Some proposal for the improvement of the simulations of the acoustic noise propagation

Petru Cardei

***Abstract*—**This paper tries to compare the theoretic results in the acoustic noise propagation with the experimental data and with the simulation techniques, using by the very useful software programs. In the paper are formulated some suggestions for improve the experimental formulae using for the noise propagation simulation.

***Keywords*—** Acoustic, Noise, Theory, Experiment, Simulation.

I. Introduction

THE paper author's work in the environmental protection, and the results shown in this paper are part of the noise propagation domain. They try to investigate the relation between the theoretic result of the Acoustic and the techniques which the simulation software uses. The results are verified using some measuring data.

Finally the author's try to formulate solution for improving the theory of acoustic waves.

II. Problem Formulation

Is very known the classical solution of the sound wave propagation: plan wave, cylindrical wave, spherical wave. Each of these solutions has some disadvantages. The plane wave is not diminution in space, the cylindrical and spherical solution have an infinite value in the source point.

A. Basis of the Numerical Simulations

Unexpected or not, the simulation software for sound propagation (LimA, Predictor, Encustic, SoundPlan), uses for noise level prediction only experimental formulae. The formulae using in these software have as well as theoretical problems: infinite value in the source point, and at great distances, negative values. For example the CUSTIC software for noise prediction uses the next formula for the noise level generate by a point source:

$$L_{eq} = L_W - 20\lg r - 11, \quad (1)$$

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where: L_{eq} is the noise level of the source, r is the distance and L_W the source power. However, after [1], for an industrial complex, the next equation will be used:

$$L_{eq} = L_i + 10\lg S - 20\lg r - 14, \quad (2)$$

where S is the external surface and L_i is the internal noise power. Similar formulae are using for other industrial complexes, for the traffic on the roads or highway, for the railway. Generally, these formulae have the form:

$$L_{eq} = A - B\lg r, \quad (3)$$

where A and B are constant.

B. Theoretical Predictions

Mathematically, the problem of sound propagation is modeled by the wave equation. The wave equation is a generic name for large categories of propagation phenomena. From the point of view of the noise prediction is important only space attenuated waves. One for of the classical equation of the acoustic wave:

$$\Delta\psi - \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} = 0, \quad (4)$$

where ψ is the wave function and where c is the speed of sound. Δ is the Laplace operator. For the equation (3), there are two attenuated solutions: the cylindrical solution and the spherical solution. In this paper we comment only the spherical solution and many remarks for this solution are valid for the cylindrical solution. The spherical solution for the equation (4) has the form:

$$\psi(t,r) = \frac{\psi_0}{r}\cos\left(\omega t - kr + \phi\right), \quad (5)$$

which satisfy the equation (4), allows the relations:

$$v_f = \frac{\omega}{k} = \frac{\lambda}{T} = c, \quad (6)$$

where: v is the frequency of the wave, ω is the angular frequency of the wave, k is the wave number, λ is the wave length, T is the period of the wave (monochromatic wave), and ψ_0 is a constant.

C. Energetic Relations for the Acoustic Waves

In aim to use the solution (5) for predict the noise in a boundless space, it is necessary to introduce some notions of the wave energetic.
If ρ is the air density, then the kinetic energy is the next:

$$w_c = \frac{1}{2}\rho\left(\frac{\partial\Psi}{\partial t}\right)^2, \tag{7}$$

and

$$w_p = \frac{1}{2}\rho c^2\left(\nabla\Psi\cdot\nabla\Psi\right), \tag{8}$$

is the potential energy. Then, the total energy carriage by the wave is the sum of the kinetic and potential energy:

$$w = w_c + w_p . \tag{9}$$

Because the energy oscillates in time, is considering the time average of the wave energy:

$$W = \langle w\rangle = \frac{1}{T}\int_0^T w(t)dt . \tag{10}$$

The energetic intensity of the sound wave is the energetic flux which carriages the unit of surface on a direction normal of this surface:

$$I_s = W\cdot c . \tag{11}$$

Now, the sound level intensity is given by the formula:

$$N_s = 10\lg\frac{I_s}{I_{s0}}, \tag{12}$$

where I_s is the magnitude of the energetic intensity, and I_{s0}= 10^{-12} W/m^2 is the reference magnitude energetic intensity, and lg is the logarithm in base 10.

