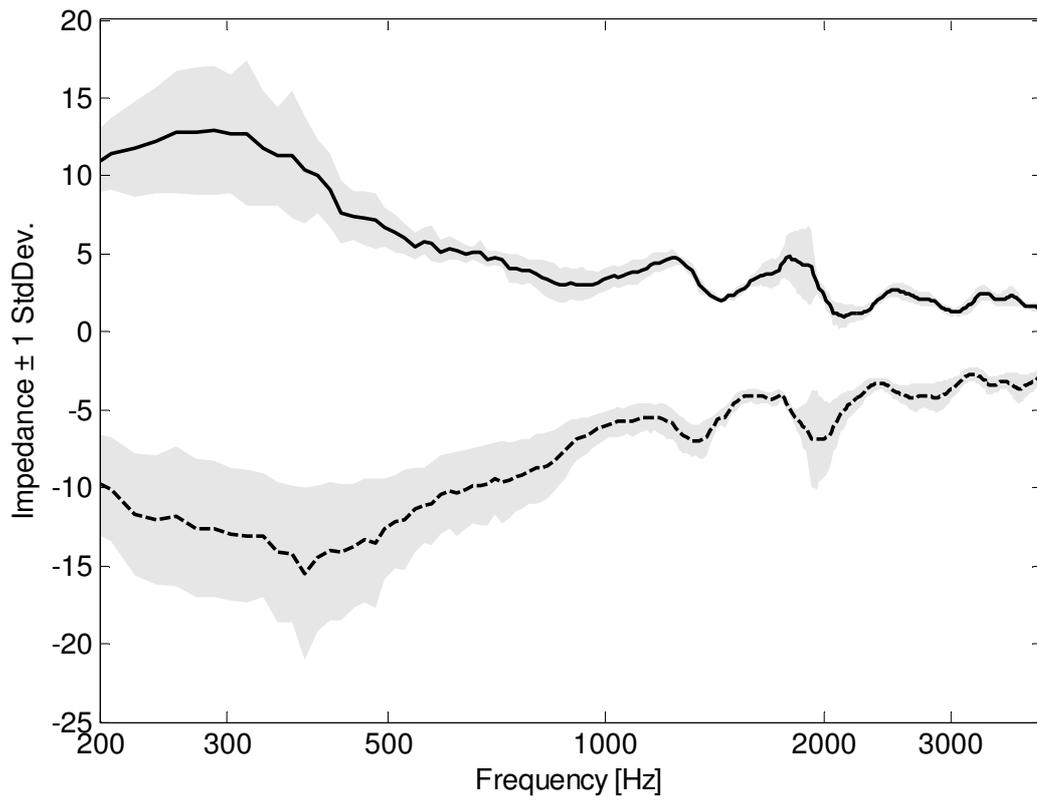
Fig. 3: Predicted surface impedance of a lawn. Mean and standard deviation of five measurements at different locations. Real part (⎯⎯), imaginary part (⎯ ⎯)
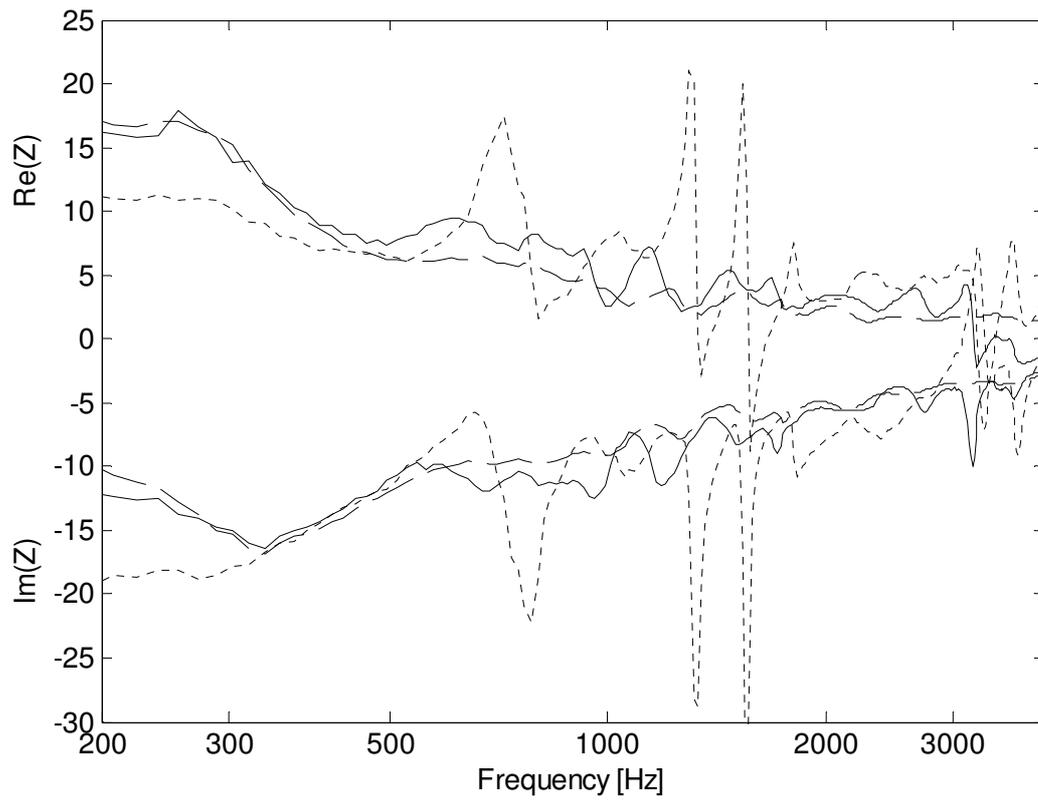
Fig. 4: Predicted surface impedance of a