Applied Acoustics 74 (2013) 561–565

Contents lists available at SciVerse ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Technical Note

Point source equalised by inverse filtering for measuring ground impedance

Pedro Cobo *, Santiago Ortiz, David Ibarra, Carlos de la Colina

Centro de Acústica Aplicada y Evaluación no Destructiva (CAEND), CSIC, Serrano 144, 28006 Madrid, Spain

ARTICLE INFO

Article history:
Received 25 June 2012
Received in revised form 25 September 2012
Accepted 9 October 2012
Available online 5 December 2012

Keywords:
Point source
Inverse filtering
Ground impedance

ABSTRACT

A point source for measuring ground impedance which complies with the omnidirectionality requirements of the ANSI S1.18 standard is presented. The source consists of a small aperture connected to a conventional loudspeaker through a cone. Whilst this source radiates with deviations lesser than ±1 dB within ±45°, its frequency response exhibits strong peaks arising from resonances of air inside the cone. To equalise these resonances, inverse filtering is applied. Inverse filters pre-emphasise the electrical signal driving the sound source so that zero-phase (or minimum-phase) cosine-magnitude signals are radiated. Equalisation by inverse filtering has two main advantages in the ground impedance measurement. On the one hand, flattening the frequency response avoids large fluctuations of the excess attenuation curve, which can make difficult its inversion to ground impedance data. On the other hand, inverse filtering shorten the time response of the sound source, this in turn making easier the positioning of a time window to separate ground reflection from reflections/diffractions coming from nearby objects usually present in the acoustic scenario.

1. Introduction

Many acoustic measurement procedures require omnidirectional sources. Dodecahedra, for instance, are used as an approximation to omnidirectional sound sources for measuring room acoustic parameters. Maximum allowed deviations from source onmidirectionality are established by ISO 3382-1 standard [1]. Deviations larger than those recommended for the ISO 3382-1 are known to cause large errors on the assessment of acoustic parameters depending on the source-receiver distance, frequency band and number of measurements [2].

Omnidirectional sources are also recommended for measuring ground impedance. According to the ANSI S1.18 standard, sound sources for measuring ground impedance are required to be omnidirectional to within ±1 dB within ±45° [3]. It suggests that a 1 m large pipe with a driver connected to an end radiates through the other end like a point source provided that its diameter is shorter than $\lambda/4$, being λ the wavelength. Polak et al. [4] proposed another type of omnidirectional sound source, consisting of a powerful loudspeaker feeding a small aperture through a reverse horn for concentrating the acoustic energy. The proposed designs, both the open end of a pipe and the small aperture of a reverse horn, have proved to constitute a solution for omnidirectional sound sources that behave like a point source, but with a very irregular frequency response and a rather resonant structure. Strong resonances in the frequency response of the sound source can cause significant fluctuations in the measured excess attenuation curves used for inverse procedures to asses ground impedance. For instance, Attenborough and Boulanger [5] demonstrated that root-finding methods [6] to invert excess attenuation data directly to ground impedance are very sensitive to fluctuations in complex excess attenuation data.

Fortunately, large peaks of the frequency response of a sound source can be equalised by inverse filtering [7,8]. The main purpose of this paper is to illustrate this process with a new point source designed for ground impedance measurements. The designed point source, similar to that proposed by Polak et al. [4] is described in Section 2. Section 3 presents the details of the inverse filtering process applied to flatten the originally strongly resonant frequency response of the point source. The benefits of this inverse filtering in the measurement of two soil impedances are demonstrated in Section 4.

2. Point source

Fig. 1 shows a sketch of the designed point source. The sound is radiated through a small aperture connected to a 10-in. loudspeaker through a steel cone. Both the loudspeaker and the cone are enclosed in a wooden box with 3 cm thick walls. The box has dimensions $(79 \times 36 \times 36)$ cm, and he cone is 42.5 cm long. The small aperture has a diameter of 3 cm.

* Corresponding author. Tel.: +34 91 5618806; fax: +34 91 4117856.
E-mail address: pedro.cobo@csic.es (P. Cobo).