III. Objections at the formulae

Some objections at the formulae have the reason for started this paper. The aim of paper consist in to elaborate, if is possible, any answers or solutions at these objections.
The formulae used by the software programs, (S1) – (S4), have four problems:
S1) the noise level has infinity values in the source location;
S2) there is a distance at the source, where the noise level became negative;
S3) the prediction formulae no contain explicit the dependence of the noise level on the sound frequency;
S4) the logarithmic term variable is not dimensionless.
As well as the theoretical solution (5), and the sound level defined using this solution, have one of these problem:
T1) the noise level has infinity values in the source location;
T2) there is a distance on the source, where the noise level became negative.

IV. Some Suggestions

If the prediction software remains of the formulae (3), then is possible to solve the problem S1), by introduction of a constant r_0, which can be meaningful as a radius of the real source (modeled by a point source) or as a radius which defines a neighborhood of the source where the source power is constant (for example the distance to the nearest point of measurement). It is proposing the next formula:

$$L_{eq} = A - B\lg\left(r + r_0\right), \tag{13}$$

This formula eliminates the problem S1) but not the problem S2). The problem S2) is ignored because the predictable distance is, normally, much less than the distance where the noise level became negative. This is only a proposal. To obtain a dimensionless variable and to eliminate the S4) objection, the formula (14) can be modified in the next form:

$$L_{eq} = A - B\lg\left(\frac{r}{r_0}+1\right) - C, \tag{14}$$

The S3) problem cannot be solved on this way, but the theoretical solution (5) takes into account the influence of the sound or noise frequency. A numerical example allows seeing this influence in the next chapter.

V. Experimental Results and Simulation

A good understanding of the noise level estimation, using the experimental and theoretical formulae, is obtain for a simulation of the noise emission of an agricultural source, a combine. The noise emission of the combine has been made after the standard [2]. Beside the 12 measurement point at 7.5 m distance on the combine, indicate by [2], the noise lever is measured on the others 12 points at 3.5 m distance on the combine. The measurement schedule and the noise level distribution in the neighborhood of the combine are shown in the figure 1. The result of the noise level measurement is shown in the figure 2, where the noise level is represented as maps.

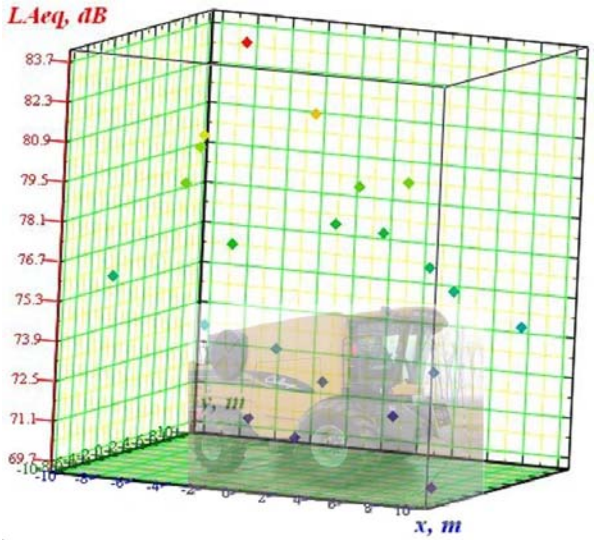

Fig. 1 Scheme of the measurement space.

