A DIFFUSION MODEL FOR SOUND PROPAGATION THROUGH FORESTS

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ABSTRACT

A new model has been developed allowing sound propagation through forests to be accurately calculated. Ground and trunks scattering effects are taken into account as well as meteorological effects. The scattering model relies on a modal decomposition of the trunk scattered energy. Simplified statistical formulations have been derived and implemented in a GFPE approach in order to assess for interactions between diffusion, ground and meteorological effects. Theoretical results have been satisfactorily compared to in situ measurements carried out in the French Landes Forest

THEORETICAL APPROACH OF DIFFUSION

Modal Model of Diffusion

A Modal Model of Diffusion (MMD) has been developed by Barrière [1] based on works from Twersky [2] and Felbacq [3]. On one hand, Twersky's multi-diffusion model deals with a configuration of arbitrary parallel cylinders illuminated by an incident plane wave. In this approach, the incident field on one cylinder is described as the sum of the direct field and the field diffused by the other cylinders. For a given cylinder, the first order of diffusion represents the diffusion due to cylinder m under the influence of the incident wave [1]. At the second order of diffusion, the model describes the acoustical response of cylinder m to all waves diffused at the first order by the other cylinders. One can then write a recurrent relation which enables for each cylinder to calculate each order of diffusion versus diffusion coefficients of lower orders.

On the other hand, Felbacq's theory of diffusion deals with a finite number of parallel cylinders of any radius illuminated by a plane wave. In this approach, there is no notion of diffusion order; the total field is expressed as the sum of a global incident field and a diffused field. This theory leads to a diffusion matrix which gives a linear system to be solved.

For both theories, the calculation of the total field is based on the development of the incident wave as a sum of Bessel cylindrical functions of first kind, and the development of the diffused waves as a sum of Hankel cylindrical functions [1].

The surface impedance of the cylinder is taken into account by means of a boundary condition that can be chosen different for each cylinder. Figure 1 shows the comparison between MMD and BEM (Boundary Element Method [4]) results in terms of Insertion Loss (IL) at 500 Hz for the case of a cylindrical incident wave illuminating 63 parallel reflective cylinders (arranged on 6 rows) whose radius is of 10 cm. Negative values of IL mean a sound attenuation due to the cylinders. The agreement between the two results is very good. Other comparisons show also good accordance which validates the MMD theory.

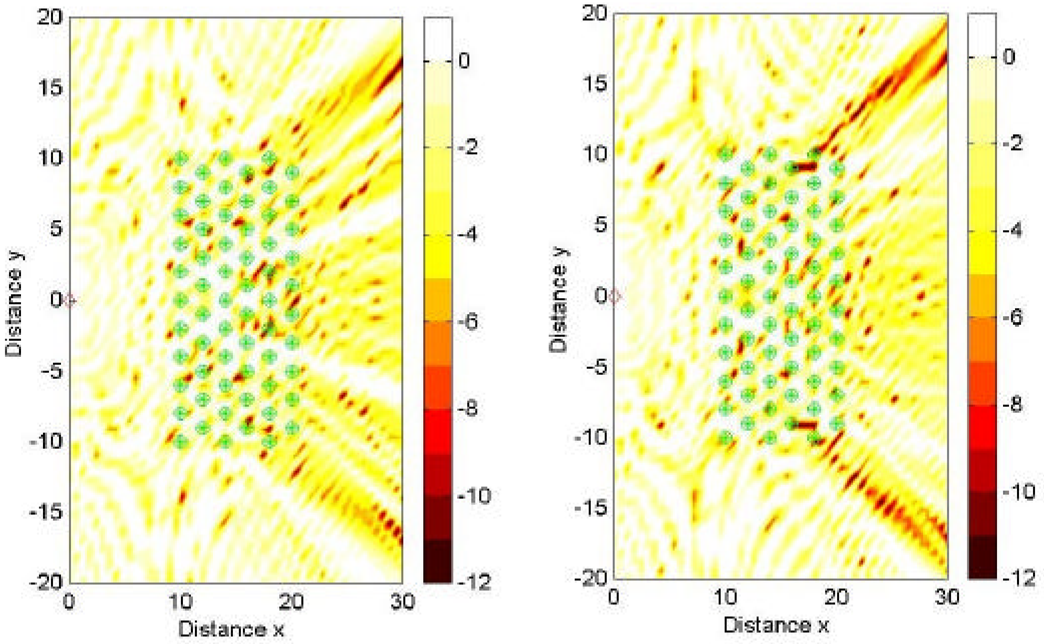

Fig. 1. *Insertion Loss at 500 Hz due to a strip of 63 reflective cylinders of radius 10 cm for an incident cylindrical wave located at (0, 0). BEM (left) and MMD (right) calculations. Distances are in meters.*

Analytical Multi-Diffusion Model

The use of MMD is restricted by the number of cylinders and the calculation frequency. In order to study realistic road configurations (such as the diffusion by a deep long strip of forest) as well as take into account meteorological effects during sound propagation, an analytical model validated by the MMD has been developed hereafter.