0003-682X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apacoust.2012.10.003

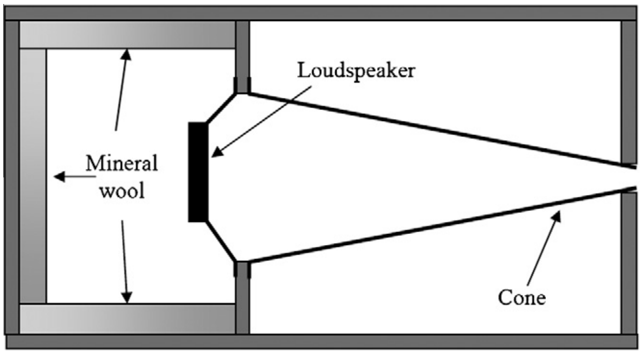

Fig. 1. Sketch of the point source.

2.1. Frequency response

The frequency response function (FRF) of the source was measured in the anechoic room of the CAEND using a B&K 4191L microphone situated 1.5 m far from the aperture. The time response between the source and the microphone was measured first using a MLS signal (order 16, 10 averages). Assuming that the microphone has a flat response, the FFT of the measured time response affords directly the FRF of the source. Fig. 2 shows the time response and the FRF of the source. The strong resonant structure of the source is clearly seen in both time and frequency responses. The amplitude of the resonances deviates more than 20 dB from the flat part of the FRF. These resonances can cause strong peaks in the measurement of excess attenuation curves which can produce incertitude in the assessment of the ground impedance.

2.2. Directivity patterns

The directivity of the point source was measured in the anechoic room of the CAEND. A turntable is situated above the point source. A B&K 4191L microphone suspended at the end of a rod turns around the point source describing an angle θ_1 between $-90°$ and 90°. The microphone is $R_1 = 2.03$ m far from the centre of the turntable, being R_2 and θ_2 the distance of the microphone and the turning angle with respect to the centre of the source aperture, respectively. Since the centre of the source aperture is displaced a distance $L = 0.425$ m from the centre of the turntable, the measured directivity pattern $D(R_1\theta_1)$ must be mapped into the corrected pattern $D(R_2, \theta_2)$.

The ISO 3382-1 standard [1] recommends providing the directivity patterns of sources averaged in frequency and angle. To average in frequency, narrowband FRFs are transformed to octave band FRFs. Angle smoothing is achieved by gliding averaging in ±15° arcs around the measurement angle. Fig. 3 shows the resulting polar directivity diagrams of the designed point source at the selected octave band central frequencies between 125 Hz and 4000 Hz. It is seen that the designed point source complies with the ANSI S1.18 requirement of omnidirectionality for ground impedance measurements [3]; namely, it deviates from a semi-sphere less than ±1 dB within ±45°.

3. Equalisation by inverse filtering

Cobo et al. [7] have demonstrated that the FRF of a sound source can be equalised by pre-emphasising the MLS signal with the inverse filter given by

$$x_s(t) = \mathfrak{F}^{-1}\left\{ Y_s(f)\frac{H^*(f)}{|H(f)|^2 + p^2} \right\}, \quad (1)$$

where $\mathfrak{F}^{-1}$ stands for inverse Fourier transform, $H(f)$ is the FRF of the sound source, p is a regularization constant,

$$|Y_s(f)| = \begin{cases} \cos^g\left[\frac{\pi(f-f_0)}{B}\right] & f_1 \leqslant f \leqslant f_2 \\ 0 & f < f_1, f > f_2 \end{cases}, \quad (2)$$

for cosine-magnitude spectra, with $B = f_2 - f_1$ the frequency band where the source must be equalised, $f_0 = (f_2 + f_1)/2$ the central frequency, and

$$\Psi_{Y_s(f)} = \begin{cases} 0 & \textit{for zero} - \textit{phasepulses} \\ -\frac{1}{\pi}\int_{-\infty}^{\infty} \frac{|Y_s(\xi)|}{f-\xi} d\xi & \textit{for minimum} - \textit{phase pulses} \end{cases}. \quad (3)$$

The equalisation process outlined above depends on four parameters: f_1 and f_2, the low and high frequency limits of the frequency band, p, the regularization parameter, and g, the cosine shaping parameter. They are chosen according to the natural frequency response function of the sound source. In this case, the selected parameters were $(f_1, f_2, p, g) = (18$ Hz, 6358 Hz, 1% of the spectral maximum, 0.2).