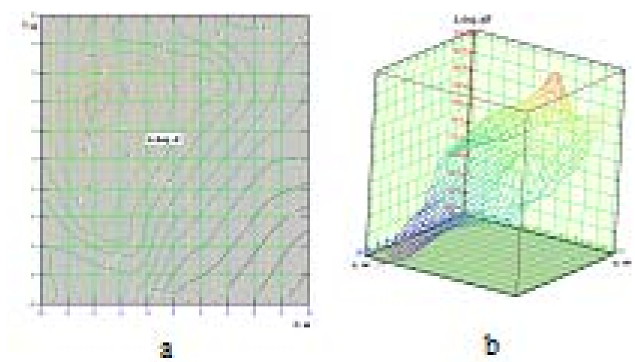

Fig. 2 Maps of the noise distribution in the neighborhood of the combine, resulted by measuring and graphical processing.

The measurement results are used for the simulation of the combine noise emission, because is necessary to estimate the distance where the value of the emission is equal with a reference value. This distance cannot be estimated by measurement because there is not an enough large measurement network.

The results are used in this paper for compare the noise emission simulation quality using an experimental formula (see, for example, [3], [4], [5], and [8]):

$$L_{eq} = L_W - 20\lg r - 8, \tag{15}$$

and using the theoretical calculus which is given in II, *B*.

Expected or not, the two noise level simulation curves, which are shown in the figure 3, are very approaching. Only in the first meter distance on the source, there is a visible difference. For the simulation is chosen the parameters L_w, for the experimental formula (15), and ψ_0, for the theoretical calculus (see II, *B*), using the method of the least squares, where the reference values are the values of the noise emission measured in the front of the combine at 4.125 m and at 7.5 m at the combine, respective 7.625 and 11 m at the origin of the reference system.

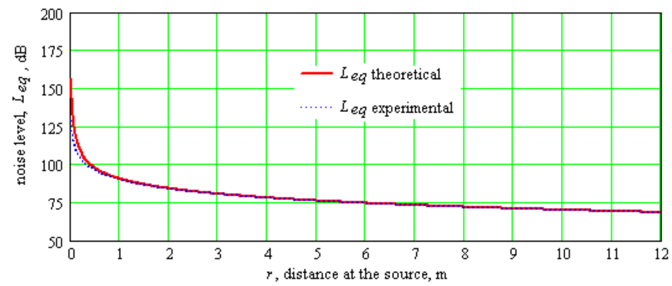

Fig. 3 The theoretical and the experimental noise emission simulation curve.

For the experimental curve is used the source power L_w = 98.0363 dB, and is obtain the result 72.392 dB at 7.625 m and 69.208 dB at 11 m. From the theoretical calculus is obtaining: 72.389 dB at 7.625 m and 69.202 dB at 11 m, for ψ_0= 0.00000276 m. The measured value of the noise level is 71.9 dB at 7.625 m, and 69.7 dB at 11 m. Because the distance interval, where the difference between the experimental and the theoretical curve is remarked, is not significant for the simulation, result that the experimental curve is sufficient for the simulation of the noise emission.

VI. Applications in The Improving The Simulation Using The Experimental Formulae

Using the objections S1 – S4, at the experimental formulae, enunciated in chapter III, and the suggestion from chapter IV, is possible to improve the quality of the noise propagation simulation. For an easy understanding, is considering only one source of noise.

First, in my opinion in the noise propagation simulation operation is that the pure computer simulation, in absence of measured data, cannot have a good quality. A minimum of measured data are necessary for realize a good hypothesis for the acoustic load. Simultaneous, the measured data will be used for verify the simulation results.

For obtain a good simulation is using an experimental formula like (1):

$$\begin{aligned} &L_{eqsim}(x,y,z,X,Y,Z,Ls) = \\ &= Ls - 20\lg\left(r(x,y,z,X,Y,Z)\right) - 11 \end{aligned}, \tag{16}$$

where *Ls* is the noise level of the source, x, y, z are the space coordinates, *X*, *Y*, *Z* are the source coordinates. The function *r*(*x*, *y*, *x*, *X*, *Y*, *Z*) is distance between the space point and the source location:

$$r(x,y,z,X,Y,Z) = \sqrt{(x-X)^2 + (y-Y)^2 + (z-Z)^2}, \tag{17}$$

In (16), Ls, X, Y, Z, there are the parameters that will be able to calculate using, for example, the method of least squares, minimizing the next functional:

$$\boldsymbol{F}(L_S, X, Y, Z) = \\ = \sum_{i=1}^{N} \left(L_i - L_{eqsim}\left(Xm_i, Ym_i, Zm_i, X, Y, Z, Ls \right) \right)^2, \quad (18)$$

where N is the number of the noise level measuring, i is the index of the measuring, given by the noise level, L_i, and the location coordinates in space, Xm_i, Ym_i, Zm_i, i=1, 2,…, N.

