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PREDICTIONS OF GROUND EFFECTS OVER UNEVEN AND DISCONTINUOUS TERRAIN IN THE PRESENCE OF REFRACTION AND TURBULENCE

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ABSTRACT
The De Jong semi-empirical formulation for sound propagation above a ground with an acoustic impedance discontinuity has been modified to incorporate effects of atmospheric refraction and turbulence. The revised model is described and used to predict the effect of an acoustically hard region of ground near the source on the sound level received by an observer. The predictions of the modified model for a non-turbulent atmosphere are compared with those of a hybrid Boundary Integral Equation/Fast Field Program (BIE/FFP) method developed previously. The predictions indicate that the extended model agrees reasonably well with the BIE/FFP at 1 kHz but not very well at 200 Hz.

1 - INTRODUCTION

Propagation of sound over a ground that includes an impedance change along the direction of propagation has been subject of many publications since it is of practical interest. Noise from highways and the noise of aircraft moving along a runway are both examples of this type of problem. There are a number of methods for computing sound pressure field propagating over an impedance discontinuity in a neutral medium [1-11]. These include the formulation by De Jong et al [8] that is extrapolated from Pierce's solution of the diffraction by a wedge problem [12,13]. Boulanger et al [14] have reviewed the existing models of sound propagation above an impedance discontinuity and compared them with scale model measurements. They showed that, while De Jong's model agreed reasonably well with measured field over a single discontinuity, the extension of De Jong model to multiple discontinuities did not agree with data. Furthermore, the model was less successful at grazing angles. They also made a number of improvements to the Fresnel zone model [10] that resulted in better agreement with their data. For multiple discontinuities they tested Nyberg's theory [11] and showed it to be in good agreement with data. Finally, they found that a Boundary Element routine [15,16] was a reasonably accurate model in all cases. There have been various methods based on the Parabolic Equation method [17-19] with some allowing for a refracting atmosphere.

In Section 2 we extend De Jong's formulation to allow for a refracting, turbulent atmosphere. To test the validity of the assumptions inherent in our heuristic extensions to the De Jong's model to allow for refraction, predictions of the modified De Jong formulation are compared with an alternative numerical procedure based on the Boundary Integral Equation. This model was developed to investigate the performance of noise barriers in downwind conditions [20,21] and to enable simulation of the effect of an impedance strip on the sound field above it.

In Section 3 the predictions from the two methods, in the absence of turbulence are compared at high and low frequencies and the extended De Jong model is used to investigate the influence of turbulence on propagation over an impedance discontinuity.

2 - EXTENDED DE JONG'S MODEL

De Jong considered Pierce's formulation of sound diffraction from a wedge [9] with different surface acoustic impedance at either side. He then allowed the wedge to fold and collapse and derived his expressions for the propagation of sound over an impedance discontinuity. We extend his expressions further to include multiple rays by using the geometrical acoustics approximation. We also examine further assumptions that need to be made. De Jong's expression can be written as:

$$\begin{aligned} P_t = \frac{e^{ikR_1}}{R_1}\left\{1+(Q_b-Q_a)\frac{e^{-i\pi/4}}{\sqrt{\pi}}\cdot\frac{R_1}{R_d}F\left(\sqrt{k(R_d-R_1)}\right)\right\}+ \\ \frac{e^{ikR_2}}{R_2}\left\{Q_{a,b}\pm(Q_b-Q_a)\frac{e^{-i\pi/4}}{\sqrt{\pi}}\cdot\frac{R_2}{R_d}F\left(\sqrt{k(R_d-R_2)}\right)\right\} \end{aligned} \quad (1)$$

where R_1 and R_2 are the direct and image ray paths from the source to the receiver respectively, R_d is the source-discontinuity-receiver path. Subscripts a and b refer to the two impedance surfaces and $Q_{a,b}$ is the appropriate spherical reflection coefficient with $Q_{a,b}$ being equal to Q_a together with the + sign in the expression if the point of specular reflection falls in region b, and equal to Q_b together with the - sign, if the point of specular reflection falls in region a. The wave number is denoted by k and $F(x)$ is the Fresnel integral function.

