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ON SITE DETERMINATION OF SOUND ABSORPTION COEFFICIENT OF ROAD PAVEMENTS USING MOBILE LABORATORY

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In this paper we will present a new on-site acoustical absorption coefficient measurement system implemented on a mobile Laboratory, based on pressure-velocity probe, that will be developed inside the NEREiDE LIFE project. Discussion will point out pros and cons of the proposed method compared to other methods such as the Adrienne (ISO 13472-1) and the impedance tube (ISO 10534).
Keywords: Absorption, pavement, road noise, model

1. Introduction

Urban noise is one of the main problems reported by citizens, and the World Health Organization has repeatedly pointed out the health risks associated with exposure to noise. The Noise in Europe 2014 report highlights road traffic as the most dominant source of environmental noise, with an estimated 125 million people affected by noise levels greater than 55 dB(A). Dealing with the acoustical indicators, the main ones to assess the road surface acoustical performances are related to the tire/road noise emission and the influence on the propagation to the roadside, including the absorption coefficient.

Moreover the effect of ageing can be particularly dramatic on the acoustic performance of some porous surfaces. Road traffic and weathering causes the voids in the surface to become clogged with detritus reducing acoustic absorption, resulting in increased noise levels even more than 5 dB.

In the next sections we will describe a new in-situ acoustical absorption coefficient measurement system implemented on a mobile Laboratory, based on pressure-velocity probe, that will be developed inside the NEREiDE LIFE project. Discussion will point out pros and cons of the proposed method compared to other in-situ methods such as the Adrienne (ISO 13472-1) [1] and the spot method based on an impedance tube (ISO 10534) [2].

2. Absorption coefficient measurement methods

The measurement of the absorption coefficient, performed by a vehicle that is in motion, requires a contactless measurement method. Two contactless methods will be described in the Adrienne method [3] and its variation using a pressure velocity, p-u, probe instead of the microphone only [4-5]. In order to find the best height of the receiver from the road, considering that the height of the vehicle from the surface is not constant but change with the vehicle acceleration and speed or in case of holes in the pavement, we have focused our study on the sensitivity of the absorption coefficient to variation of the receiver and source height respect to the road plane.

2.1 Pavement absorption model

On porous media, sound energy can be absorbed by the mean surface due to its porosity. Sound waves enter in the channel and are partly reflected back and partly absorbed and converted in other kind of energy such as thermal energy. In order to simulate the absorption characteristic of the pavement has been selected the Hamet-Berengier's model [6].

The input parameters to describe the porous media are the porosity, Ω, (nominal value 0≤ Ω ≤1), the air flow resistivity, σ, (expressed in kg/m^3s), the shape factor or tortuosity, K, (nominal value ≥ 1) and thickness, *l*, (expressed in m).

Considering that given the impedances Z_1 and Z_2 respectively of the first and second layer then the reflecting coefficient at the interface is defined as

$$\Gamma = \frac{|Z_2 - Z_1|^2}{|Z_2 + Z_1|^2} \quad (1)$$

if Z_1 is the impedance of the air, Z_2 the impedance of the road of thickness *l* and Z_3 the impedance of the ground under the pavement (that for single layer pavement can be considered $Z_3=\infty$), then the road absorption coefficient is given by

$$\alpha = 1 - \frac{|Z_{23} - Z_1|^2}{|Z_{23} + Z_1|^2} \quad (2)$$

where

$$Z_1 = \rho_0 c_0 \quad (3)$$

$$Z_{23} = Z_2 \frac{Z_3 \coth(\gamma_2 l) + Z_2}{Z_2 \coth(\gamma_2 l) + Z_3} \quad (4)$$

$$Z_2 = \rho_0 c_0 \frac{\sqrt{K}}{\Omega} \left(1 - i \frac{\sigma\Omega}{\omega \rho_0 K}\right)^{1/2} \quad (5)$$

$$\gamma_2 = i\omega \frac{\sqrt{K}}{c_0} \left(1 - i \frac{\sigma\Omega}{\omega \rho_0 K}\right)^{1/2} \quad (6)$$

ρ_0 is the density of the air, c_0 is the speed of sound, γ_2 is the propagation constant of the layer.