soccer field. Mean of five measurements at different locations (averaged transfer functions). Geometry A (——), B (— —) and C (····).
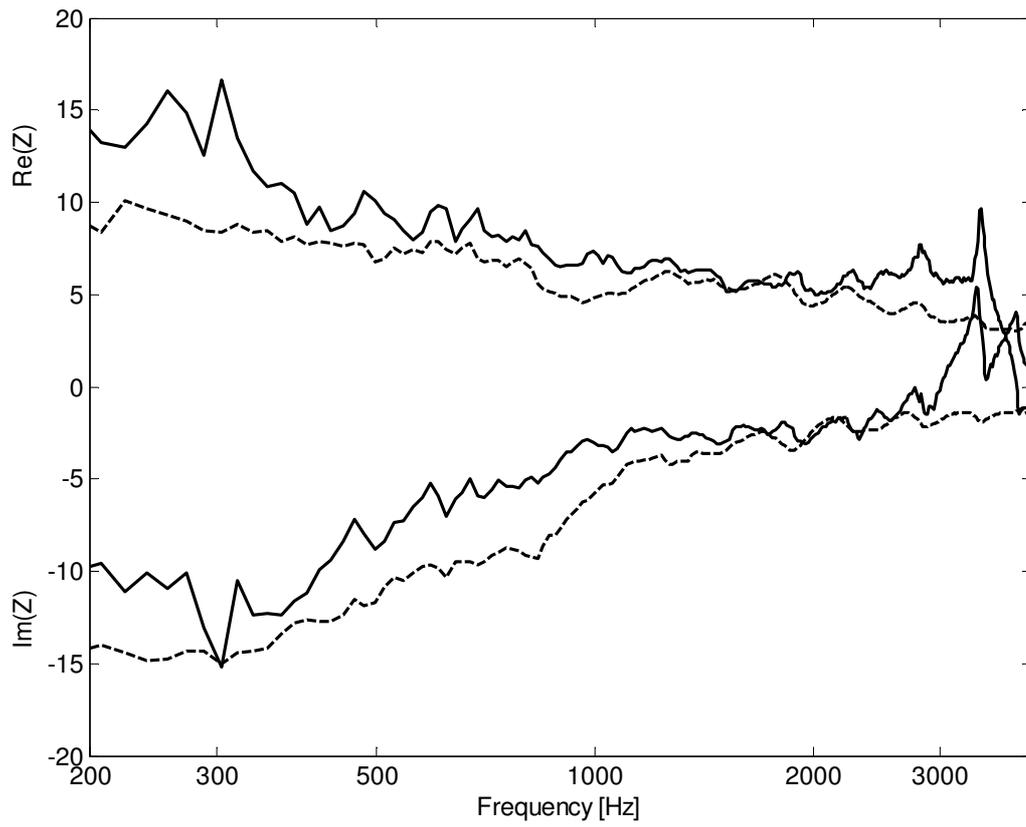
Fig. 5: Predicted surface impedance of a sand area. Measurement at one location. Geometry A (———) and B (— —).
