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A two-microphones method for the determination of the acoustic source height of a moving rectilinear source above a flat ground with impedance discontinuity

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Abstract

Equivalent acoustic source height is an important parameter for accurate predictions of the acoustic impact of new transportation infrastructures. Recent research has shown that this parameter can be obtained from a two-microphone technique in the case of a rectilinear distribution of point sources which are parallel to a flat homogeneous ground. As an homogeneous ground is not quite common in the field, the present paper introduces a generalization of the procedure to a ground with impedance discontinuity. The latter is taken into account by the replacement of Rudnick's propagation model by Rasmussen's model. Both surfaces are modelled as Delany-Bazley absorbers. It is demonstrated that the two-microphone method is relatively insensitive to ground parameters. Actually measuring the ground impedance when performing a source height determination in the field is not necessary. Qualitative assessment of ground parameters is sufficient to obtain an accurate source height determination. The effect of source misalignment due to the fact that the method takes a sound photograph of the moving sources is shown to be negligible for the speeds of interest. The reliability of the method is established by experiments with controlled noise sources.

INTRODUCTION

Far-field models of emission for noise impact studies usually consider sources as a distribution of equivalent monopolar point sources. As ground effects strongly depend on the position of each source, the height of each source is a very important parameter. The present paper focuses on the case of a moving rectilinear sources (tramways for example). An experimental method using only two-microphone has already been used to determine sources height for one [4] or several sources [3] but only for an homogeneous ground. Because this last condition seldom occurs in the field, the present paper introduces a generalization of the method when a ground impedance discontinuity occurs (road/grass discontinuity for ex.). The principle of the measurement is outlined and formulated as an optimization problem. An experimental validation is presented and three studies on the influence of different parameters on the method is also investigated.

THEORY

The method consists in fitting the difference of frequency spectra measured at two different microphones with a theoretical one. This method has been used for one [4] or several moving sources [3] at the same height z_S and for an homogeneous ground.

The 2-microphone method

We consider here a rectilinear distribution of sources, parallel to the ground, at the same height z_S (Figure 1), whose relative acoustic power level is known and given by a series a_i.

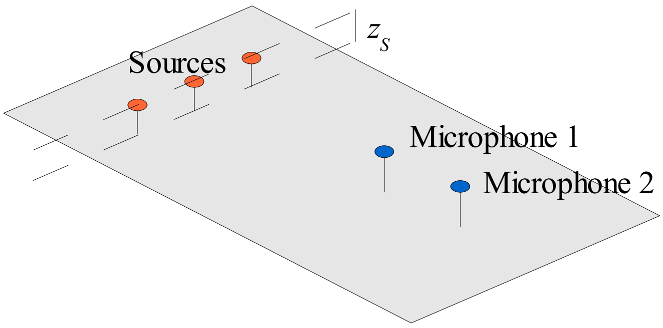

Figure 1 - Sources and microphones positions

The pressure created by the source i at the microphone j is given by

$$\frac{p_{ij}}{p_0} = a_i A H_{ij} \quad , \tag{1}$$

where $p_0 = 2.10^{-5}$ Pa and A is a global amplitude coefficient. H_{ij} is an operator describing the propagation between the source i and the microphone j, independent of the amplitudes of the sources.

For n uncorrelated sources, the sound pressure level at point j is

$$L_j = 10 \ \log_{10} \sum_{i=1}^{n} \left| \frac{p_{ij}}{p_0} \right|^2 \quad , \tag{2}$$

and the attenuation between the two microphones

$$\Delta L(f) = L_2(f) - L_1(f) = 10 \ \log_{10} \left(\sum_{i=1}^{n} \left| a_i H_{i2} \right|^2 \right) - 10 \ \log_{10} \left(\sum_{i=1}^{n} \left| a_i H_{i1} \right|^2 \right) \tag{3}$$

is independent of the global amplitude factor of the sources, but not of the relative power coefficients a_i . For simplification, we assume here that $a_i=1$, which is not unrealistic for rectilinear sources like tramways for example.

