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ANIME3D: A full 3D method for calculating the impact of industrial noise on the environment

Fabrice JUNKER[1]

[1] EDF R&D – Département Analyses Mécaniques et Acoustique (AMA)

1, avenue du Général de Gaulle - 92141 Clamart Cedex, France

ABSTRACT

The prediction of industrial noise impact on the environment has to consider numerous sources and large distances. Though, realistic situations have to be studied with a reasonable calculation cost. This is achieved by using engineering methods based on geometrical approaches. For many years now, such methods have been developed based on 2D approaches, first of all to deal with transportation noise and then extended to industrial noise in a more or less straightforward way. However, industrial noise has specific features. Among them, especially due to the limited size of the sources, 3D effects have to be taken into account. Moreover, it should be noticed that, today, no available method has fully specified its geometrical part. The aim of this paper is to present an acoustical method called ANIME3D including a 3D optimized ray tracer and acoustical calculations able to deal with 3D multiple diffractions and reflections, an inhomogeneous ground and meteorological effects, in a reasonable computation time. ANIME3D will be soon available in the Code_TYMPAN open source software.

1. INTRODUCTION

Predicting industrial noise requires to deal with real situations. Most of the time, they involve many sources placed in a large 3D geometrical model. These complex models are too heavy to be studied using equations-based numerical methods [1] [2] [3]. So, only geometrical approaches comply with the computer power and time span dedicated to engineering studies.

Geometrical approaches are all based on paths finding between source and receivers and the use of a mix of empirical and analytical formulas to calculate the attenuation of sound along the paths. Both to reduce the calculation cost and due to the fact that methods where first developed to answer to transportation noise impact studies purposes, all the methods available today are based on 2D approximations [4] [5]. If the 2D approximation first shows the advantage to reduce the calculation cost, it does not answer properly to multiple 3D reflection and diffraction situations which can be most critical for industrial noise. To circumvent this, some methods have introduced artifices and finally recover the complexity which was sought to get rid of using a simplified 2D approach.

Considering the need for a full 3D approach, we propose to rethink a method based on a real 3D ray tracing. The effective calculation cost of the method is both ensured by an optimized 3D ray tracer to find paths in a reasonable time [6] and also by using simple formulas to optimize the acoustical part of the method. The method is called ANIME3D which stands for Assessing Noise IMpact on the Environment in 3D.

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[1] fabrice.junker@edf.fr

The 3D optimized ray tracer will be presented in another paper during the congress [7]. Its output is a list of rays travelling between the source and the receiver and satisfying the Fermat's principle [7]. It returns the list of all possible paths between the source and the receiver, at a certain degree of complexity defined by a maximum number of reflection and diffraction.

The aim of this paper is to describe ANIME3D. Section 2 describes the way the meteorological effects are taken into account. Section 3 and 4 describe the acoustic calculations.

2. Modeling meteorological effects

The meteorological effects are taken into account using a curvilinear transformation of the geometry. This approach is widely used both in wave-based methods [8] and also in engineering methods [5]. The originality of the approach is to base the transformation on the solution of the ray equations including wind and temperature effects:

The process is achieved by:

1. Solving the ray equations [9] using a Runge-Kutta 4 time difference scheme for a very small number of rays (figure 1) launched from the source horizontally (assuming that most of the energy propagates horizontally). These ray equations are the followings:

$$\begin{cases} \dfrac{d\overrightarrow{X}}{dt} = \dfrac{c^2\vec{s}}{\Omega} + \vec{v} \\ \dfrac{ds_i}{dt} = -\dfrac{\Omega}{c}\dfrac{\partial c}{\partial x_i} - \sum_{j=1}^{3} s_j \dfrac{\partial}{\partial x_i} v_j \quad i = 1,3 \end{cases} \tag{1}$$

Where,

$\overrightarrow{X}$ is the position of a ray at time t;

c is the sound speed (m/s) depending on temperature;

$\vec{s}$ is the "slowness" vector collinear to the normal $\vec{n}$ of the front wave $\vec{s} = \dfrac{\vec{n}}{c + \vec{v}.\vec{n}}$;

$\vec{v}$ is the wind speed.

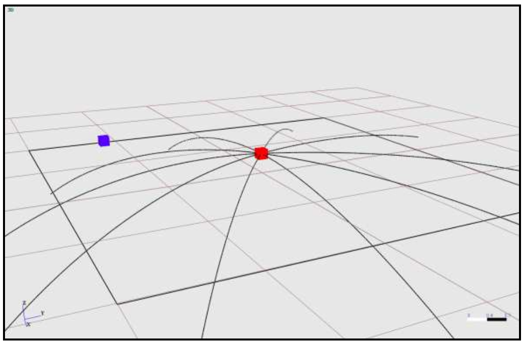


figure 1– Result of the solution of the ray equation.