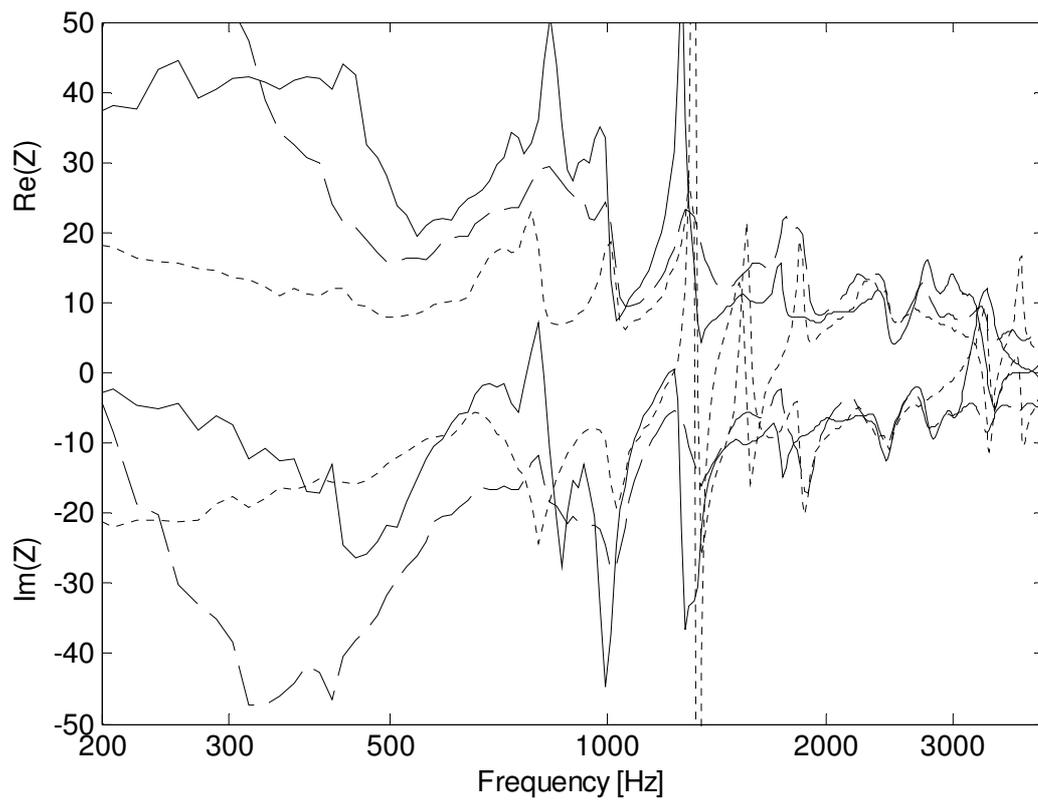
Fig. 6: Predicted surface impedance of an ash covered sports field. Mean of five measurements at different locations (averaged transfer functions). Geometry A (———), B (— —) and C (····).