This attenuation is evaluated both by measures and by calculation, and the source height z_S is obtained by minimization of the cost function

$$F(z_S)=\sum_{f=100\ Hz}^{6kHz} \left|\Delta L_{calculated}(f, z_S)-\Delta L_{measured}(f)\right|^2 \quad . \tag{4}$$

which a typical curve is represented on figure 2. This non-convex one-parameter cost function can be easily minimized by systematic search.

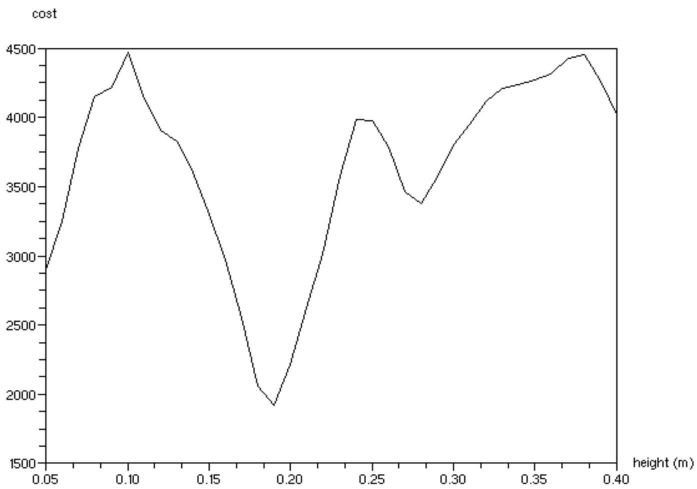

Figure 2 - Typical F function, for three sources placed at a 18 cm constant height.

Propagation model

Rassmussen's model

For an acoustic propagation over a flat ground with an impedance discontinuity, the propagation operator given by the Rasmussen's model [5] is used :

$$H_{ij}=\frac{1}{k}(8\ \pi k)^{1/2} d_{ij} \frac{e^{-i\frac{\pi}{4}}}{16\ \pi^2}\int_0^\infty G_{ij}\, dz \quad , \tag{5}$$

with

$$G_{ij}=\frac{e^{ik(R_1+R_3)}}{\sqrt{R_3^3\,R_1\,(R_1+R_3)}}+Q_2\,\frac{e^{ik(R_1+R_4)}}{\sqrt{R_4^3\,R_1\,(R_1+R_4)}}$$
$$+Q_1\,\frac{e^{ik(R_2+R_3)}}{\sqrt{R_3^3\,R_2\,(R_2+R_3)}}+Q_1\,Q_2\,\frac{e^{ik(R_2+R_4)}}{\sqrt{R_4^3\,R_2\,(R_2+R_4)}}\quad . \tag{6}$$

where k is the wave number and where the geometrical parameters $R_i, i\in\{1,2,3,4\}$ and d_{ij} are defined on figure 3. Terms of atmospheric absorption are neglected here, according to the short distance of propagation. Q_1 and Q_2 are the spherical reflection coefficient, defined by

$$Q=R_p+(1-R_p)F(w)\quad , \tag{7}$$

where R_p is the plane wave reflection coefficient, and

$$F(w)=1+2\mathrm{i}\,w^{1/2}e^{-w}\int_{-iw^{1/2}}^{\infty}e^{-u^2}du \tag{8}$$

with the so-called "numerical distance"

$$w=i\frac{2\,k_0\,R_2}{(1-R_p)^2\cos^2\phi}\left(\frac{\rho c}{Z}\right)^2\left(1-\frac{k^2}{\kappa^2}\cos^2\phi\right)\quad . \tag{9}$$

For the numerical computation of *F(w)*, approximated Chessel formulas [1] can be used.