In aim to test the method, is consider a noise field produced by two sources that coordinates locations and noise levels are given in the table I.

Table I Locations coordinate and noise level for the real sources.

Source index	*X*, m	*Y*, m	*Z*, m	*Law*, dB
1	-1.0	0.0	2.0	135.0
2	0.0	1.0	2.0	135.0

I suppose that the measuring is not possible inside of the square having the corners in the points (1.0, 1.0), (-1.0, 1.0), (-1.0, -1.0) and (1.0, -1.0), in horizontal plan *coy*, where *O* is the origin point of the axes. All distances are given in meters. I suppose that the operator don't know how many sources produce the noise and where are these located. Then the operator uses experimental formula (16) with an only one source for simulation the noise field. There are three measuring data given in the table II.

Table II Locations coordinate and noise level for the measured data.

Measuring index	*X*, m	*Y*, m	*Z*, m	*Lw*, dB
1	3.0	3.0	2.0	114.679
2	-3.0	0.0	2.0	119.441
3	0.0	-3.0	2.0	116.109

Minimizing the functional (18), using the measuring data given in table II, are obtained the next values for the formula (16) parameters: X=-0.579 m, Y= 0.598 m, Z= 2.0 m, Ls= 138.363 dB.

For an easy understanding, in the figure 4, is shown the noise field generated by the two sources, by theoretical way, and the simulated noise field, obtained with the procedure described in this chapter.

The procedure described in this chapter is possible extended to simulation formulae which depend on two or three or more noise levels. The procedure permits to detect the location and the noise level sources.

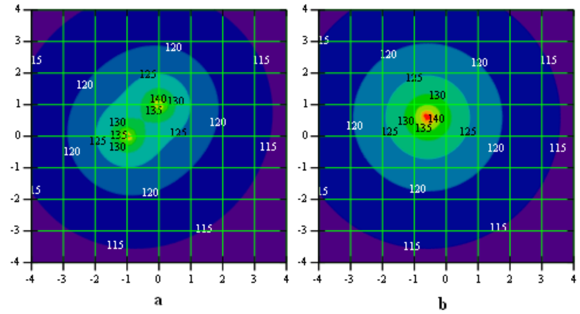

Fig. 4 Real noise field, a, and the simulated noise field, using only a noise source, b.

Same procedure is used for a simulation experimental formula proposed in this paper, (14), for example, which solve to the infinite value in the source location. In this aim is considering the simulation formula:

$$L_{eqsim}(x, y, z, X, Y, Z, A, B, C, r0) = \\ A - B \lg\left(\frac{r(x, y, z, X, Y, Z)}{r0} + 1 \right) - C, \quad (19)$$

where A, B, C, $r0$ are the parameters. These parameters will be calculated after the same procedure described for the simulation formula (16). For the same noise real field generated by the two sources, is obtaining the next values: A= 141.256 dB, B= 22.398 dB, C=9.966 dB, r0= 0.977 m, X= -0.734 m, Y= 0.54 m, and Z= 2 m. The distribution of the noise level, using the (19) simulation formula, in the space is shown in the figure 5. This distribution must be compared with the distribution given in the figure 4.

In the formula (19) is possible to consider C=0, and the parameters remain A, B, $r0$, X, Y, Z. Minimizing the functional obtained after the described method, is obtaining the next values for the parameters: A= 131.229 dB, B= 22.226 dB, $r0$= 0.975 m, X= -0.751 m, Y= 0.62 m, Z= 2.0 m. The noise level distribution in same 4x4 m space is shown in the figure 6. The differences between the last two prediction formulae are very small.