2.2 Absorption measurement model based on Adrienne method

This first method to measure the absorption coefficient is described in the CEN/TS 1793-5:2003 [3] and ISO 13471-1:2002 [1] standards. It consists in a sound source positioned above the surface to be tested and a receiver, a microphone, located between the source and the surface as shown in fig 1. Signal can be generated by a pistol shot [] or by a loudspeaker driven by a short frequency sweeps or an MLS signal in order to increase the signal to noise ratio [8].

The absorption is calculate knowing the geometry of the system and the impulse response of the direct path, H_i, and the impulse response of the reflected path, H_r, that is

$$\alpha(f) = 1 - \Gamma(\mathrm{f}) = 1 - \frac{1}{K_r^2} \left| \frac{H_r(f)}{H_i(f)} \right|^2 \quad (7)$$

where the spreading factor, K_r, is defined the ratio of directed an reflected path, that is

$$K_r = \frac{h_s - h_r}{h_s + h_r} \quad (8)$$

Where h_s is the distance between the sound source and the pavement and h_r is the distance between the microphone and the pavement too.

The reflection coefficient, $\Gamma(f)$, can be obtained from reflection factor, *R(f)*, knowing the incident sound pressure, $p_i(t)$, to the microphone and that reflected back, $p_r(t)$, to microphone from the pavement. In fact the reflection coefficient is given by ratio of the incident power, W_i, to the reflected power, W_r

$$\Gamma = \frac{W_r}{W_i} \cong \frac{|p_r|^2}{|p_i|^2} = |R|^2 \tag{9}$$

Considering an impulse and its spectrum, P, as a sum of monochromatic waves of different frequency, then for each frequency we can write

$$\left|\frac{P_r\ (f)}{P_i\ (f)}\right|^2 = \left|\frac{R(f)\frac{A(f)}{h_s+h_r}e^{-ik(h_s+h_r)}}{\frac{A(f)}{h_s-h_r}e^{-ik(h_s-h_r)}}\right|^2 = \left|R(f)\,\frac{h_s-h_r}{h_s+h_r}\,e^{-i2kh_r}\right|^2 = |R(f)|^2\left|\frac{h_s-h_r}{h_s+h_r}\right|^2 \tag{10}$$

$$|R(f)|^2 = \frac{1}{K_r^2}\left|\frac{P_r(f)}{P_i(f)}\right|^2 \tag{11}$$

The lower frequency is set by the impulse width, τ , and by the time windows used to separate the incident and reflected wave, in order to avoid overlapping between waves, that is

$$f_{min} \approx \frac{1}{2\tau} \tag{12}$$

The time windows have to be less than the time, $\Delta t = (2h_r)/c$, needed to the reflected wave to reach the receiver, where c is the speed of sound

High-frequency limitation arises mainly from pavement surface irregularities and orientation that reflect the incident sound in different ways.

In order to know the sensitivity of α respect to the variation of h_s or h_r, we have to consider the following eqs. [9]

$$\frac{\partial\alpha}{\partial h_r} = \frac{\partial|R|^2}{\partial h_r} = -\frac{4h_s(h_s-h_r)}{(h_s+h_r)^3}\left|\frac{P_r(f)}{P_i(f)}\right|^2 \tag{13}$$

$$\frac{\partial\alpha}{\partial h_s} = \frac{\partial|R|^2}{\partial h_s} = \frac{4h_r(h_s-h_r)}{(h_s+h_r)^3}\left|\frac{P_r(f)}{P_i(f)}\right|^2 \tag{14}$$

2.3 Mobile laboratory absorption measurement model based on p-u probe

In this second model we consider an acoustic monopole source located over the ground at an height equal to h_s and a receiver locate at an height equal to h_r from the ground too as shown in fig.1. The receiver measures both the acoustic pressure, p, and the particle velocity, u, [10] [11].

The news respect other systems that implement this methods [12] is the adoption of a stabilization system used to reduce the variation of the height of the source and the receiver in accordance to their sensitivities.

The acoustic impedance at the receiver is calculated from the ratio of the complex pressure to complex velocity amplitudes.

$$Z_r(r,\omega) = \frac{p_r(r,\omega)}{u_r(r,\omega)} \tag{15}$$

In the simulated model the pressure and velocity values can be calculated, considering a spherical wave, as [13]

$$p(r,t) = \frac{A}{r}e^{-kri}e^{i\omega t} \tag{16}$$

$$u(r,t) = \frac{A}{\rho c r}\left(1-\frac{i}{kr}\right)e^{-kri}e^{i\omega t} \tag{17}$$

where A is the wave amplitude, ρ is the air density, c is the speed of sound, $\omega = 2\pi f$ is the angular frequency, $k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}$ is the acoustic wave number, λ is the wavelength.