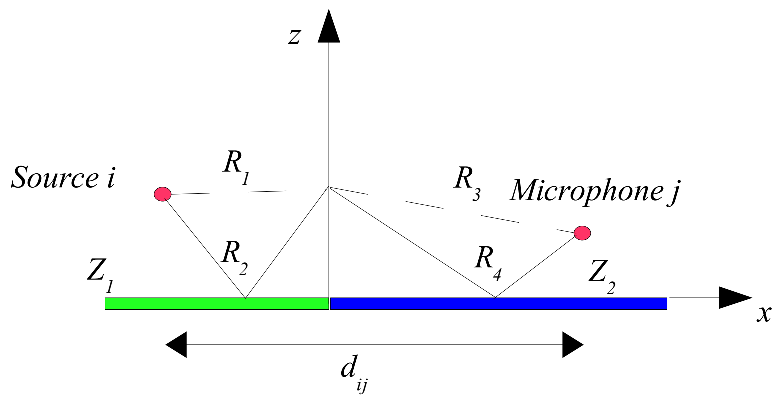

Figure 3 : Geometrical parameters for Rasmussen's model for a ground with an impedance jump. x<0 : ground impedance Z_1. x>0 : ground impedance Z_2.. z axis is set on the impedance jump.

Note that if $Z_1=Z_2$ (homogeneous ground) Rasmussen's model converges to Rudnick's one [6] and that the two-microphone method is then equivalent to the one used in [3].

Ground parameters and plane wave reflection coefficient

We use the Delany-Bazley model [2], from which we obtain the impedance Z and the wave number in the ground κ, knowing the specific flow resistivity of the ground. This values are sufficient to obtain the needed value of R_p, the plane wave reflection coefficient, using the extended reaction model of the ground.

EXPERIMENTAL VALIDATION

Experimental set-up

The experimental set-up consists in one or several sources (loudspeakers) and two microphones (height : 2m, orthogonal distance from the source : 2 and 4m respectively). Sources and microphones are separated by an impedance jump.

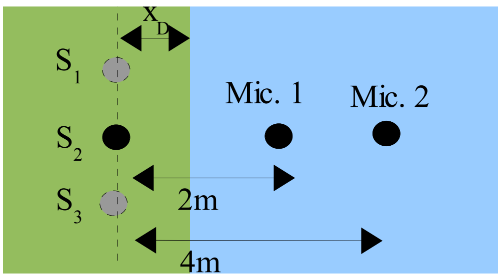

Figure 4 - Aerial view of the experimental set-up

Homogeneous ground

The first experimentation consists in validating the reliability of the method when handling several sources. Three loudspeakers at the same height and separated by 5m gaps were set on an homogeneous ground (asphalt). For each source height, from 7,5cm to 1m, two measurements were carried out with 125ms shots. Results show a good agreement between the source height determined by the two-microphone method and the loudspeakers height (see Figure 5).

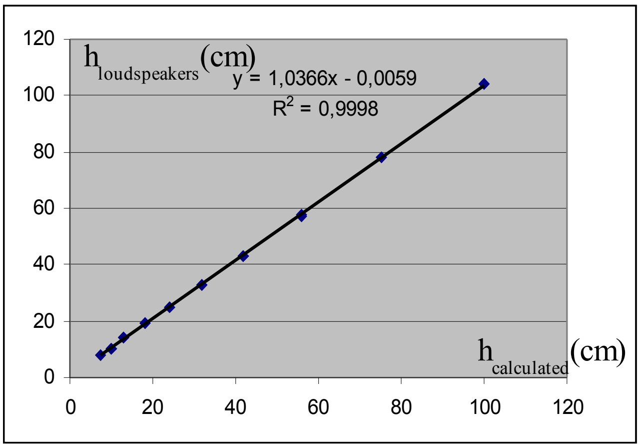

Figure 5 - Homogeneous ground : loudspeakers height (cm) versus source height (cm) determined by the two-microphone method

Inhomogeneous ground

One or two loudspeakers were put on a lane (small gravels) near a meadow (grass) where were the two microphones. Specific flow resistivity has been directly measured for each ground. Despite a small ground slope between sources and microphones, source height determined by the two-microphone method are in a good agreement with loudspeakers heights (see figure 6). Note that in figure 6 the regression line is computed from the heights below 0.1 m and extrapolated to higher values. During the tests, the emphasis was put on grazing incidences, in the perspective of application to tramways..