In this approach, the effect of sound diffusion by a tree trunk is represented by the scattering from an infinite rigid cylinder [5]. The diffusion by an incident plane wave is characterized by the radius a of the cylinder and the wavenumber k. The directivity and the intensity of the diffused energy depends on the value of ka. Embleton approach [6] derived from Twersky's theory of diffraction [2] consists in assessing analytically the mean energy diffused by an infinite strip of depth d of infinite parallel cylinders. The total acoustic field is calculated as the sum of the incident plane wave and the mean diffused field neglecting the phenomenon of multiple-diffusion between cylinders.

Embleton assumes that the diffused field is identical as the one obtained in the case of a mean homogeneous medium composed of rigid isolated cylinders whose radius is the average of the trees radii and whose density is the average trees density in the strip. The heuristic attenuation Att_{heur} of a plane wave of wavenumber k by an infinitely wide strip of depth d of infinitely long cylinders of mean radius a is given by, in dB:

$$Att_{heur} = 20d \times \mathrm{Im}(k_{eq}) / \ln(10) \tag{1}$$

with:

$$k_{eq} = \sqrt{k^2 - 4jNg + (g_1{}^2 - g^2) \times (2N/k)^2} \tag{2}$$

where N is the number of cylinder per m^2, **Im** is the imaginary part, and:

$$g = \sum_{n=-\infty}^{+\infty} A_n \,, \quad g_1 = \sum_{n=-\infty}^{+\infty} (-1)^n A_n \tag{3}$$

with:

$$A_n = \frac{i\, J_n(ka) + Z\, J'_n(ka)}{i\, H_n(ka) + Z\, H'_n(ka)} \tag{4}$$

Z is here the cylinders normalised impedance, J_n and J'_n are the Bessel functions of order n and their derivative, respectively, and , H_n and H'_n are the Hankel functions with positive imaginary part of order n and their derivative.

Heuristic Approach

In the previous statistical approach, the infinite cylinders strip is represented by a material of fixed width with a given density of obstacles. This theory allows to describe only the energy of the square mean of the transmitted sound field $\left|\langle y \rangle^2\right|$ instead of the quadratic mean of the transmitted energy $\left\langle |y|^2 \right\rangle$ which is the value of interest since it characterizes the global attenuation. The statistical approach neglects the incoherent diffusion between cylinders and thus introduces an error which is of importance only at high frequency. This error has been empirically estimated by Price [7] by comparing to scale model measurements results. It appears that this model is in agreement with the experiments for a cylinder density artificially reduced by 60%, the frequency dependence being the same. Equation (1) can finally be rewritten as follows:

$$Att_{heur} = 20d \times \mathrm{Im}(k_{heur}) / \ln(10) \tag{5}$$

with:

$$\mathrm{Im}(k_{heur}) = 0.4 \times \mathrm{Im}(k_{eq}) \tag{6}$$

The ground impedance has been evaluated from impulse measurements with an iterative method. Attenborough's two-parameter impedance model [8] has been used here with a flow resistivity s_e of *200 and 7.5 kPa s m*$^{-2}$, and a rate of exponential change of porosity of a_e of *0* and *25 m*$^{-1}$, for the plain ground and the forest ground, respectively. The ground impedance Z_g is given by:

$$Z_g = 13.79(\boldsymbol{s}_e / f)^{1/2}(1 + j) + 9.74\, j(\boldsymbol{a}_e / f) \tag{7}$$

where f is the frequency.

IMPLEMENTATION OF DIFFUSION IN A GFPE APPROACH

In order to precisely bring to the fore the effect of meteorology on sound propagation through forests, a 2D GFPE code has been developed [9] and adapted to road traffic noise situations [1] where road line sources are modeled as series of equivalent point sources of height 0.5 m. In the case of non-uniform wind conditions, GFPE calculations are made for each equivalent source by projecting the wind profile on the source-receiver direction. For each equivalent source, the acoustic field is initialized by an analytical expression [10] on a vertical axis containing the source point, and then propagated step by step to the receiver.

Geometrical configuration

The omni-directional point source is located 0.5 m high above a rigid surface and 20 m away from a 100 m deep and 10.5 m high forest strip. The trees have an average circumference of 0.16 m and their density is of 0.14 trunks/m^2.