De Jong introduced the term (Q_b-Q_a) into the Pierce's equations so that it gives a logical result in the limit of the two sections having the same reflection coefficients (in other words no discontinuity at all). In downwind or temperature inversion conditions there may be multiple ray arrivals and rays may have multiple reflections from the ground. Generally, in a refracting medium we apply ideas of geometrical acoustics. The second term in equation (1) becomes a sum over all rays with $Q_{a,b}$ replaced by

$$Q_{l,m} = Q_a^l \times Q_b^m \quad (2)$$

where l is the number of bounces the ray makes at the first region and m is the number of bounces at region b. There will be more than one diffracted ray path from the source to the point of discontinuity and from the point of discontinuity to the receiver. In general, if the numbers of ray paths from source to the discontinuity and from the discontinuity to the receiver are K and L respectively, then the total number of diffracted ray paths will be $K \times L$. Moreover, there is more than one R_d. The expression for the total field becomes

$$P_t = \sum_{n=1}^{N} \aleph_n \frac{e^{ikR_n}}{R_n} \quad (3)$$

with

$$\aleph_n = Q_{l,m} + (Q_b - Q_a)\sum_{j=1}^{M}\mathrm{sgn}\left[\cos\left(\frac{\mu_{1,j}+\mu_{2,j}}{2}\right)\right]\frac{e^{-i\pi/4}}{\sqrt{\pi}}\cdot\frac{R_n}{R_{d,j}}F\left(\sqrt{k\,|R_{d,j}-R_n|}\right) \quad (4)$$

being the amplitude function for the n-th ray.

In this expression R_n are sound ray trajectories from source to the receiver with n=1 taken as the direct ray path and M the total number of possible ray paths, is equal to $K \times L$. The parameters $\mu_{1,j}$ and $\mu_{2,j}$ are the polar angles of the incident and diffracted wave at the point of discontinuity for any R_d respectively and sgn(x) is the sign function. Its value is -1 for a negative x and $+1$ otherwise. The evaluation of $R_{d,j}$ requires computation of all possible combinations of ray trajectories from the source to the point of discontinuity at the ground plus trajectories from the point of discontinuity to the receiver. This will involve multiple values of R_d in the downwind case.

Incorporating atmospheric turbulence into this model is straightforward (albeit in a heuristic approach) following the ideas of L'Esperance et al [22]. Once all the possible rays are determined, the averaged square of the pressure is given by

$$\langle p^2\rangle = \sum_{n=1}^{N}\frac{|\aleph_n|^2}{R_{g,n}^2} + 2\sum_{i=1}^{N}\sum_{j=1}^{i-1}\frac{1}{R_{g,i}R_{g,j}}\cos\left[k_0\left(R_{a,j}-R_{a,i}\right)+Arg\left(\frac{\aleph_j}{\aleph_i}\right)\right]T_{i,j} \quad (5)$$

where R_g and R_a are the geometrical and acoustical path lengths of a ray respectively. They, together with μ_i in equation (4), can be evaluated for all rays by geometrical ray acoustics formulations [22,23]. The amplitude function $\aleph$ is defined in eq. (4) and $T_{i,j}$ is the *coherence factor* between i-th and j-th ray. This factor accounts for the reduction in coherence between any two rays due to turbulence. For a Gaussian turbulence spectrum the coherence factor T is given by [24,25]:

$$T = e^{-\sigma^2(1-\rho)} \tag{6}$$

where σ^2 is the variance of the phase fluctuation along a path and ρ is the phase covariance between paths. They are given by:

$$\sigma^2 = 0.5\sqrt{\pi}\left\langle \mu^2 \right\rangle k^2 R L_0 \tag{7}$$

Here R is the horizontal separation of the source and the receiver; $\left\langle \mu^2 \right\rangle$ is the variance of the index of refraction, and L_0 is the outer scale of turbulence. The parameters $\left\langle \mu^2 \right\rangle$ and L_0 are to be determined by field measurements. The phase covariance is given by

$$\rho = \frac{\sqrt{\pi}}{2}\frac{L_0}{h} erf\left(\frac{h_{ij}}{L_0}\right) \tag{8}$$

where h_{ij} is the maximum transverse path separation between the i-th and j-th rays and $erf(x)$ is the Error function.

