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CALCULATION OF METEOROLOGICAL CONDITIONS EFFECTS ON OUTDOOR SOUND PROPAGATION USING PARABOLIC EQUATION

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ABSTRACT
For long distance sound propagation, the variation of the atmospheric conditions can produce large modification on the sound pressure level (SPL) at the receiver. With respect to homogeneous conditions i.e when wind and temperature effects are negligible, the range of SPL variation due to vertical wind and temperature gradients can exceed several decibels. When simple sites (flat, without obstacle, etc...) have to be studied, analytical model are sufficiently accurate to predict long distance SPL. When complex environments have to be considered, only numerical models permit to consider all the parameters in a global approach. The Parabolic Equation (PE) method are one of these. In this study, we solve our problem through the Split-Step Padé (SSP) approach and the discrete random Fourier modes technique, method which seems to be very powerful and reliable for traffic noise prediction.

1 - INTRODUCTION
The presence of high-trafficked roads around large cities produces substantial noise disturbances for neighboring inhabitants. Due to the source traffic composition and the outdoor propagation conditions, the populations can be submitted to large sound pressure level variations. In order to predict the sound pressure level for these real conditions, we need to be able to model as well as possible the effects of all the physical parameters involved in the propagation phenomena, i.e. ground effects, meteorological conditions, turbulence, screening effects. Many analytical models [1-3] developed in recent past years can be used. By these techniques, the consideration of numerous parameters implies to introduce in the calculation various simplifying hypothesis which rapidly lead to inaccurate results. Thus, for complex situations, analytical approaches become very quickly unsatisfactory. In order to give a first response in such complicated situations, numerical methods based on the parabolic approximation have been investigated [4]. Among these, the " Split-Step Padé " method [5] appeared to be the most reliable with respect to its obvious advantages in terms of angular aperture and CPU time, and to its capability to consider the most involved phenomena: homogeneous or mixed grounds, acoustic barriers, etc... The atmospheric turbulence is taken into account through the " discrete random Fourier modes " technique. It is considered as isotropic, homogeneous and essentially due to temperature scalar fluctuations. The 2D spectral density is assumed to have a Gaussian distribution or a von Karman profile [6]. The corresponding numerical code has been first validated through comparisons with literature data. Then, the propagation conditions have been progressively complexified in order to simulate more realistic propagation situations.

2 - THE THEORETICAL MODEL
In the linear acoustic approximation, the sound pressure p is solution of the elliptic Helmholtz propagation equation:

$$\Delta p + k_0^2 p = 0 \tag{1}$$

where k_0 is a reference wave number. Assuming the azimuthal symmetry for the acoustic field, the sound pressure $p(r,z)$ can be splitted into two components: a 2D far field approximation for the Hankel function and an envelope function $u(r,z)$ slowly range dependent. The acoustic field is dominated by forward propagating waves which are solutions of the one-way parabolic equation written in the 2D cylindrical coordinates system [4]:

$$\frac{\partial u(r,z)}{\partial r} = ik_0 (Q-1)\, u(r,z) \tag{2}$$

where Q is a pseudo-differential operator which varies very slowly in the interval $[r_0, r_0 + \Delta r]$. Thus, Eq. (2) can be directly integrated. This, introduce an exponential operator [5] $\exp[\sigma(Q-1)]$ which is approximated by a second order Padé expansion of $Q = \sqrt{1+\Im}$. In that case, we can write [6]:

$$u(r_0 + \Delta r, z) = \exp[\sigma(Q-1)]\, u(r_0, z) \approx \frac{1 + p_1 \Im + p_2^2 \Im^2}{1 + q_1 \Im + q_2^2 \Im^2} u(r_0, z) \tag{3}$$

