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Technical Note

Characterization of the road surfaces in real time

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ABSTRACT

The main factor in the propagation of traffic noise is the road surface, where the vehicles generate noise due to the contact between tire and pavement, in addition to the noise produced by the engine.

The aim of this work is to obtain the parameters of ground surfaces in real time at different speeds by using an on-board data acquisition system. The system is based on two small microphones with flat response frequency, a small directional speaker, audio interface and a laptop for signal processing.

The contribution of this system is to know, in real time, the physical parameters of ground surface measured at different speeds, minimizing the influence of aerodynamic noise. The low cost and its portability make the system to be a very useful tool for noise predictions in outdoors propagation and could be used as a complement instrument in noise mapping.

The acoustic impedance was measured by the method recommended by the ANSI S1.18 standard, but with some adjustments. This method consists of measuring the sound level difference from two microphones close to the surface, and calculating the level difference according to an impedance model of the ground.

1. Introduction

The effect of the surface is the most influential factor in sound propagation. When noise propagates from the source to the receiver on a reflective surface, the direct and the reflected signals interfere. If the surface has finite impedance, the reflected part interferes with the direct field, allowing a significant reduction of the original noise if the reflective conditions are adjusted properly. These conditions can be modeled either as a local reaction or an extended reaction [1]. The local reaction condition for noise propagation outdoors is very simple, but valid only on a limited range of frequencies. For the study of surfaces that enable the noise transmission inside themselves, the simplest model was developed by Delany and Bazley [2]. It expresses the impedance of the material and its propagation constants based on empirical relationships that depend only on flow resistivity. In this work we show the results obtained using models for one to four parameters.

We aimed to work with an analytical approach allowing us a rough prediction of the noise produced by a source spreading on a ground surface. The attenuation depends on frequency, propagation distance, angle of incidence and geometric configuration of sources and sensors.

For measuring the ground impedance *in-situ*, 'impulse-techniques' are the best choice, since they make it possible to remove unwanted reflections from the recorded signal. Some experiments have used spark-sources, gunshots, recorded pulses and tone-bursts [3]. However, measuring impulse-responses indirectly using e.g. pseudo-random MLS-sequences [4], has proved to be superior, due to the fact that they are perfectly reproducible, have a high dynamic range and can be applied in noisy environments. Time-windowing, subtraction of free-field signals or other techniques (e.g. cepstral deconvolution) can remove unwanted signals [5].

2. Theoretical model

Let us consider a point source and receiver at heights h_s and h_r, respectively, over a flat surface, separated a lateral distance R, Fig. 1. Let R_1 and R_2 be the source–receiver distance for the real and image sources, respectively, and θ the incidence angle of sound on the surface.

The sound pressure at the receiver is the sum of the direct signal, which comes from the real source, plus the reflected signal from the ground, which is assumed to come from the image source. If a plane wave model is applied, the sound pressure at the receiver should be $p = p_d + R_p\, p_r$, where p_d and p_r are the direct and reflected contributions, respectively, and R_p is the plane wave reflection coefficient, given by [1]

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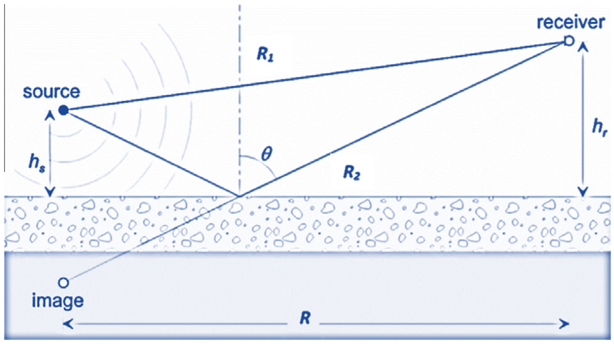

Fig. 1. Geometry for spherical waves propagating on the ground.

$$R_p = \frac{Z_s cos\theta_0 - Z_0}{Z_s cos\theta_0 + Z_0} \tag{1}$$

where Z_s is the surface impedance of the ground, Z_0 is the impedance of the air, θ_s is the transmission angle on the ground, but a spherical wave model must be taken into account. For such a model, Attenborough [5] shows that the sound pressure at the receiver is

$$p(x,y,z) = \frac{e^{jk_0R_1}}{4\pi R_1} + Q\frac{e^{jk_0R_2}}{4\pi R_2}, \tag{2}$$

where

$$Q = R_p(\theta) + [1 - R_p(\theta)]F(w), \tag{3}$$

is the spherical wave reflection coefficient on the ground. Therefore, the spherical wave reflection coefficient is the sum of the plane wave reflection coefficient plus a second term named the ground wave, which depends on the complex function $F(w)$, the so-called boundary loss factor, defined as [6]

$$F(w) = 1 + j\sqrt{\pi}we^{-w^2}erfc(-jw), \tag{4}$$

Erfc being the complementary error function. The complex variable w, in Eq. (4), also known as numerical distance, is

$$w = \frac{1+j}{2}\sqrt{k_0R_2}\left(\frac{Z_0}{Z_s} + cos\theta\right), \tag{5}$$

w is the numerical distance [7,8].

