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COMPUTER SIMULATION OF THE FREQUENCY RESPONSE OF TRAFFIC NOISE MEASUREMENTS AS A FUNCTION OF MICROPHONE POSITION

Federico Miyara[a,b], Vivian Pasch[a,c], Susana Cabanellas[a,c], Marta Yanitelli[a,c], Pablo Miechi[a]

[a]*Grupo Ruido, Facultad de Arquitectura, Planeamiento y Diseño, Universidad Nacional de Rosario. Riobamba 220 bis, 2000 Rosario, Argentina, fmiyara@fceia.unr.edu.ar*
[b]*Laboratorio de Acústica y Electroacústica, Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Universidad Nacional de Rosario, Riobamba 245 bis, 2000 Rosario, Argentina, http://www.fceia.unr.edu.ar/acustica*
[c]*Departamento de Física, Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Universidad Nacional de Rosario, Av. Pellegrini 250, 2000 Rosario, Argentina, scabanel@fceia.unr.edu.ar*

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Abstract. Traffic noise measurements are usually performed with the microphone located at a standardised position. In order to test the influence of microphone position (including its height and its distance from façade) a computer model has been developed which includes noise reflection at neighbouring surfaces as well as vehicle trajectory and its associated Doppler spectral warping. Detailed FFT spectrum as well as octave and one third of an octave spectra have been computed for different microphone configurations. Results show that influence is not negligible when measuring noise spectrum, for instance, for spectral noise mapping. Hence, measurement position must be specified accurately.

1 INTRODUCTION

Nowadays the tight scientific, cultural, technological and economic interaction between nations poses a variety of problems whose solutions demand common strategies. Environmental issues, particularly noise pollution, are among these problems.

The trend in noise management involves measurement or prediction of outdoor noise both for assessment and planning. Noise maps are the most widespread diagnosis tool for noise pollution in large cities. In order that results from different cities or even countries can be compared it is necessary to state standard measurement conditions. The kind of instrument, indicators, measurement duration, and microphone position should be carefully specified.

One of the most controversial specifications is the microphone height and distance from the façade for outdoor measurements. While the first edition of International Standard ISO 1996-1 (1982) preferred a height of 1.2 m to 1.5 m, the latest version of ISO 1996-2 (2007) recommends a height of 4.0 m except for one-storey areas. Directive 2002/49/CE of the European Union also prefers 4.0 m and goes a step further requiring values measured at other heights to be corrected to the standard 4.0 m. The distance from the façade is also subject to different opinions. In England ant the Wales, measurements are taken at 1 m from the façade (Hopkins et al., 2000) while in other European countries the standard distance is 2 m. Sometimes, as when measuring sonic booms, the microphone should be flush with the surface.

The purpose of this paper is to present the effects of receiver position on the frequency response of the measuring system. These effects are due to the interference between direct sound and sound reflected off the different neighbouring surfaces. Frequency response is particularly important when measuring noise spectrum, such as in spectral noise mapping (Pasch et al., 2002). The approach has been to simulate computationally the interference pattern due to reflections in a canyon-like street for a moving source such as a car.

2 PROPAGATION MODEL SENSITIVE TO PHASE

When multiple reflection paths are present, ray tracing is a useful technique as long as the reflecting surfaces are large compared with wavelength. If a and b are the sides of a rectangular reflector, d_1 and d_2 are the lengths of the incident and reflected paths with an incident angle θ (contained in a plane parallel to side a), then the absolute level deviation is bounded by (Makrinenko, 1994)

$$\left|\Delta L_p\right| \;\leq\; 6{,}22\sqrt{\lambda\frac{d_1 d_2}{d_1+d_2}\left(\frac{1}{a\cos\theta}+\frac{1}{b}\right)}. \tag{1}$$

We shall assume that the façade dimensions are large enough to neglect ΔL_p.

Often the superposition of the different rays is performed on an energy basis, which is equivalent to assume that rays are incoherent (Walerian, 2001). While this may be true for wide-band noise and wide-band indicators such as L_{Aeq}, this is not the case when prominent tonal components are present. Hence, care should be taken to retain phase information due to the different delays of sound reflection paths.

Figure 1 depicts the geometric layout for the analysis. The receptor R, the real source F_0 and several virtual sources F_n are considered. The absolute value of index n indicates the number of reflections experienced by the wavefront.