Meteorological Sound Speed Profiles

Temperature profiles used in the following calculations are obtained from Raynor [11]. Daytime and night profiles haver been interpolated up to 50 m high for both the forest and the plain situations [12]. The PE method requires the knowledge of the sound speed profiles between the ground and a top limit depending on the frequency. Knowing the characteristics of wind speed profiles at some particular points above the plain and within the forest, it is necessary to determine their evolution inside the forest and after it. Accoprding to Liu's works [13], the wind profile inside the forest is considered to be constant after 100 m of propagation. Moreover, it is assumed that the wind profile after the end of the forest strip becomes similar to the plain situation one at a distance of 20 times the mean height of the trees [12].

Results and Discussion

Figure 2 shows three maps of iso-efficiencies calculated in a vertical plane perpendicular to the road and corresponding to three different typical meteorological conditions: negative temperature gradient (unfavorable condition to propagation), positive temperature gradient and downwind (favorable conditions).

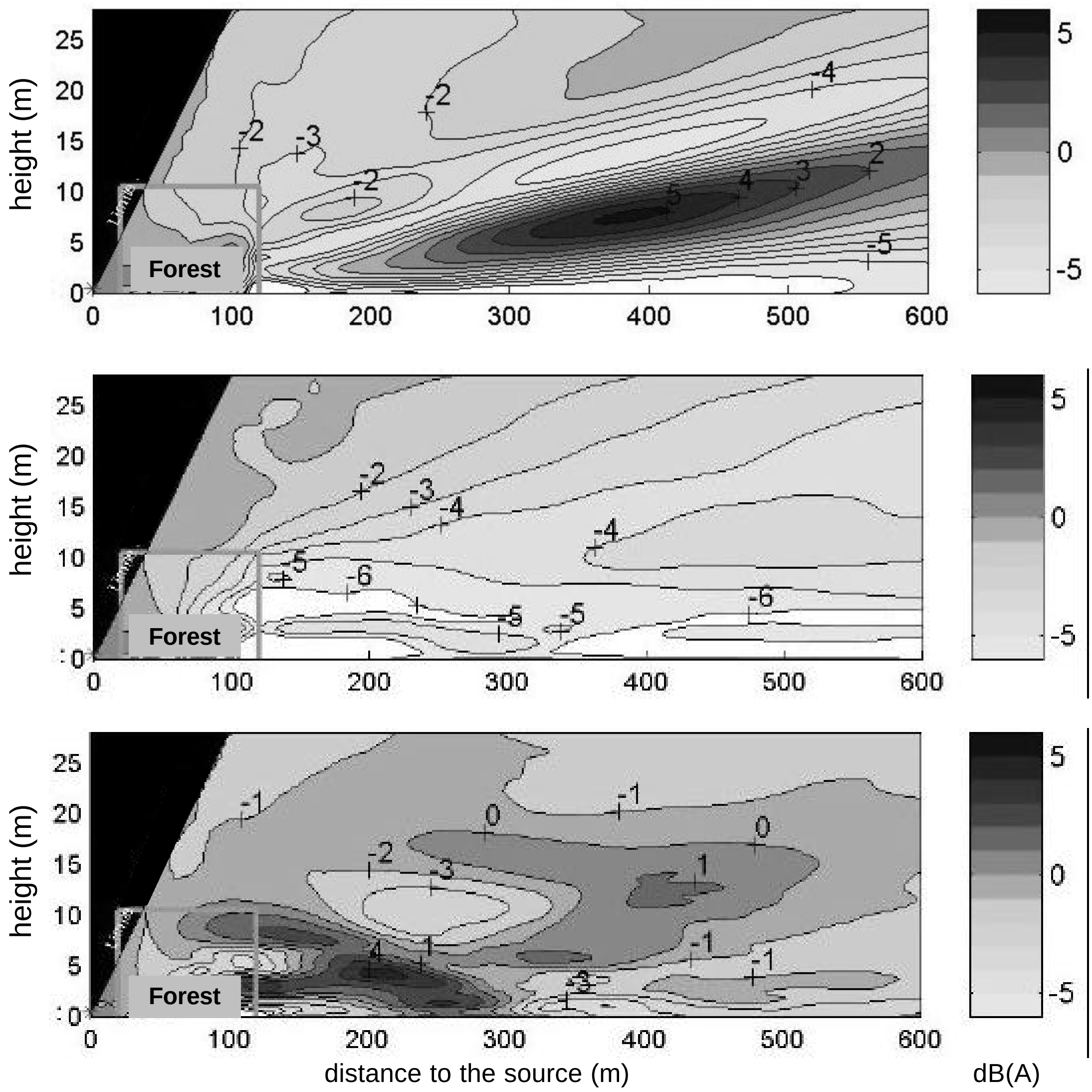

Fig. 2. *Acoustical efficiency of a 100 m wide and 10.5 m high pine forest referred to the plain situation, in dB(A), in the case of: (a) typical day temperature profile (unfavorable to propagation), (b) typical night temperature profile (favorable) and (c) typical downward situation for a positive gradient wind speed profile (favorable)*