2. Building a surface *z=h(x,y)* by the interpolation using the rays previously found as shown on figure 2.

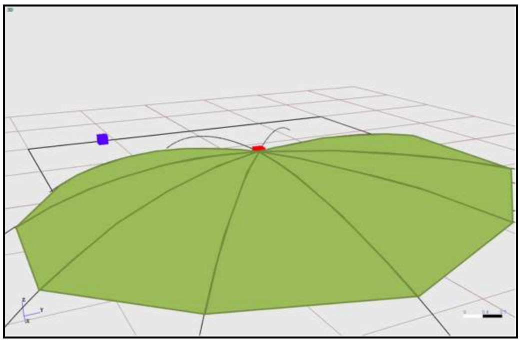


figure 2– Interpolated surface h(x,y)

3. Transforming the geometry using the following transform:

$$\begin{cases} x' = x \\ y' = y \\ z' = z - h(x,y) \end{cases} \tag{2}$$

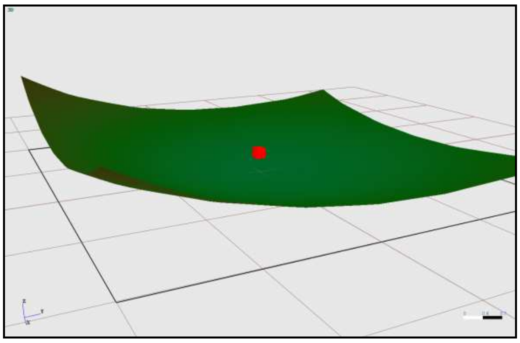


figure 3– Transformed geometry

4. Launching straight rays in the transformed geometry

<u>Remarks:</u>

- This process:
  - neglects the horizontal gradients and makes the assumption that most of the refraction is due to vertical sound speed and wind gradients;
  - assumes that most of the energy propagates horizontally.
- The main properties of the rays (length and reflexion angles) can be recalculated using the transformation
- As the rays are launched from one single source, the transform can be strictly used only for this source but can be assumed to be valid for all the sources in the neighboring of this source, as far as the receiver is far enough from the sources.

Once the transformation is computed, the optimized straight ray ray tracer is used to find all the relevant paths.

3. Attenuation calculation along a single ray

3.1 General formula

Considering that all the relevant rays paths between the point source S and a receiver R have been found, the mean square root pressure p_i for each ray i for the third octave band f is written as:

$$p_i(f,S,R)=\sqrt{\frac{\rho_0 c_0 W H(f,\theta,\phi)}{4\pi r^2}}\,a_{atm}a_{ref}a_{dif}e^{j\kappa r_i} \qquad (3)$$

Where

$\rho_0 c_0$ =400 kg.m^{-2}.s^{-1},

W is the acoustic power of the source (W),

$H(f,\theta,\phi)$ is the directivity function of the source (normalized such as: $\sum_{\theta,\phi} H(f,\theta,\phi)=1$),

r is the length of a “virtual ray” including only the reflexion points between S and R (m),

r_i is the total length of the ray i (m),

j^2=-1,

a are the coefficients resulting from atmospheric absorption, reflection and diffraction of the sound along the ray path. They are detailed in sections 3.2 to 3.4,

κ is the wave number (m^{-1}).

3.2 Atmospheric absorption (a_{atm})

The atmospheric absorption along the ray i is calculated according to ISO-9613-1 [10]. It depends on T, the mean air temperature, h_r, the relative air humidity and P_{atm}, the atmospheric pressure.

For each one third octave band f, the attenuation is calculated as :

$$a_{atm}=10^{\frac{-\alpha_{atm}(T,h_r,P_{atm},f)r_i}{20}} \qquad (4)$$

Where α_{atm} is calculated according to ISO 9613-1(dB/m).

3.3 Reflection (a_{ref})

The reflection effect is taken into account by calculating an averaged reflection coefficient using a Fresnel zone definition given in the HARMONOISE [5] method. Let σ_0 be the surface where the reflection takes place, the principle is:

1. To determine all the surfaces j connected to σ_0 within the Fresnel zone;
2. To calculate for each frequency band the ratio τ_j of the area Σ_j of each face σ_j included in the Fresnel zone to the area Σ_j of the Fresnel zone (i.e. the intersection between the Fresnel zone and a plan including σ_0);

$$\tau_j=\frac{\Sigma_j}{\Sigma_f} \qquad (5)$$

3. To calculate w_j ,the Fresnel, weighting as:

$$w_j = \frac{\tau_j}{\sum_j \tau_j} \tag{6}$$

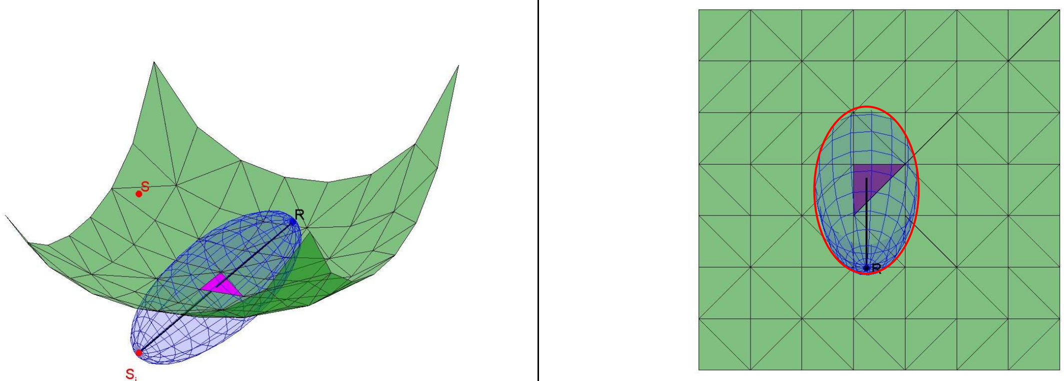
4. To calculate an average reflection coefficient as a weighted average of the spherical wave reflection coefficient of all the j surfaces:

$$\overline{Q} = \sum_j w_j Q_j \tag{7}$$

Where Q_j is the spherical wave coefficient calculated using the Rudnick model over the plan including σ_0 with the impedance value corresponding to σ_j. figure 4 shows an example of a Fresnel zone construction .

The surface (s0) where the reflection takes place.

The image source relative the plan including s0.



The Fresnel zone according to HARMONOISE.

The red area including all the surface sj connected to s0.

figure 4– Example of Fresnel zone construction.

If the ray undergoes n reflections during its way from the source to the receiver, a_{ref} is calculated as:

$$a_{ref} = \prod_n \overline{Q_n} \tag{8}$$

3.4 Diffraction

When a ray undergoes n successive diffractions, a path difference δ_k is calculated at each diffraction point P_k, as:

$$\delta_k = P_{k-1}P_kP_{n+1} - P_{k-1}P_{n+1} \quad k = 1, n \tag{9}$$

Where

P_{n+1} is the receiver or the reflexion point following the last diffraction point of the sequence.

By convention the sign of δ_k is changed from positive to negative when $P_{k-1}P_{n+1}$ does not intersect the faces that define the diffraction edge.

Finally, a_{diff} is calculated as the product of all the attenuations due to each single diffraction as:

$$a_{diff} = \prod_{k=1}^{n} f(\delta_k) e^{j\kappa\delta_k} \tag{10}$$

$$\begin{aligned} & if \quad \delta_k > 0 \\ & \qquad f(\delta_k) = 1/\sqrt{3 + \frac{40\delta_k}{\lambda}} \\ & else \\ & \qquad f(\delta_k) = 0 \end{aligned} \tag{11}$$

Where

λ is the wavelength (m),

n is the total number of diffraction points along the ray.

The above formula is taken from ISO 9613-2[11]. This formula has been shown to be a good choice compared to BEM calculation in the shadow zone on a thin 3D rectangular screen [12]. Multiple diffraction and results outside the shadow zone are currently being studied in details and the above formula for diffraction will be compared to other classical diffraction formulas and potentially be adapted depending on the results.

4. Overall contribution of a source at the receiver

The quadratic pressure due to one source at a receiver is calculated as a weighted sum of all the elementary contribution of each ray coming from this source:

$$p^2(f,S,R) = \left| \sum_i C_i p_i(f,S,R) \right|^2 + \sum_i (1 - C_i^2) \left| p_i(f,S,R) \right|^2 \tag{12}$$

C_i is the coherence factor calculated according to the HARMONOISE method [5] as:

$$C_i = e^{-(kr_i)^2 \left[(\frac{1}{3}(2^{\frac{1}{6}} - 2^{-\frac{1}{6}})^2 + \frac{\sigma^2(r_i)}{r_i^2} \right]} \tag{13}$$

It allows to take into account both the third octave bandwidth smoothing effect and a variance $\sigma^2(r_i)$ of the length of the ray path. This variance can be used to include geometrical uncertainties effect in the calculation.

5. CONCLUSION

ANIME3D is based on an optimized ray tracer. It takes into account 3D diffraction and reflection with a reasonable computation cost. Moreover, the use of a transformation based on the solution of the ray equation simulates the effect of refraction using the curved geometry analogy in 3D. As ANIME3D is currently under integration in the Code_TYMPAN open source software [13] the first results will be shown during the oral presentation.

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