3 - EXAMPLES AND DISCUSSION

In this section we compare predictions of the extended De Jong model (without turbulence) with those of a hybrid Boundary Integral Equation/Fast Field Program (BIE/FFP) formulation discussed earlier. Figure 1 is a schematic drawing of the problem under consideration here.

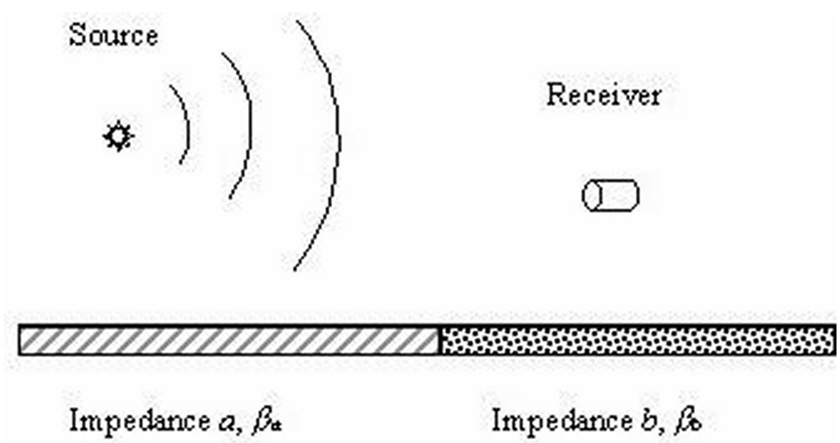

Figure 1: The geometry of the problem of propagation over an impedance discontinuity. The receiver can be placed in any position above either section.

Figures 2 and 3 compare the predictions by the extended De Jong model (equation (3)) and the BIE/FFP at frequencies of 200 Hz and 1 kHz. In these examples a wind speed gradient of 0.25 ms^{-1}/m is assumed with an impedance discontinuity at 200m from the source. The ground is assumed to be acoustically rigid from the source position up to the point of discontinuity and an absorbing one thereafter. The source and receiver heights are 5m and 1.2m respectively. At the higher frequency the hard section extends only up to 100m. While the two models agree well at 1kHz, the performance of the extended De Jong model is not as good at the lower frequency.

It was remarked earlier that sound around airports and highways normally involves a ground that has an impedance discontinuity (from tarmac to the grass for example), however, usual outdoor conditions involve atmospheric turbulence also. Although it is straightforward to incorporate effects of turbulence in the De Jong model, the addition of such effects into the hybrid BIE-FFP model is not straightforward and is subject of an ongoing research. We will demonstrate the influence of atmospheric turbulence by using the modified De Jong model only for a non-refracting atmosphere. The geometry of the test case is as follows: Source height=5.0m, receiver height=1.2m, separation=100.0m. The ground consists of a hard section stretching from the source up to a distance of 90.0 m and absorbing ground thereafter. Figure 4 shows excess attenuation spectra with (solid line) and without (broken line) turbulence. The parameters used to model the turbulence are the variance of index of refraction, $\left\langle \mu^2 \right\rangle = 2.0 \times 10^{-6}$ and