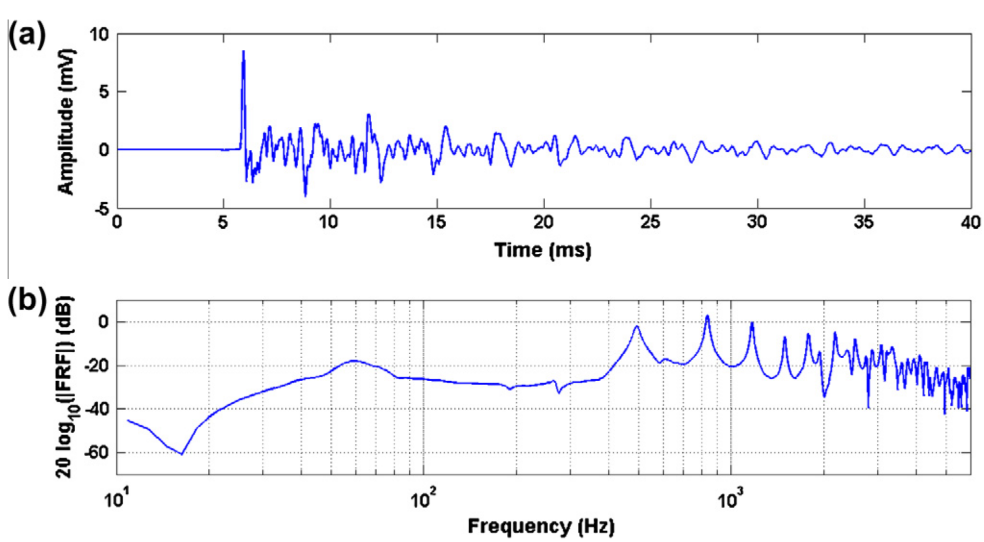

Fig. 2. Time (a) and frequency (b) responses of the original point source.

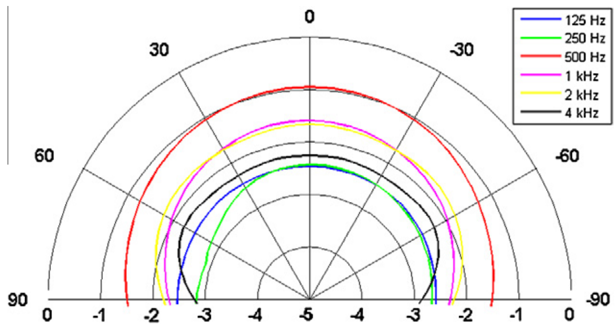

Fig. 3. Smoothed polar directivity diagrams of the point source at central octave band frequencies.

3.1. Frequency response

Fig. 4 shows the time and frequency responses of the point source without and with inverse filter equalisation. The effect of inverse filtering is appreciated in both time and frequency responses. The inverse filtered time waveform is much shorter than the original one (see Fig. 2). In the frequency domain, the strong peaks in the unequalised FRF have been flattened in the equalised response in the frequency band from 18 Hz to 6300 Hz.

3.2. Directivity patterns

Fig. 5 shows the polar directivity diagrams of the inverse filtered point source at the central frequencies of octave bands between 125 Hz and 4000 Hz. These directivity diagrams have been smoothed by averaging in gliding arcs of ±15° around the measurement angle. It can be seen that the designed point source, when equalised by inverse filtering, deviates less than ±1 dB within ±90°, resulting even more omnidirectional than the original source without inverse filtering.