where the coefficients p_1, p_2, q_1 and q_2 are easily deduced from a fourth order Taylor development. A marching algorithm is finally defined [7]. The numerical scheme leads to a stable linear system with pentadiagonal matrices, solved at each step with a standard LU decomposition method. In that condition, this second order Padé scheme can accommodate propagation angles as large as 54°.
The ground is modeled as a locally reacting surface with a complex impedance, which may change along the sound wave path (Fig. 1). The impedance values are calculated through the Delany and Bazley's model function of the single parameter σ (airflow resistance) [8].
The mean vertical sound speed profiles are set constant along the distance and are logarithmically shaped as follows:

$$c(z) = c_0 + a \ln(z/z_0) \tag{4}$$

where z_0 is the rugosity parameter and " a" the refraction parameter.
The atmospheric turbulence is considered as isotropic and homogeneous, and only due to temperature fluctuations. It is modeled by an averaging on N realizations of the refraction index, which random field is generated by a superposition of discrete random Fourier modes, with a gaussian distribution or a von Karman spectrum of the turbulent eddies [6].
The introduction of an acoustic barrier along the sound wave path is modeled by setting all the $u(r,z)$ to zero at the step $r=R_b$ for $z \leq H_b$. The oscillations due to numerical integration are smoothed through a spatial averaging. This, gives more reliable predictions. An important element has to be noticed. No diffraction coefficient has been considered in the PE code: the diffracted energy is only due to coupling between the equations.

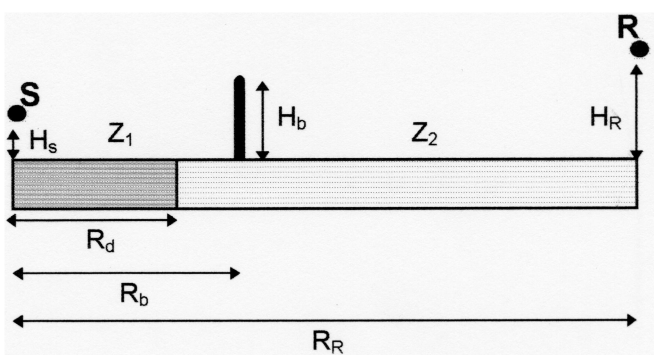

Figure 1: General geometrical set up.

Running until 1 km without turbulence for a grid spacing $\Delta r = \lambda/2$ and $\Delta z = \lambda/6$, CPU time is about 30s for 100 Hz and 20mn for 5 kHz with a SUN Ultra 10 360 MHz work station.

3 - RESULTS OF THE VALIDATION

The numerical code has been validated for various configurations in presence of homogeneous or mixed grounds, various atmospheric conditions represented by a distance dependent vertical sound speed gradient (positive, negative or equal to zero) and a noise barrier.

Fig. 2 shows the effect of a noise barrier together with a refractive atmosphere. First, without turbulence and secondly with turbulence, for the highest traffic noise frequency (5 kHz). The preponderant mechanism responsible for the enhanced sound levels just behind the screen is the diffraction by its edge, and the SPL are homogenized by the decorrelation role of turbulence. For longer distances and for upward refraction, the scattering role of turbulence reappears and the relative contribution of diffraction and scattering to the sound spreading in the shadow region is reversed.

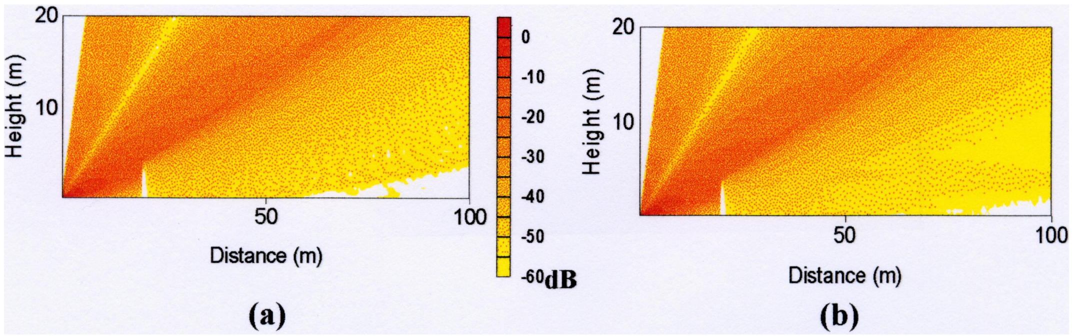

Figure 2: Numerical prediction of a screen effect for upward refraction; (a): without turbulence; (b) with turbulence (von Karman spectrum − 20 realizations) H_s=0.03 m; $\sigma_1 = \sigma_2 = 3.10^5$ kNsm^{-4}; $a = -2$ m/s; R_b=20 m; H_b=4 m.