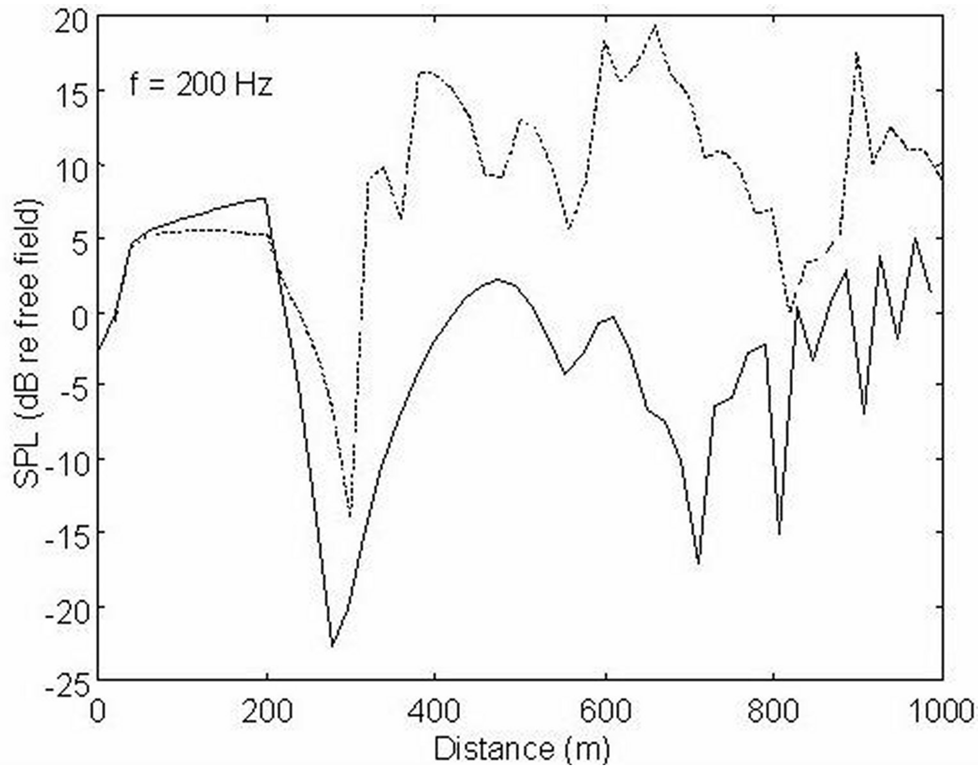

Figure 2: Predictions, obtained by using the extended De Jong model (dashed line) and the BIE/FFP (solid line) at a frequency of 200 Hz, of the sound field in a downwind condition over an impedance discontinuity at 200m; the source and receiver heights are as in figure 3; the De Jong model does not agree very well with BIE/FFP beyond 300 m.

outer scale of turbulence, $L_0 = 1.1$m. Its effect is what one would expect i.e. it reduces the total coherence between direct and reflected ray paths thus decreasing the depth of the minima in the spectrum.
De Jong's model has been extended and used to investigate sound propagation over an impedance discontinuity in a complex outdoor environment involving atmospheric refraction and turbulence. The De Jong model for propagation over a discontinuous impedance boundary in a homogeneous atmosphere has been extended here to include effects of a linear sound speed profile and turbulence. In the absence of turbulence, its validity has been tested against a model based on a hybrid Boundary Integral Equation / Fast Field Program method. The results here indicate that the extended De Jong model agrees well with the more accurate (but more computationally demanding) BIE/FFP at high frequencies but less well at low frequencies. Other workers [14] have noted also that the original De Jong method fails at grazing angles. The lack of agreement at low frequencies obtained here may be due, in part, to the same deficiency in the original model.

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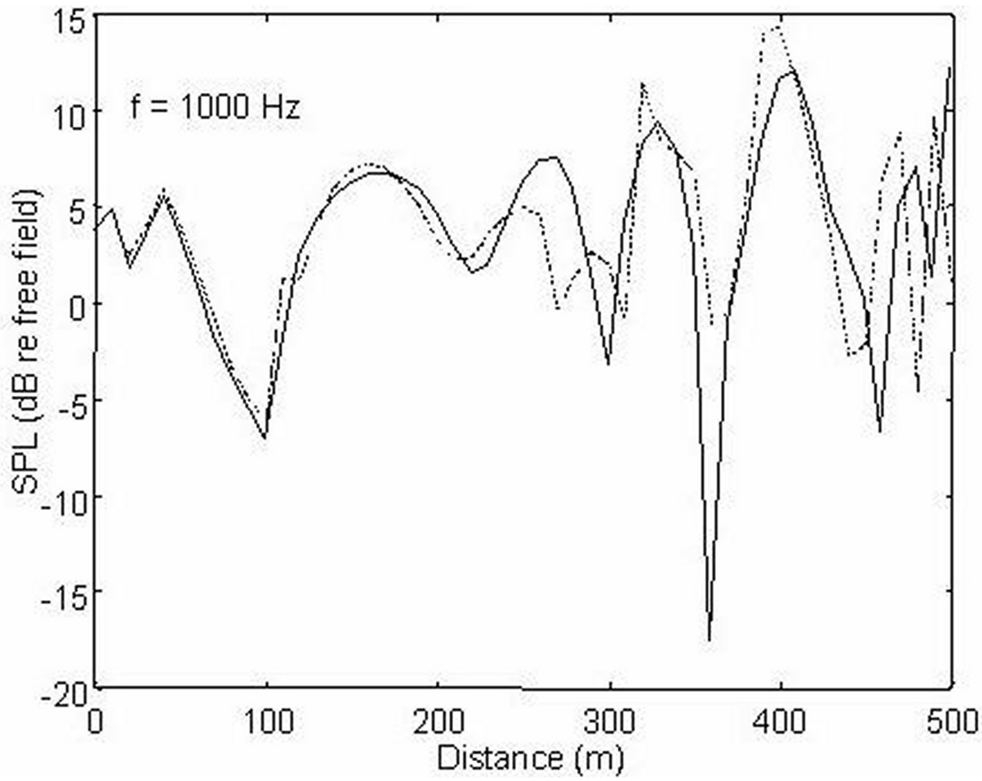