4. Measuring ground impedance with the designed point source

The acoustic impedance of two soils, one hard and other soft, Fig. 6, has been measured by the method recommended by the ANSI S1.18 standard [3], using the point source described in

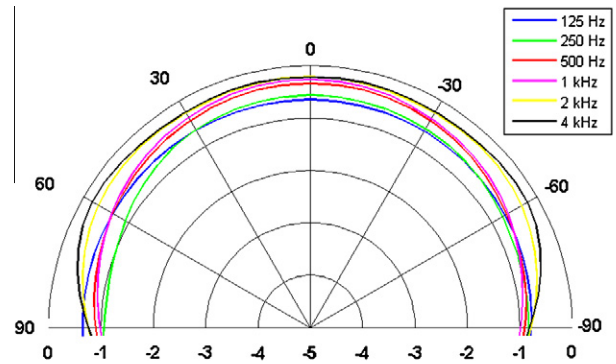

Fig. 5. Smoothed polar directivity diagrams of the inverse filtered point source at central octave band frequencies.

Sections 2 and 3. This method consists of measuring the sound level difference at two microphones close to the point sound source, ΔL_{exp}, calculating the level difference according to an impedance model of the soil, ΔL_{the}, and varying the parameters of the impedance model so that the square difference $|\Delta L_{the} - \Delta L_{exp}|^2$ achieves a minimum. Three geometries for the source-microphones arrangement are recommended depending on the type of soil and the frequency range of interest [3]. Kruse and Mellert [9] have suggested another slightly different geometry which minimises the measurement errors in the frequency range between 100 Hz and 400 Hz. Here, an intermediate geometry between both recommendations has been adopted with a sound source h_s = 0.295 m, a top microphone height h_t = 0.8 m, a bottom microphone height h_b = 0.1 m, and a source-microphones horizontal distance d = 2 m.

4.1. Hard ground

The first ground impedance measurement was carried out on the concrete soil of the CAEND courtyard, Fig. 6a. Time responses were measured using MLS signals of order 16, 10 averages, and sampling frequency f_s = 120 kHz. Fig. 7 shows the time responses measured at the top microphone. To illustrate the effect of inverse filtering, two time responses are shown for each microphone; namely, the original signal, without inverse filtering, and the inverse filtered signal to generate a zero-phase cosine-magnitude

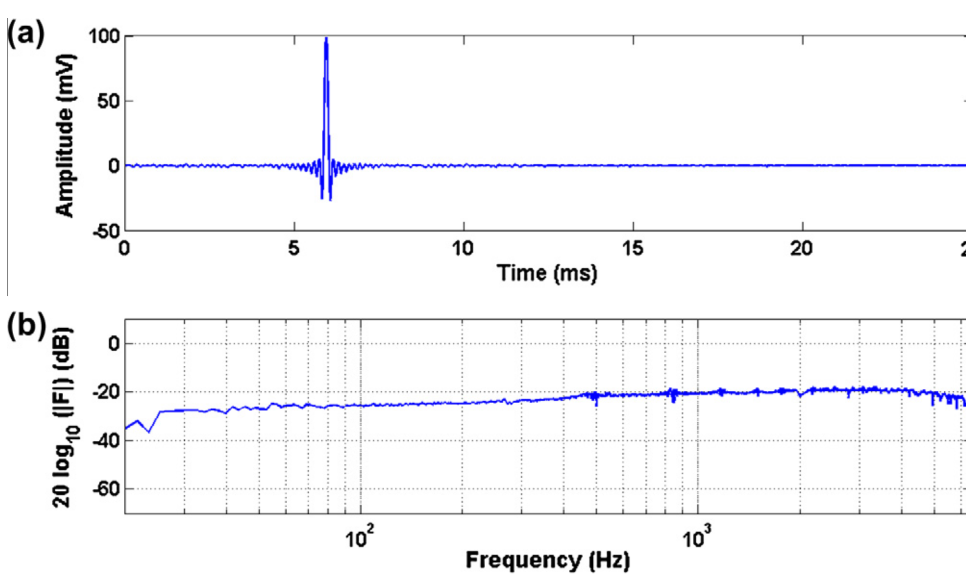

Fig. 4. (a) Time and (b) frequency responses of the point source with equalisation by inverse filtering.