One effect of the atmospheric turbulence on acoustic field is decorrelation which minimizes destructive interferences and which smooths out sound level profiles when $H_s/\lambda >> 1$ or $a>0$. A second effect of turbulence is scattering sound energy downward the shadow region when we consider propagation above a convex surface or for upward refraction ($a<0$). This latter case is studied in Fig. 3. We plot SSP predictions with and without turbulence in the same propagation conditions as in the Wiener & Keast campaign [9]. For deterministic calculations, the SPL predictions rapidly decrease, whereas turbulent predictions are very close to the experimental values. Turbulent results are indicated for three different numbers of realizations, in order to give an idea of their convergence. The slight discrepancy between experimental and numerical results can be explained in terms of uncertainty in the acoustic, climatic and impedance measurements. However, the SPL profiles are very similar as far as turbulence is considered.

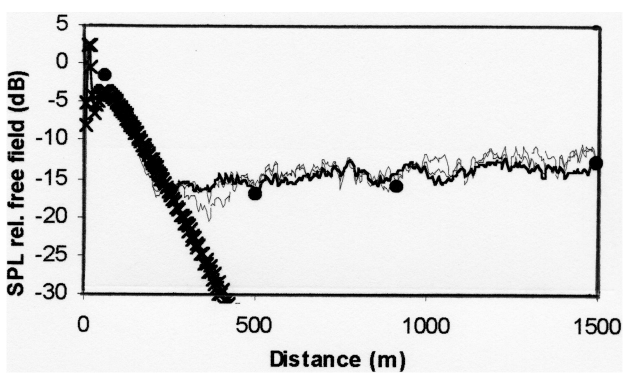

Figure 3: Comparison between Split-step Padé predictions for deterministic (×) or turbulent atmosphere and Wiener and Keast experimental data (•); frequency=424 Hz; H_s=1.2 m; H_R=0.6 m; $\sigma_1 = \sigma_2 = 3.10^2$ kNsm^{-4}; $a = -0.5$ m/s.

A more complex situation involves a sound wave propagating above a heterogeneous ground (without screen) through a stratified atmosphere, only upward refraction cases exist in literature. In [10], Bérengier and Daigle compared indoor experimental data obtained for propagation of sound above a curved surface having an impedance discontinuity, with analytical predictions given by a residue series solution. Assuming a far field approximation in our PE method, we proceed to a scale change (factor 10) in order to correctly compare results obtained from both techniques (Fig. 4).
In this example, the shorter range split-step Padé results fit better the experimental ones than the analytical predictions. This deviation beyond the discontinuity could be explained by an edge diffraction

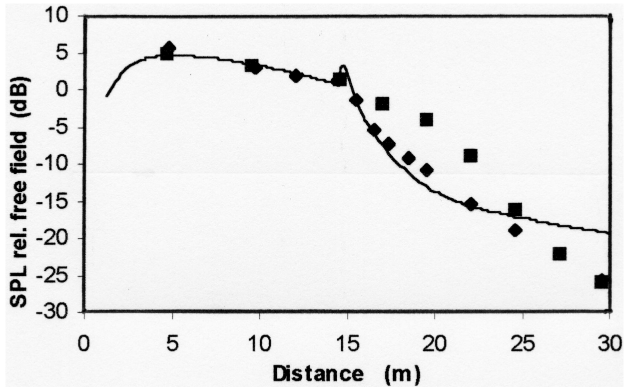

Figure 4: Comparison between Split-step Padé predictions (−), experimental (♦) and theoretical (■) results from Bérengier and Daigle [10]; frequency=400 Hz; H_s=H_R=0.5 m; σ_1=5.10^4 kNsm^{-4}; σ_2=50 kNsm^{-4}; Rd=15 m; a=− 68.8 m/s (linear gradient until an altitude of 1.2 m).