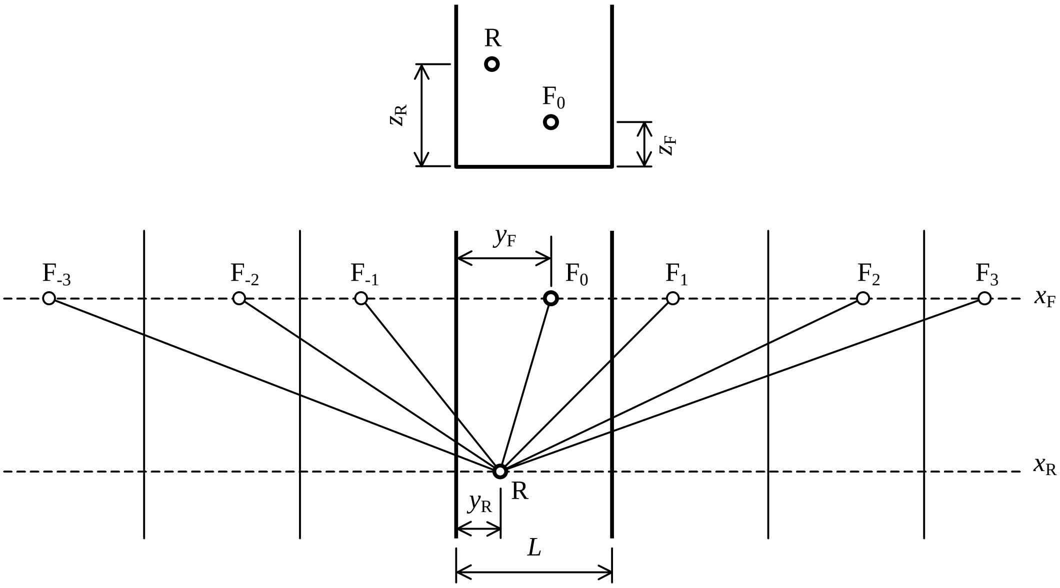

Figure 1. Top, schematic transverse section of a U-profile street. Bottom, top view of the street where both the source F_0 and the receiver R are shown. Toward the right and the left, specular images of the street including virtual sources F_n.

We want to superpose the direct and reflected waves arriving *simultaneously* at the receiver. Since the source (vehicle) is currently moving with velocity $\boldsymbol{v} = (v_x, v_y)$ and reflected paths are longer than the direct path, reflected wavefronts must have been radiated *earlier* than the direct path, when the source was located at different positions along its trajectory. This situation is shown in figure 2.

In order to take account of geometric divergence and delay, we need to compute the distance d_n between a given virtual source and the receiver. With the notation of figure 2 we have, for n even,

$$d_{2k}^{\ 2} = (x_F - x_R - v_x \Delta t_{2k})^2 + (2kL + y_F - y_R - v_y \Delta t_{2k})^2 + (z_F - z_R)^2, \tag{2}$$

and also

$$d_{2k} = c\,\Delta t_{2k}, \tag{3}$$

where c is the velocity of sound. Substituting into (2), and solving for Δt_{2k}, we get

$$\Delta t_{2k} = -\frac{B}{2A} + \sqrt{\left(\frac{B}{2A}\right)^2 + \frac{C}{A}} \tag{4}$$