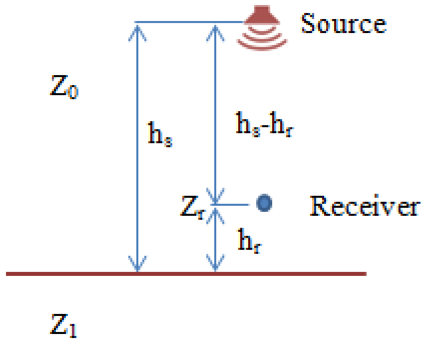

Figure 1: Geometrical set-up of the absorption coefficient measurement system

The value of the absorption coefficient, α, is defined as [14-15]

$$\alpha = 1 - \Gamma \tag{18}$$

where Γ is the reflection coefficient defined as the ratio of the reflected power, P_r to incident power P_i

$$\Gamma = \frac{P_r}{P_i} \cong \frac{|p_r|^2}{|p_i|^2} = |R|^2 \tag{19}$$

where R is the sound pressure reflection factor.

The pressure at the microphone is the sum of the direct and reflected pressure wave. In the same way the velocity at the velocity probe is the sum of direct and reflect velocity wave but considering their versus, thus the impedance from eq. (15) is

$$Z_r(r,t) = \frac{p(h_s - h_r, t) + p(h_s + h_r, t)}{u(h_s - h_r, t) - u(h_s + h_r, t)} =$$

$$= \frac{\frac{A}{d_1} e^{-kd_1 i} e^{i\omega t} + R\frac{A}{d_2} e^{-kd_2 i} e^{i\omega t}}{\frac{A}{\rho c d_1}\left(1 - \frac{i}{kd_1}\right) e^{-kd_1 i} e^{i\omega t} - R\frac{A}{\rho c d_2}\left(1 - \frac{i}{kd_2}\right) e^{-kd_2 i} e^{i\omega t}} =$$

$$= \rho c \frac{\frac{1}{d_1} e^{-kd_1 i} + R\frac{1}{d_2} e^{-kd_2 i}}{\frac{1}{d_1}\left(1 - \frac{i}{kd_1}\right) e^{-kd_1 i} - R\frac{1}{d_2}\left(1 - \frac{i}{kd_2}\right) e^{-kd_2 i}} \tag{20}$$

Reversing the equation above we obtain the value of R

$$R(r,t) = -\frac{(h_s + h_r)\left(\frac{Z_r[k(h_r - h_s) + i]}{\rho c k (h_r - h_s)} - 1\right)}{(h_r - h_s)\left(\frac{Z_r[k(h_s + h_r) - i]}{\rho c k (h_s + h_r)} + 1\right)} e^{-2kh_r i} \tag{21}$$

$$|R|^2 = \left[\left(\frac{h_s + h_r}{h_s - h_r}\right) \left| \frac{\frac{Z_r[-k(h_r - h_s) - i]}{\rho c k (h_r - h_s)} + 1}{\frac{Z_r[k(h_r + h_s) - i]}{\rho c k (h_r + h_s)} + 1} \right| \right]^2 \tag{22}$$

In order to know which parameter majorly affect the value of α we have to calculate the sensitivity of α respect to h_s or h_r, that is [9]

$$\frac{\partial\alpha}{\partial h_r} = \frac{\partial |R|^2}{\partial h_r} \tag{23}$$

$$\frac{\partial\alpha}{\partial h_s} = \frac{\partial |R|^2}{\partial h_s} \tag{24}$$

The expression of the eq. (23) and eq. (24) has not been reported here due to their excessive length. Their result are shown in the next session.

2.4 Absorption measurement based on the spot method

The spot method is described in the ISO 13472-2 [16]. It is based on propagation of the test signal from the source to the road surface and back to the receiver through an impedance tube, where one end of the tube is open and sealed onto the surface to be tested.