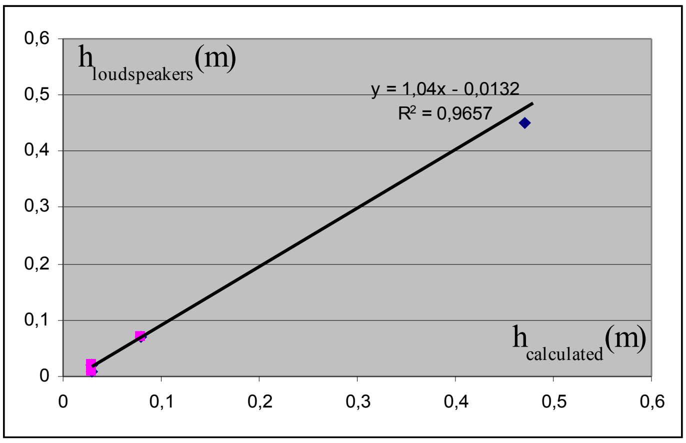

Figure 6 - Inhomogeneous ground : loudspeakers height (m) versus source height determined by the two-microphone method (m)

INFLUENCE OF DIFFERENT PARAMETERS ON THE METHOD

Several numerical investigations has been carried out to determine the limitations of the method. Two one-source configurations have been tested. Again the grazing incidences were privileged :

Test 1 : $z_S = 0.07\,m$, $\sigma_1 = 100\,000\,kN.s.m^{-4}$ (road),

$x_D = 1.8\,m$, $\sigma_2 = 100\,kN.s.m^{-4}$ (grass).

Test 2 : $z_S = 0.02\,m$, $\sigma_1 = 3\,000\,kN.s.m^{-4}$ (compact ground),

$x_D = 0.7\,m$, $\sigma_2 = 200\,000\,kN.s.m^{-4}$ (concrete).

The two microphones were numerically placed at 2 meters and 4 meters horizontal distance from the source, and 1 meter above the ground.

Sensitivity of the method to the specific flow resistivity accuracy

Errors on the specific flow resistivity value up to 60% have been numerically introduced : a maximum deviance of one centimeter has been observed for each test. The method is then quite reliable and practical as one can just give a qualitative assessment of the two ground parameters. No measurement of the acoustic absorption is required. It was also shown that underestimations are more detrimental than overestimations.

Sensitivity of the method to the horizontal position of the source(s)

Movement of sources during an experiment recording introduces an uncertainty in the exact lateral position of each source. This incertitude is proportional to the source speed : for example Table 1 gives the maximum incertitude (*i.e* speed multiplied by time of shot) on the position of the sources for a determined speed.

Speed (km/h)	Speed (m/s)	Max error 100ms (m)	Max error 50ms (m)
20	5,56	0,56	0,28
60	16,67	1,67	0,83
100	27,78	2,78	1,39

Table 1 - Values of speed and maximum error on the position

Errors of 1m and 2m were numerically introduced for both tests. The method appears to be quite robust to this uncertainty factor as only a small divergence of 1cm on test two for the 2m error.

Influence of background noise

A disturbing Gaussian noise has been artificially introduced in the temporal signals of sound levels. It appears that the method gives good results with signals with signal-to-noise ratios up to 10dB, which is quite easy to obtain in experimental conditions.

CONCLUSION

The original two-microphone method for measuring the height of a parallel to an homogeneous ground discrete line source has been extended to the case of an impedance discontinuity. This situation is quite common in the field when studying road transportation vehicles. Experiments carried out with controlled noise sources give satisfying results, both homogeneous and inhomogeneous grounds. Moreover, numerical simulations illustrate the low sensitivity of the method to noise, to errors on the geometry or to errors regarding the absorption of the ground. The method is now operational for investigations on tramways.
The ongoing research focusses on relaxing the constant height constraint in the method, in order to be able to study other vehicles like busses or trucks.

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