where

$$A = c^2 - v_x^{\ 2} - v_y^{\ 2} \tag{5}$$

$$B = 2\big((x_F - x_R)v_x + (2kL + y_F - y_R)v_y\big) \tag{6}$$

$$C = (x_F - x_R)^2 + (2kL + y_F - y_R)^2 + (z_F - z_R)^2 \tag{7}$$

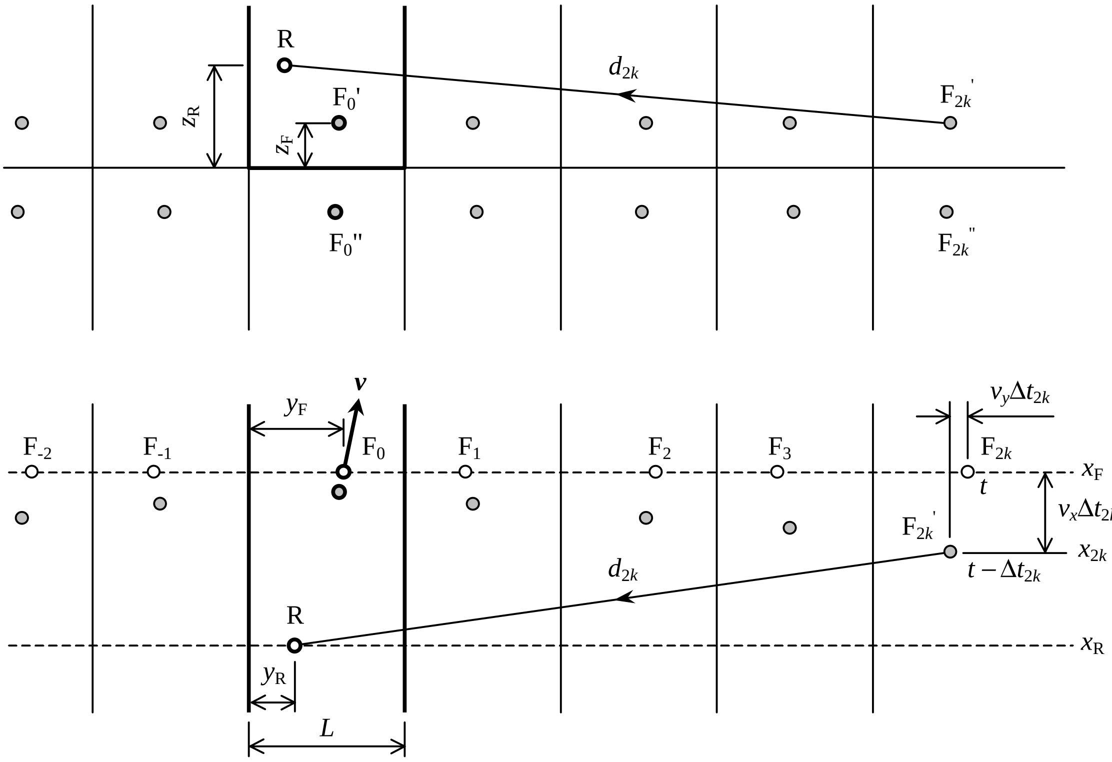

Figure 2. Empty dots show the position of virtual sources at *present time*, *t*. Filled dots represent their former positions when wavefronts arriving at instant *t* were emitted.

Finally, we get d_{2k} from (3). For n odd simply put $-y_F$ instead of y_F in (2), (6), and (7), and for reflections in the ground replace z_F with $-z_F$ in (2) and (7). It turns out that d_n is a function of time t through x_F, y_F and, possibly, v_x and v_x.

Consider now an omnidirectional source radiating sound at an angular frequency ω so that at a distance r_o it produces a peak pressure P_o in an anechoic environment. Then, at a distance d_n we shall have

$$p_n(t) = P_o r_o \frac{e^{j\omega(t - d_n/c)}}{d_n}. \tag{8}$$

Considering 2Q non-ideal reflections, the total pressure at the receiver shall be

$$p(t) = P_o r_o e^{j\omega t} \sum_{n=-Q}^{Q} R_f{}^n \left(\frac{e^{-j\omega d_n/c}}{d_n} + R_g \frac{e^{-j\omega d_n'/c}}{d_n'} \right), \tag{9}$$

where d_n' corresponds to reflections in the ground, R_f is the reflection coefficient of the façades (for the sake of simplicity we shall assume that both façades are identical and homogeneous along the street) and R_g that of the ground.

For locally reacting surfaces, if Z_{as} is the specific acoustic impedance of the surface and $\rho_o c$ that of the air, then holds the well known formula

$$R_f = \frac{Z_{as}\cos\varphi_n - \rho_o c\cos\psi_n}{Z_{as}\cos\varphi_n + \rho_o c\cos\psi_n}, \tag{10}$$

where φ_n is the incidence angle of the n-th path and ψ_n the corresponding refraction angle. In the present case these can be computed by

$$\cos\varphi_n = \frac{2kL \pm y_{\mathrm{F}} - y_{\mathrm{R}} - v_y\Delta t_n}{d_n}, \tag{11}$$

$$\cos\psi_n \cong \sqrt{1 - \left(\frac{c_f}{c}\right)^2\left(1 - \cos^2\varphi_n\right)}, \tag{12}$$

where c_f is the velocity of sound in the façade material and (+) is chosen for $n = 2k$ (n even) and (–) for $n = 2k–1$ (n odd). We proceed in a similar fashion for ground reflections. When $\cos\psi_n$ is imaginary and Z_{as} is real, we have total reflection, i.e., $|R_f| = 1$. In this case there is an extra phase delay adding to the path-length delay.

For not locally reacting surfaces the situation is usually far more complicated since the interaction between the sound wave and the structure depends on several factors that are difficult to specify. However, the response can be approximated by means of a linear filter.

Note that in equation (9) no adjustment is needed for Doppler warping, since the slowly varying delay d_n/c already accounts for it.