Fig. 6. Concrete (a) and grass (b) soils.

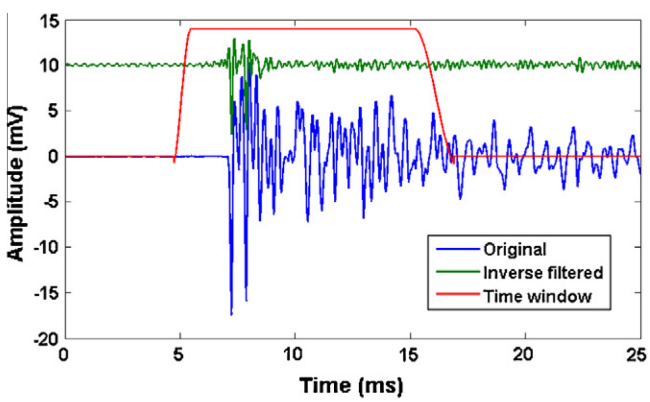

Fig. 7. Time responses at the top microphone for the concrete soil.

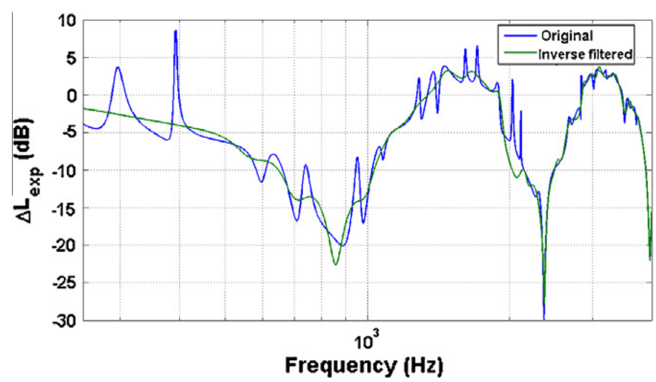

Fig. 8. Level difference curves for the concrete soil.

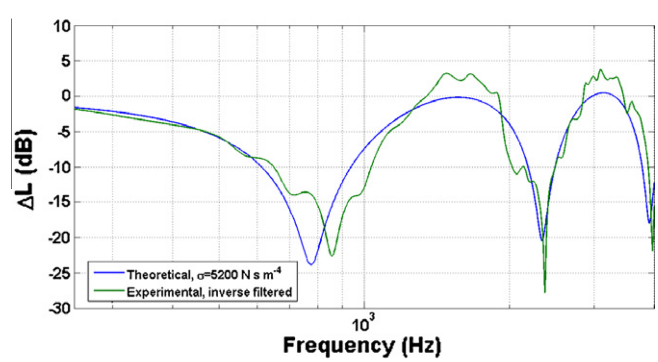

Fig. 9. Theoretical and experimental level difference curves for the concrete soil with σ = 5200 kN s m^{-4}.

pulse. Although the minimum-phase inverse filtered signal was also measured, it is not presented here as it does no differ substantially from the zero-phase inverse filtered signal. To appreciate better the differences between the two time responses, they have been displaced vertically each other. As it can be seen, inverse filtered time response is much shorter than the original one. This issue is important for this measurement, as it has been carried out in a scenario with close surfaces and objects which provide undesired reflections/diffractions to the measured time response. They can be removed by time windowing, as shown in Fig. 7. Whereas the time window fits perfectly between the desired and undesired reflections in the inverse filtered time response, it truncates energy from the soil in the original one. This is a further advantage of using inverse filtering to shorten the time response of the point source.

Fig. 8 shows the sound level difference, ΔL_{exp}, calculated from the windowed time responses at the top and bottom microphones. It can be seen that the level difference curves measured with inverse filtering are smoother than the original one, which is spikier. Peaks of the original curve are due to dips in the bottom microphone FRF. These peaks could cause difficulties in the conversion of level difference data to ground impedance [5].