According to this model, the ground attenuation will be [9,10]

$$\Delta L = 20log_{10}\left[\left|1 + Q\frac{R_1}{R_2}e^{jk_0(R_2-R_1)}\right|\right], \tag{6}$$

Thus, a ground impedance model is required to calculate the effect of this boundary in the sound field. Each of the ground layers can be characterized by impedance models of one, two, three or four parameters.

Let us consider a plane wave incident on a surface with angle θ_0, characterized by acoustic impedance Z_s and propagation constant k_s Fig. 2.

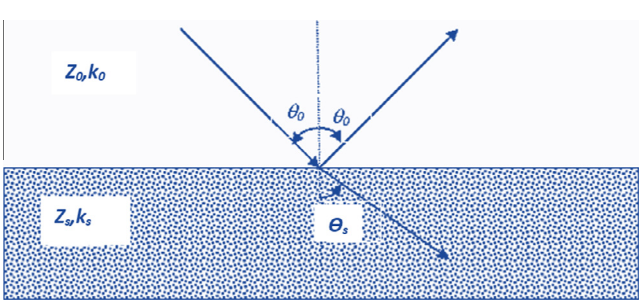

Fig. 2. A plane wave incident on a homogeneous medium.

The impedance model, Z_s, is established for the ground. In this case, a homogeneous locally reacting ground is assumed with normalized acoustic impedance given by the Delany–Bazley equation for one parameter model [2]

$$z_s = (1 + 0.0571E^{-0.754} + j0.087E^{-0.732}), \tag{7}$$

where $E = \rho_0 f/\sigma$, ρ_0 is the air density and σ is the flow resistivity and f the frequency.

This model, which depends on just one parameter (the flow resistivity) has been adopted in some works for calculating the excess attenuation of grounds [11–13].

There is evidence that the one parameter model tends to overestimate the attenuation within a porous material with a high flow resistivity. Attenborough [5] proposed a two parameter model, which includes an exponential change of porosity with depth. This model, also assumed by the ANSI S1.18 [14] standard, proposes

$$Z_s = Z_0\left\{\frac{1}{\sqrt{\pi\gamma\rho_0}}\sqrt{\frac{\sigma_e}{f}} + j\left[\frac{1}{\sqrt{\pi\gamma\rho_0}}\sqrt{\frac{\sigma_e}{f}} + \frac{c_0\alpha_e}{8\pi\gamma f}\right]\right\}, \tag{8}$$

where $\gamma = 1.4$ for an ideal gas, σ_e is the effective flow resistivity of the ground, and α_e (in 1/m) represents the effective rate of porosity change with depth.

Attenborough et al. [15] describe the phenomenological model of three parameters (also named the Zwickker and Kosten model), based on the equation

$$Z_s = \frac{Z_0}{\phi}\left(T + \frac{j\phi\sigma}{\rho_0\omega}\right)^{1/2}, \tag{9}$$

where ϕ is the porosity, T is the tortuosity and σ is the flow resistivity. This model assumes adiabatic conditions in the pores. Other authors proposed a modified model, also called Hamet model [15], more appropriate for porous asphalt. Another three parameter impedance model is the Wilson model [15].

The four parameter impedance model recommended by ANSI S1.18 [14] is

$$Z_s = Z_0\frac{\rho_s(\omega)}{k_s(\omega)}, \tag{10}$$

where

$$\rho_s(\omega) = \left(\frac{4}{3}\frac{T}{\phi} + j\frac{4s_p^2\sigma}{\omega\rho_0}\right), \tag{11}$$

$$k_s^2(\omega) = \gamma\phi\left[\left(\frac{4}{3} - \frac{\gamma-1}{\gamma}N_{pr}\right)\frac{T}{\phi} + j\frac{4s_p^2\sigma}{\omega\rho_0}\right], \tag{12}$$

and γ is the specific heat ratio of air, N_{pr} the Prandtl number, σ the dc component of the flow resistivity, ϕ the ground porosity, T the tortuosity, and S_P a shape factor. Assuming that $T = \phi^{-n}$, where n depends on the shape of the grains.

3. System and equipment

The experimental measurements were performed along several avenues, in the south part of Mexico City. The following equipment was used: two small omnidirectional microphones, with frequency response of 20–20,000 Hz; small directional speaker with frequency response of full range; audio interface of 2 channels, with sampling frequency of 96 kHz; a laptop and software for signal processing.

The two microphones were mounted on a support and a base of wood for the source, and were installed in a sports utility vehicle as shown in Fig. 3. The microphones were placed at different heights from the soil: 0.06 m and 0.165 m; the source was at a height of 0.165 m, and the distance between microphones and speaker was