3 COMPUTER SIMULATION

In order to apply the model it was first attempted to compute a frequency response by just removing $e^{j\omega t}$ and then integrating along the trajectory. This technique works properly for stationary systems since it relies on the fact that tones of different frequencies obey a long-term energy-superposition principle (in the present case the "long-term" requisite would be accounted by the integration). This is not the case here, since the interference between the different reflections yield a very complex and slowly-varying envelope. The result was huge variations for slight modification of the trajectory.

It was thus decided to calculate the complete time history of the pressure signal at the microphone during a pass-by and then compute its Fast Fourier Transform (FFT) spectrum. While we could carry out this plan with several sinusoids one at a time, it is better to use other signals such as standard traffic noise or pink noise. Equation (8) turns into

$$p_n(t) = r_o\frac{p_{fo}(t - d_n(t)/c)}{d_n(t)}. \tag{13}$$

where $p_{fo}(t)$ is the pressure caused by the source at a distance r_o. The signal p_n is sampled at sampling rate f_s. Since p_{fo} is generally not known at warped time $t_k - d_n(t_k)/c$, cubical interpolation is used to avoid jitter distortion which can affect seriously the spectrum if one just takes the value of the nearest sample.

The filtering action of the reflection is taken into account with a first order finite impulse response (FIR) filter such as

$$y(k) \;=\; b_o\, x(k) \;+\; b_1\, x(k\!-\!1). \tag{14}$$

This filter is applied n times for the n-th reflection, yielding the binomial formula

$$y(k) \;=\; \sum_{h=0}^{n} \binom{n}{h} b_o{}^{n-h}\, b_1{}^{h}\; x(k-h)\,, \tag{15}$$

where $x(k) = p_n(t_k)$. This kind of filtering is performed on each reflected component and then all components are added together, as in equation (9).

4 RESULTS

Several simulations have been performed, particularly assuming that the microphone is at a height of 1,5 m or 4 m and at 1 m or 2 m from the reference façade. A street with a 14-m separation between façades has been considered. The source has been assumed to move along a straight line along a trajectory parallel to façades and at a distance of 6 m from the reference façade. The line spectrum obtained by FFT (f_s = 22050 Hz, N = 32768, Blackman window) has been converted to a one-third-of-an-octave spectrum. In figure 3, pink noise (flat 1/3-octave spectrum) has been used to get a sort of frequency response of the measurement system. Figure 4 shows the resulting 1/3-octave spectra for several positions of the source superimposed on the spectrum of standard traffic noise used as a source.

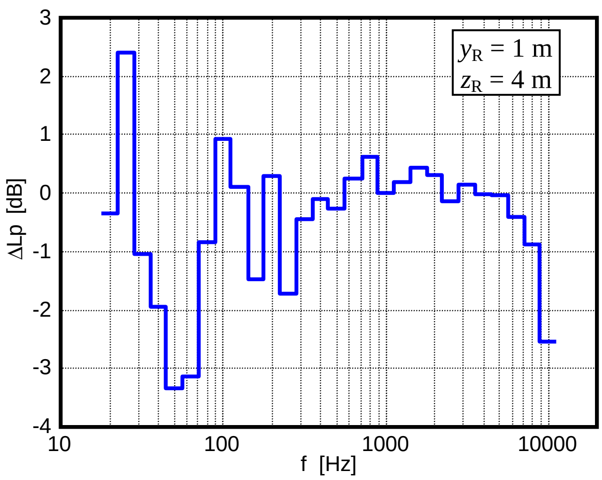

Figure 3. Sample frequency response between static anechoic pink noise and its non-static multipath reflected version, after normalising to the same L_{Aeq}. Microphone is located at a height of 4 m, and 2 m from façade. Façades are 14 m apart and the source moves during 16 s at 60 km/h along a straight line 4 m from microphone.