Figure 3: As in figure 2 but at a frequency of 1000 Hz and with the impedance jump at only 100m from the source; clearly, the De Jong model performs better than at the lower frequency.

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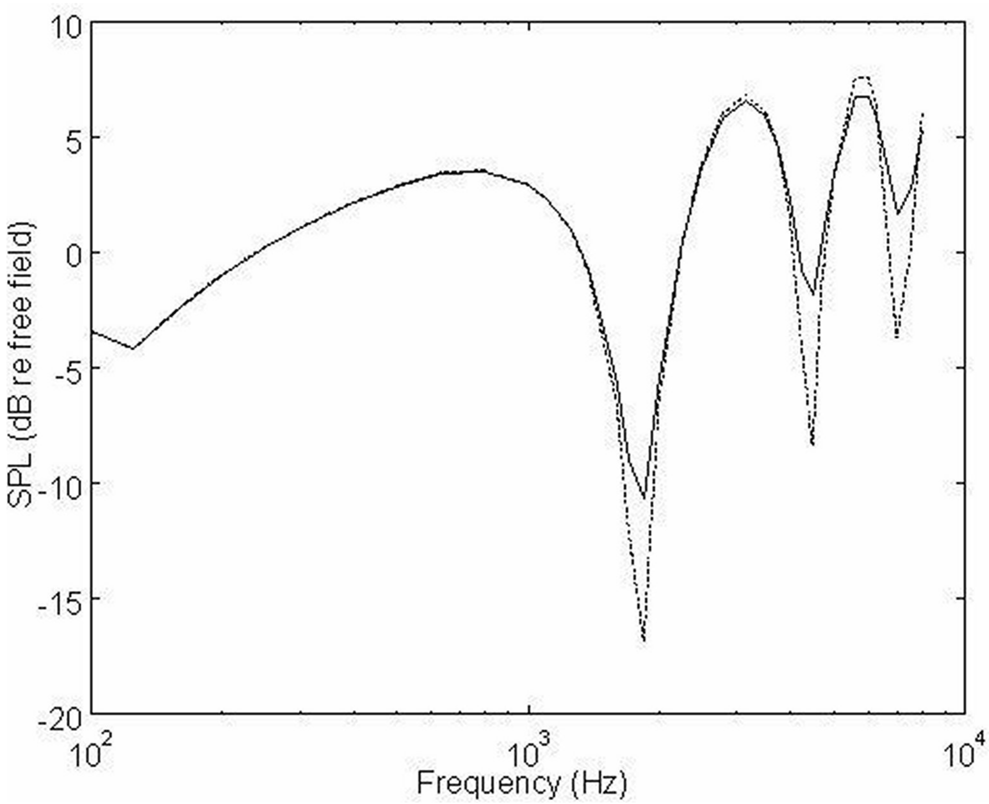

Figure 4: Relative SPL spectrum predicted by the extended De Jong model with and without the effects of atmospheric turbulence; the solid line represents the predicted excess attenuation with turbulence and the broken line represents the spectrum if turbulence is ignored; the source and the receiver heights are 5.0m and 1.2m respectively and their separation is 100.0m; a neutral atmosphere is assumed.

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