As the standard suggests this method is not reliable if the measured absorption coefficient exceeds 0.15. The area covered by the incident sound is about 0.008 m^3.

The result obtained with such tube are comparable with that obtained inserting the bore cores taken from the surface in the impedance tube made in accordance with the ISO 10534-1 [2]

The working frequency range is set by the tube dimension and the need to preserve a plane wave mode propagation inside the tube. In case of circular tube

$$f_{min} \geq \frac{250}{L-3d} \tag{25}$$

$$L \geq \frac{3}{4}\frac{c}{f_{min}} \tag{26}$$

$$f_{max} \leq \frac{200}{d} \tag{27}$$

where *L* is the length of the test section of the tube, *d* is the inside diameter of the tube and c the speed of sound

Study on the sensitivity to the change of the height of the microphone has not performed because in this method the microphone height is fixed and set by the tube that is in contact to the surface under test.

3. Results and discussion

In order to evaluate the position of the receiver from the pavement plane, the equations described in the previous session were implemented on Matlab [17]. The source and the receivers have been considerate ideal. The best height is that where the error of the absorption coefficient calculation is the smallest, taking also into account the receiver/source height variation due to the running vehicle.

In the Adrienne method the ratio of absorption coefficient sensitivities to the height of receiver and to the height of the source (see eq. (13), eq.(14) and fig. 2) is a constant and equal in module to the ratio of the heights, that is

$$\frac{\frac{\partial\alpha}{\partial h_r}}{\frac{\partial\alpha}{\partial h_s}} = -\frac{h_s}{h_r} \tag{28}$$

This means that the sensitivity to variation of height of receiver is higher in module than that respect to the variation of the height of source.

In the second method, where the receiver is a p-u probe, the ratio of the sensitivities is not equal as in eq. (28), but it changes with the frequency, the pavement impedance, the receiver and source height. Its behavior is shown in fig. (3) for some input parameters. In this case, the values used to simulate the impedance of the pavement and its absorption coefficient (see fig. 4) were Ω = 0.25, σ =45000 N-s/m4, K=3.7, t=0.05 m, ρ_o=1.22 Kg/m^3, c_o=340 m/s. With the same values, it is possible to observe how would change the absorption curve respect to the receiver height, as shown in figure 4. Here we can observe the spread of the absorption coefficient values of the Adrienne method respect to the second method. In fact comparing the graphs in fig. 2 and fig. 5, the absorption coefficient sensitivity to the variation of the height of the probe is higher in the Adrienne method. The error on the evaluation of the absorption coefficient is shown in figure 6, where we can observe that for the second method (fig. 6a) the best height for the probe is at 0.16 m from the pavement. Figure 6b shows that assuming 0.25 cm the height of the microphone, as suggested by the standard, the root mean square error of the absorption coefficient, evaluated on all the frequencies greater than 315 Hz, evaluated according the Adrianne method is higher than the second method around ± 0.05 m to the minimum of both curves. All the principal features of the described methods are summarized on table 1, where we can see that the second method offer a wide frequency band width and less sensitivity to the receiver height variation in the absorption measurement. For these reasons the second method is more appropriate than the Adrienne to be implemented on the running vehicle.

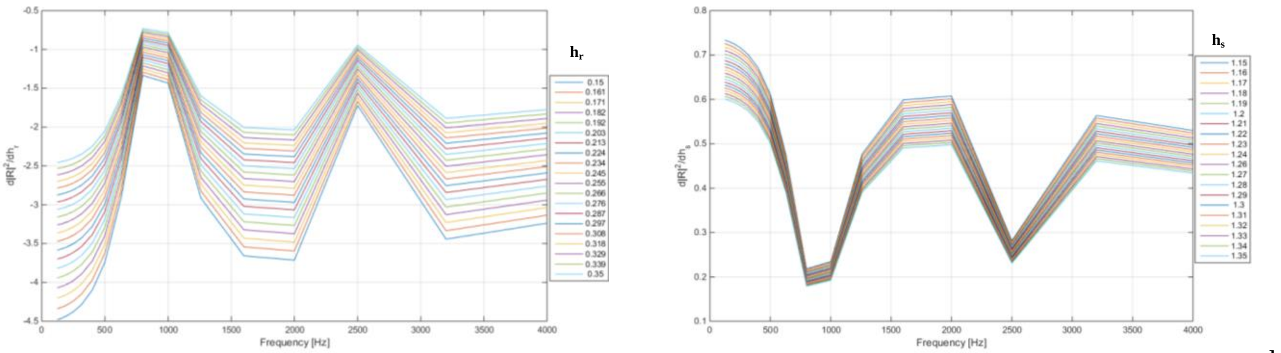

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Figure 2: Graphical behaviour in the Adrienne method of the absorption coefficient sensitivity respect to the receiver height (a) and to the source height (b)