In favorable conditions, the attenuation brought by the forest is between 2 and 6 dB(A) with the receiver at least 100 m away from the road. In unfavorable conditions, the forest may increase somewhat the received sound levels at large distances but it is of less importance since levels are there quite low. In homogeneous conditions, sound propagation through the forest is not significantly affected by meteorology anymore but only by the scattering by trunks and foliage. A forest strip of at least 100 m wide appears thus to be an efficient natural acoustic barrier.

However, in the case of a typical downward wind situation (favorable to propagation), zones of negative acoustical effects exist (the darkest areas in Fig. 2c). In this class of meteorological situations, the forest is acoustically efficient only for receivers sufficiently close to the strip of trunks. A strong sound level increase is noticeable in this latter case in Fig. 2c 200 m away from the road at a height of 5 m.

EXPERIMENTAL APPROACH

Presentation of the Experiment

An extensive measurements campaign has been carried out in the Landes forest near Bordeaux (France) mainly composed of pine trees. This experimental approach has been presented elsewhere [14]. The originality of this experiment is that road traffic noise and meteorological conditions have been measured simultaneously for both a forest situation and a plain situation for different positions of the receiver. All valid measured data have then been classified according to three propagation conditions: favorable to propagation, unfavorable to propagation and homogeneous conditions. As expected, the results strongly depend on these conditions. The wooded part is made up of pine trees with an average height of 11.83 m, an average circumference of 53.1 cm and a density of 0.1078 trunks/m^2. Four microphones were located 2 m high on the plain at different distances from the road: 50, 100, 150 and 300 m. On the other hand, a set of four microphones were located 2 m high within the forest, at the same 4 distances. Only results obtained 150 m away from the road (corresponding to a depth of the forest strip of 100 m) are discussed hereafter. In order to get wind speed and temperature vertical profiles in simultaneity with acoustic measurements, two meteorological masts, 20 m high, have been setlled 150 m inside the forest and inside the plain.

Road traffic has been assessed by means of a counting loop on the road. During the measurement period, the mean flow was of 2200 vehicles per day, for each of the two lanes, with 5% of heavy trucks. The mean speed of light vehicles was 85 km/h.

Measured Efficiencies

In favorable conditions, the forest efficiency (compared to the plain situation) measured *150 m* away from the line of traffic (corresponding to a *100 m* deep forest strip) is of *-3 dB(A),* a negative value of the efficiency meaning a reduction of noise due to the forest. This phenomenon is mainly due to the decrease or cancellation of the positive temperature gradient inside the forest, especially at night. As expected, the efficiency seems to increase (negatively) with the width of the forest strip.

In homogeneous conditions, this efficiency is of *-2 dB(A)*. However, this meteorological situation being rarely encountered, the data generally correspond to only around 20 minutes of measurements making somewhat difficult the interpretation of results. In unfavorable conditions, the measured efficiency is of *-1 dB(A)*. This negative value does not correspond to the expected one; indeed, the GFPE calculation predicts a positive value of the attenuation corresponding to an increase of the sound levels in a forest situation compared to a plain one. Actually a small signal-to-noise ratio made difficult the acoustic analysis. It should be noticed that the efficiency at *150 m* has been calculated and referred to the plain situation where the ground is very absorbing (recent deforested area). If the comparisons had been achieved with a harder plain ground, an increase of the efficiency would have been expected.

PROSPECTS

Work is still in progress in order to develop approximate expressions of the attenuation due to forests to be included in an analytical prediction model [15] such as the French NMPB noise prediction method [16-18] or the future European unified prediction method ("Harmonoise" European Project). At the same time theoretical investigations are led to derive advanced numerical models based on BEM formulations [19,20] accounting for forest effects.

The final aim is to develop a complete numerical GFPE-BEM hybrid method taking into account all acoustical phenomena encountered during outdoor propagation: trunk diffusion as well as ground effects with impedance discontinuities coupled with diffraction and irregular terrain effects, in a turbulent inhomogeneous atmosphere where the range dependent sound speed profile is determined by relief and vegetation.

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