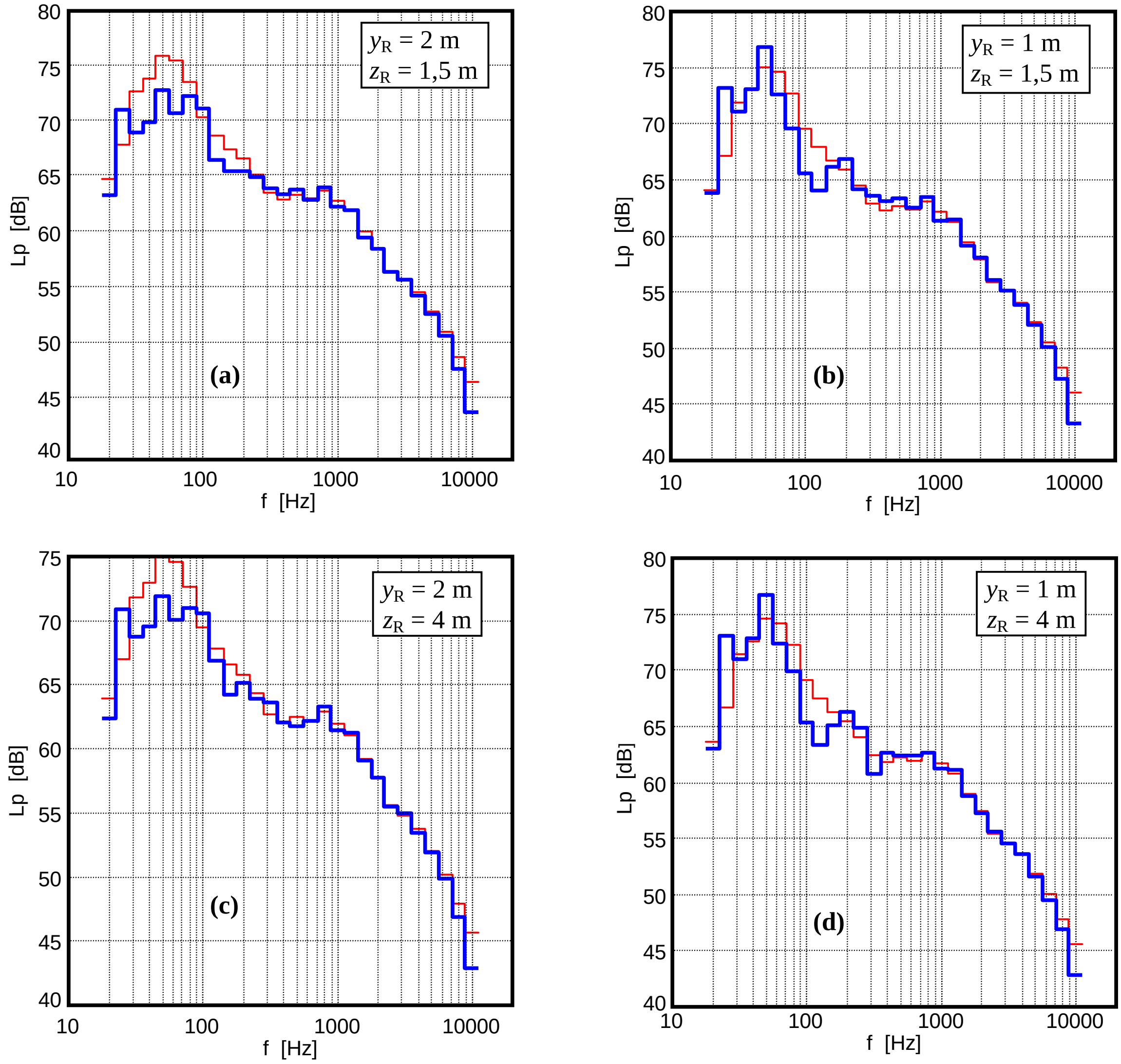

Figure 4. Blue, 1/3-octave spectrum of noise at the microphone. Red, 1/3-octave spectrum of the source. A noise extending to low and high frequencies the standard noise that appears in International Standard ISO 717-1 has been used. Source signal has been normalised to the same L_{Aeq} at the microphone. (a) The microphone is located at 2 m from the façade and at a height of 1,5 m; L_{Aeq} = 71,5 dBA. (b) The microphone is located at 1 m from the façade and at a height of 1,5 m; L_{Aeq} = 71,1 dBA. (c) The microphone is located at 2 m from the façade and at a height of 4 m; L_{Aeq} = 70,8 dBA. (d) The microphone is located at 1 m from the façade and at a height of 4 m; L_{Aeq} = 70,6 dBA.

5 CONCLUSIONS

From the graphs it can be ascertained that the position of the microphone is quite important whenever spectral measurements at a site are necessary. Figure 4 shows differences of nearly 5 dB between certain bands, and this depends particularly on the microphone location with respect to neighbouring surfaces. As it is expected, this phenomenon is particularly important at low frequencies.

Frequencies at a centre position in the spectrum are less affected, and that may be the reason why only slight differences appear when A-weighted equivalent level is measured, since very low frequencies are deeply attenuated by the A network.

However, this may grossly underestimate the incidence of low frequency, which can readily pass through façades. This is why more attention should be devoted to spectral measurements outdoors.

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