The curve obtained with zero-phase cosine-amplitude inverse filtered MLS was used to assess the acoustic impedance of the concrete soil, assumed as a local reacting soil, using a Delany–Bazley impedance model [10]. This acoustic impedance model is characterised by one parameter, the flow resistivity σ. The least square method outlined above provides an optimum value σ = 5200 kN s m^{-4}. It is lower than the value for a concrete soil (65 MN s m^{-4}) in Table B.1 of the ANSI S1.18-1999 [3]. Fig. 9 superimposes the level differences curves, ΔL_{the} and ΔL_{exp}.

4.2. Soft ground

Further measurements were done on a lawn soil at the garden of the CAEND, Fig. 6b. Time response at the top and bottom microphones were measured again using MLS signals of order 16, 10

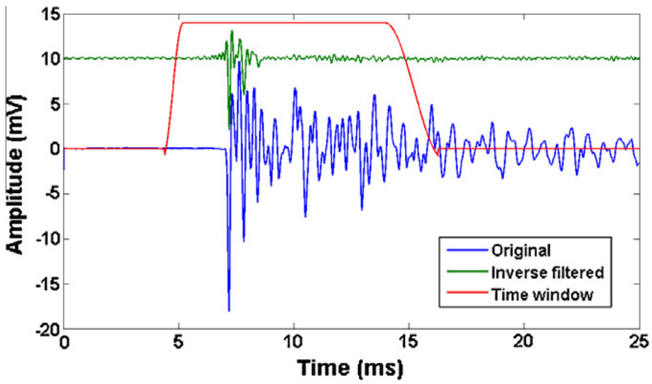

Fig. 10. Time responses at the top microphone for the grass soil.

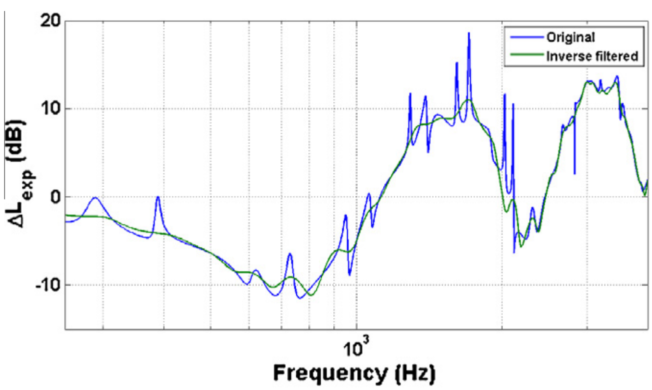

Fig. 11. Level difference curves for the grass soil.

averages, and f_s = 120 kHz, without and with inverse filtering. Fig. 10 shows the time responses at the top microphone, with a time window superimposed. Again, time responses at the microphone have been displaced vertically each other so that differences between them can be better appreciated. Due to the longer duration of the non-filtered time response, the time window truncates part of the soil reflected energy. A similar analysis to that applied in Section 4.1 provides the level difference curves of Fig. 11. Again, outstanding peaks are seen in the non-filtered curve, as a consequence of the dips in the FRF of the bottom microphone. The zero-phase cosine-magnitude inverse filtered curve is used to obtain the flow resistivity of the two-parameter acoustic impedance that minimises the square differences between theoretical and experimental level difference curves. This impedance model depends on two parameters, the flow resistivity, σ, and the rate of change of porosity with depth, α. The minimisation process outlined above results in σ = 100 kN s m^{-4} and α = 3 m^{-1}. These values correspond to an "institutional grass" in Table B.2 of the ANSI S1.18-1999 standard [3]. Finally, Fig. 12 superimposes the level difference curves, ΔL_{the} and ΔL_{exp}, obtained for this soil.