coefficient set to 1 in the analytical model. The discrepancy between the Split-Step Padé calculations and the experimental acquisitions at " long " distances could be attributed, in one part, to the inaccuracy in the experimental airflow resistance determination and, in another part, to the impedance discontinuity localization. This last point is amplified by the scale factor and by the very strong linear gradient value, due to the analogy between sound propagation in a homogeneous atmosphere above a curved surface and sound propagation in a stratified atmosphere above a plane surface.
A last validation concerns the effect of a noise barrier inside a turbulent atmosphere. In that case, the Split-Step Padé results are compared to those from Forssén [11] for a turbulent but non stratified atmosphere (Fig. 5). They are calculated with an averaging on 10 realizations, using a gaussian spectrum for the turbulence as the author did. In this case, the results for a homogeneous atmosphere and an absorbing barrier are calculated through the analytical Hadden and Pierce approach [12]. They are indicated as a reference. In the turbulent cases, we also plot predictions given by Daigle's model, which uses diffraction and scattering cross section theories [13]. SPL existing behind the barrier are given for a 1 kHz frequency and for the following heights H_R=H_b=10 m.
For deterministic cases, the three methods exactly give the same results. For turbulent cases, when the receiver is high enough, our results are also very close to Daigle and Forssén ones. On the other hand, when the receiver is near the ground, SSP predictions are closer Daigle's predictions than Forssén ones. His PE predictions sometimes underestimate the sound pressure levels existing in the shadow zone [7]. On the contrary, the discrete random Fourier modes technique predicts more enhanced sound levels in this region and proves again its efficiency and its accuracy.

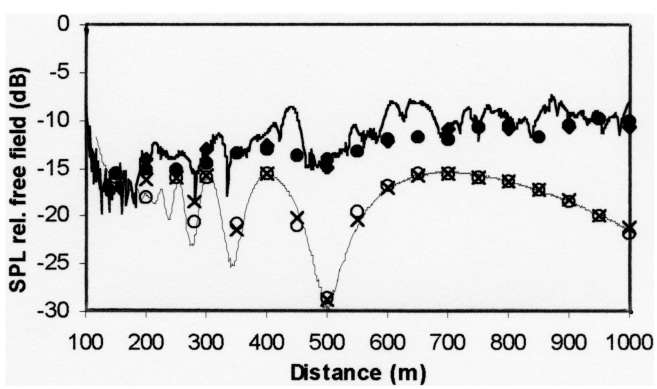

Figure 5: Comparison between SSP predictions for homogeneous (−) and turbulent (−) atmosphere with Forssén predictions (○: homogeneous) and (●: turbulent), Hadden and Pierce (×: homogeneous) and Daigle (♦: turbulent); frequency=1 kHz; H_s=0 m; σ_1=σ_2=3.10^5 kNsm^{-4}; R_b=100 m; H_R=H$_b$=10 m.

4 - CONCLUSION

The Split-Step Padé method coupled with the discrete random Fourier modes technique have been validated for a large number of propagation configurations in presence of a monopole source very close to the ground, an impedance discontinuity, an acoustic barrier, and a stratified and turbulent atmosphere. For both cases, the agreement between the Split-Step Padé predictions and the literature data is generally very good, without introduction of any diffraction coefficient. Thus, our method appears to be reliable to predict traffic noise propagation in such situations. This work opens the field for further investigations, notably the more precise description of sound speed profiles in the vicinity of multi-shaped obstacles. Outdoor controlled experiments have been realized in order to validate the code for such complex configurations, for which no data exist yet. The results of these measurements will be detailed in a further publication.

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