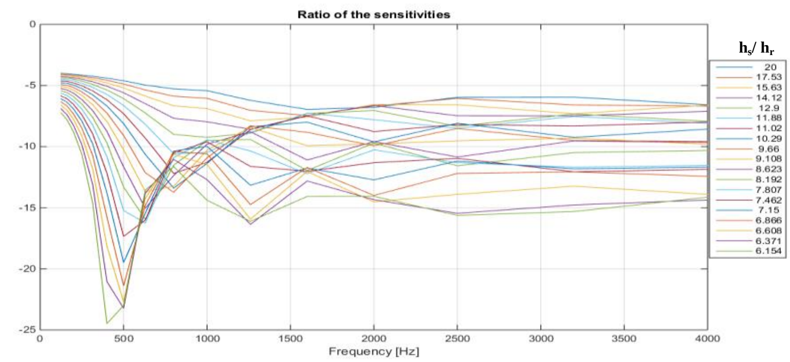

Figure 3: Ratio of the sensitivities defined by the eq.(23) and the eq.(24)

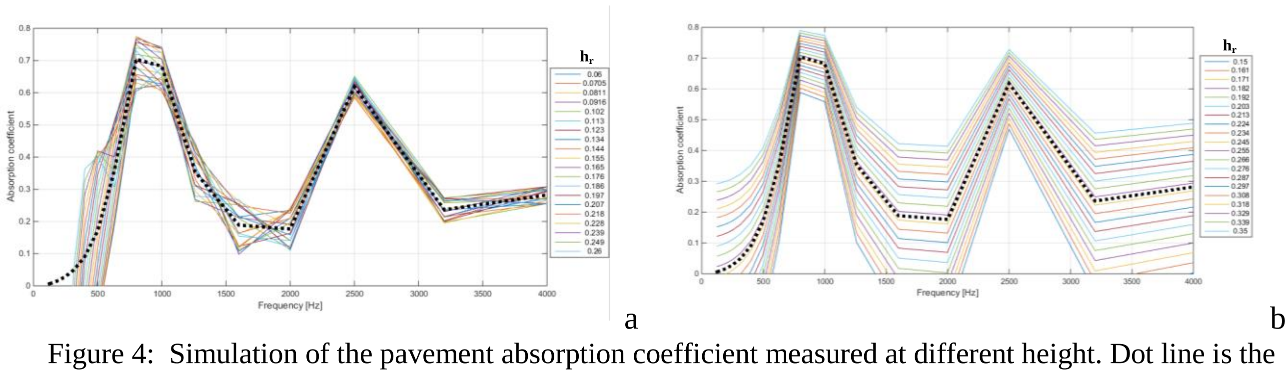

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Figure 4: Simulation of the pavement absorption coefficient measured at different height. Dot line is the real value of the absorption coefficient assumed in the simulation. Adrienne method (a), second method (b)