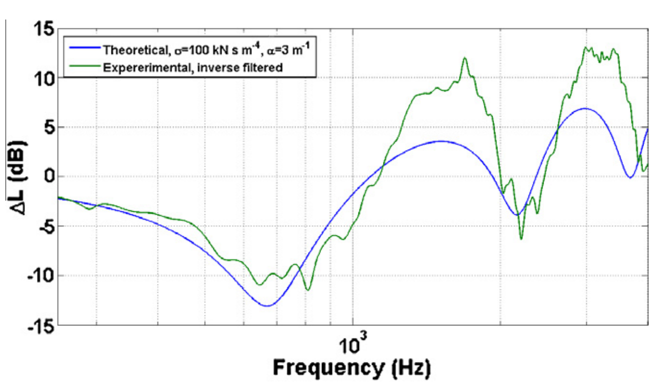

Fig. 12. Theoretical and experimental level difference curves for the grass soil with σ = 100 kN s m^{-4} and α = 3 m^{-1}.

5. Conclusions

This paper presents the acoustic performance of a point source designed for measuring ground impedance. The sound is radiated through a small aperture connected to a conventional loudspeaker through a steel cone. The acoustic performance of this point source, namely its frequency response function and its directivity pattern, has been measured in an anechoic room. The measured polar directivity diagrams at the central frequencies of the octave bands between 125 Hz and 4000 Hz show that the designed point source fulfils the omnidirectionality requirement of the ANSI S1.18 standard (deviations lesser than ±1 dB within ±45°). However, its frequency response exhibits strong peaks, which exceed more than 20 dB the flat part of the curve, and can be detrimental for inverting excess attenuation data in acoustic impedance of the investigated soil.

To solve this problem, the original frequency response of the point source has been equalised by inverse filtering. It has been demonstrated that zero-phase, and minimum-phase, cosine-magnitude inverse filtering effectively flattens the frequency response of the point source. An additional advantage of inverse filtering is to shorten significantly the length of the sound source time response, facilitating the fitting of a time window to separate desired (from the ground) and unwanted (from near objects) contributions to the time response.

Non-filtered and inverse filtered excess attenuation curves have been measured above two grounds, one hard and another soft. Whereas the non-filtered excess attenuation curves exhibit strong fluctuations, originating from the irregular frequency response of the original point source, the inverse filtered ones are much smoother. The impedance curves calculated by minimising the square difference between the inverse filtered measured and theoretical excess attenuation curves provide reasonable values of their acoustical parameters.

Acknowledgements

This work has been supported by the Spanish Ministry of Economy and Competitiveness through Grant TRA2011-26261-C04-01.

References

[1] ISO 3382-1: Acoustic measurement of room acoustic parameters. Part 1: Performance rooms. International organization for standardization; 2009.
[2] Hak CCJM, Wenmaekers RHC, Hak JPM, Luxemburg RCJ. The source directivity of a dodecahedron sound source determined by stepwise rotation. Forum Acusticum, 1875–1879, Aalborg, Denmark; 2011.
[3] ANSI S1.18: template method for ground impedance. American National Standard, Acoustical Society of America; 1999.
[4] Polak JD, Chistensen LS, Juhl PM. An innovative design for omnidirectional sound sources. Acta Acust Acust 2001;87:505–12.
[5] Attenborough K, Boulanger P. Template and direct measurements of ground impedance. ICA2004, III-1977-III1980, Kyoto, Japan; 2004.
[6] Taherzadeh S, Attenborough K. Deduction of ground impedance from measurements of excess attenuation spectra. J Acoust Soc Am 1999;105:2039–42.
[7] Cobo P, Fernández A, Cuesta M. Measuring short impulse responses with inverse filtered maximum-length sequences. Appl Acoust 2007;68:820–30.
[8] Ducoourneau J, Planeau V, Chatillon J, Nejado A. Measurement of sound absorption coefficients of flat surfaces in a workshop. Appl Acoust 2009;70:710–21.
[9] Kruse R, Mellert V. Effect and minimization of errors in situ ground impedance measurements. Appl Acoust 2008;69:884–90.
[10] Attenborough K, Li KM, Horosenkhov K. Predicting outdoor sound. London: Taylor & Francis; 2008.