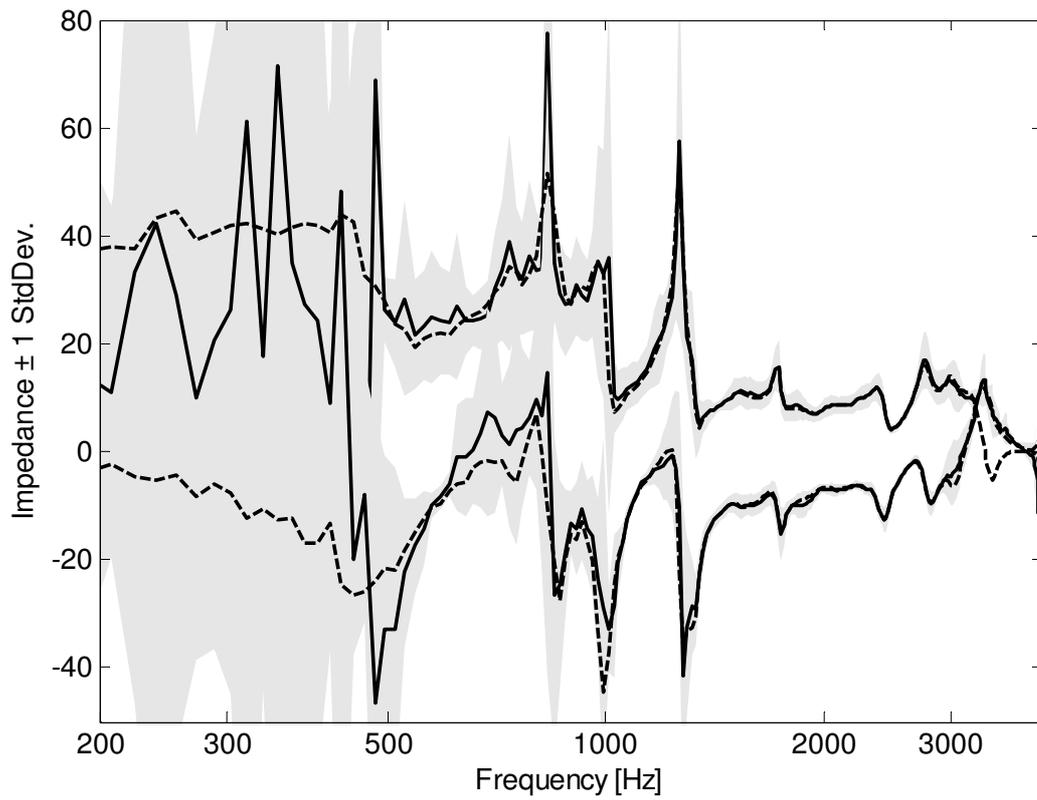
Fig. 7: Predicted surface impedance of an ash covered sports field. Geometry A, five different locations. Comparison between transfer function averaging (— —) and impedance averaging (——).

Tables

Geometry:	A	B	C
Lower microphone height [h_{rl}]	23.0 cm	5.0 cm	5.0 cm
Upper microphone height [h_{ru}]	46.0 cm	20.0 cm	40.0 cm
Source height [h_s]	32.5 cm	20.0 cm	40.0 cm
Source-receiver distance [R]	1.75 m	1.0 m	1.0 m

Tab. 1: Values for the three measurement geometries from ANSI S1.18.

	Impedance fit	Template method	ANSI S1.18	From [4]	From [11]
Lawn	365	450	125-300	30-140	150-300
Soccer field	463	525	125-300	30-140	150-300
Sand area	378	375	40-906	200	
Ash field	1711	1750	2000-4000	805-3971	800-2500

Tab. 2: Estimates for the absorber parameter σ_{eff} [kPas/m²] in comparison with the template method, tabulated values from ANSI S1.18 , [4] and [11]. Average from measurements with geometry A and B.