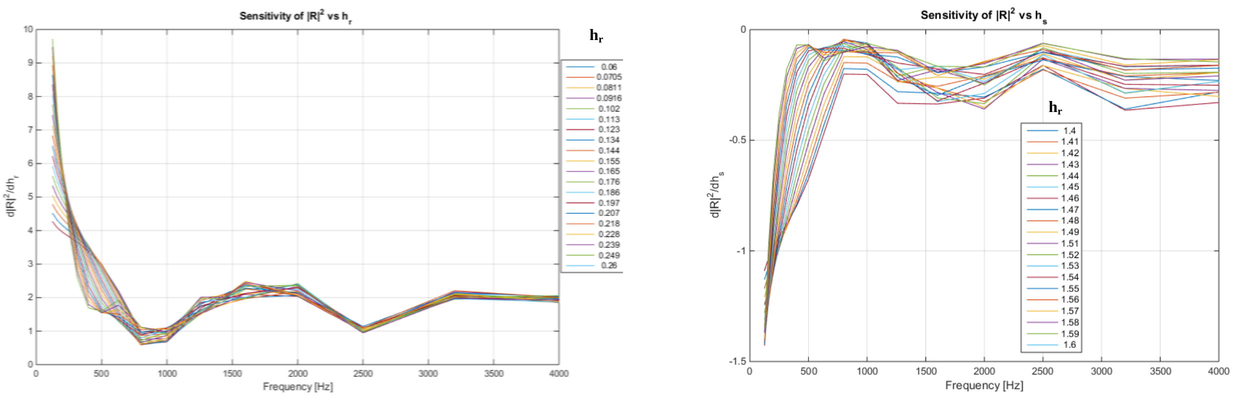

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Figure 5: Graphical behaviour of the absorption coefficient sensitivity respect to the receiver height (a) and to the source height (b). Absorption coefficient evaluated in accordance to the second method

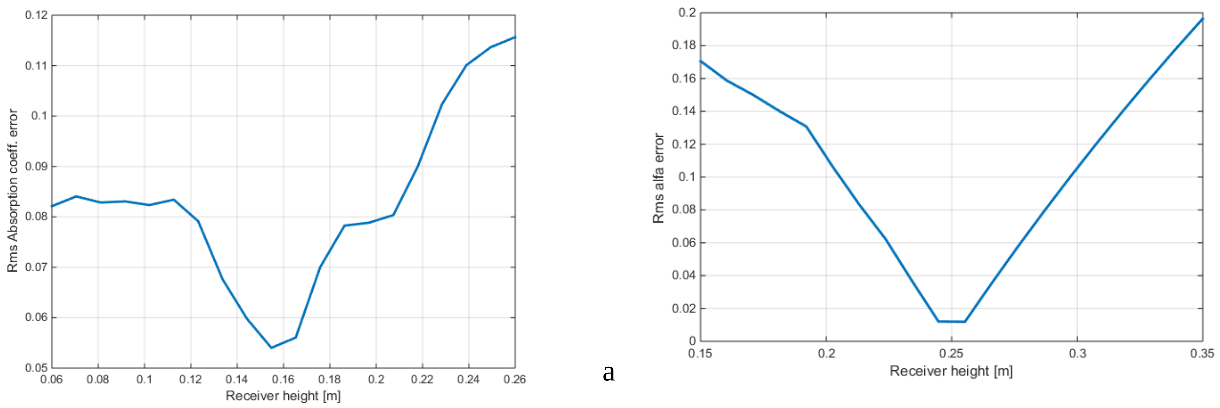

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Figure 6: Graphical behaviour of the absorption coefficient error changing the receiver height: second method (a) , Adrienne method (b)

Table 1: Comparison of in-situ measurement methods

	Spot method	Adrienne method	adopted method based on p-u probe
In situ measurement	✓	✓	✓
Contactless measurement	n.a.	✓	✓
Frequency bandwidth	250Hz÷1.6kHz [15]	250Hz÷4kHz [1]	315Hz÷10kHz [12]
Exposed area diameter	0.01 m [15]	≈ 1.4 m [1]	≈ 1.4 m
Height of the sound source	> 0.48 m [15]	1.25 m [1]	1.5 m
Height of the sound microphone / p-u probe	0.1 m [15]	0.25 m [1]	0.16 m
Absorption coefficient sensitivity to receiver height variation (f≥315)	n.a.	2.4	2.1
Absorption coefficient sensitivity to source height variation (f≥315)	n.a.	0.5	0.3
n.a.: not applicable			

4. Conclusions

In this paper it has been presented a new system for the acoustic absorption coefficient measurement, based on the modification of the Adrienne method, where the microphone has been replaced by a pressure-velocity probe. This measurement system will be mounted on a vehicle equipped with a stabilization control system able to reduce the receiver/source height variation from pavement, due to the running vehicle, in order to maintain small the error in the measure.

In order to investigate the error due to the measurement methods, their correspondent equations have been implemented on Matlab. The simulation has shown the sensibility of the absorption coefficient to the variation of the receiver/source height, from the road plane. The results show that the second method is less sensitive to the receiver height variation compared to the Adrienne method, and, as a consequence, more suitable to be implemented on a vehicle.

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