The procedure of simulation proposed in this chapter consist in the improving for the simulation procedures, but to, for the good definition of the simulation experimental formulae.

Another improvement of the experimental formula for the noise propagation simulation is possible introducing the source trajectory equation. This improvement can be made, because the experimental formulae are not subdued to wave equations or other mechanical equations. In aim to avoid some phenomena, which are developed at high speeds, is recommended to consider small values for the speed and accelerations. The sources speeds will be considered small relative to the sound speed in air.

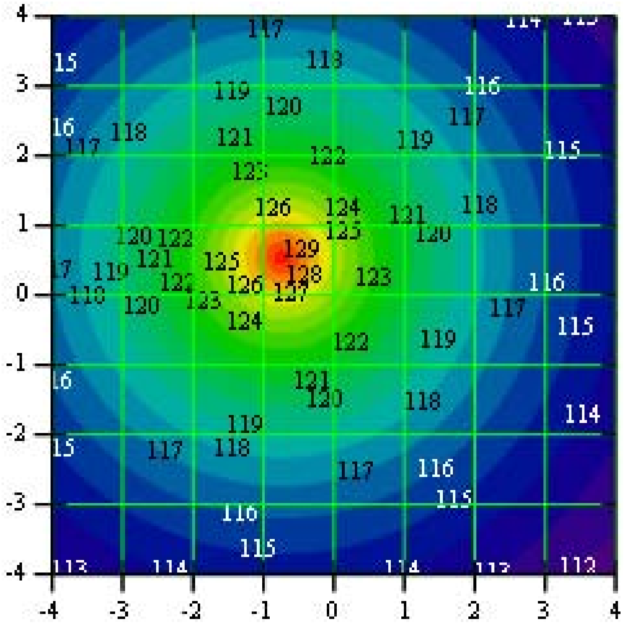

Fig. 5 The noise level distribution simulation using only one source, after (19) formula, in dB.

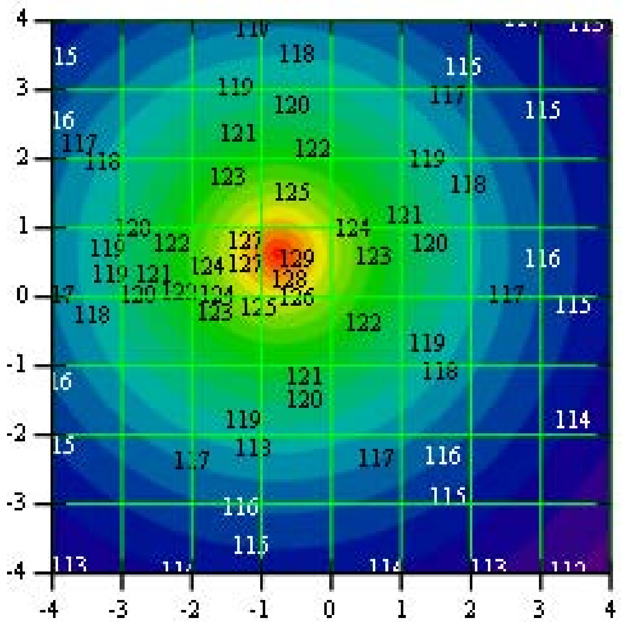

Fig. 6 The noise level distribution simulation using only one source, after (19) formula, in dB.

For a source which is moving, the coordinate will consider the form: $X=X(t)$, $Y=Y(t)$, $Z=Z(t)$, where t is the time (absolute time). For example, if the source has a rectilinear and uniform moving, along of the Ox axe, at constant 2 m high, then the coordinate of the source has the next form:

$$X(t) = vt + X_0, Y(t) = 0, Z(t) = 2, t \geq 0, \quad (20)$$

where X_0 is the initial coordinate of the source (for t=0 s), and v is the source speed, considered constant. For a source which has a rotating movement, with constant angular speed, ω, the coordinate of the source can be considered the next:

$$\begin{aligned} X(t) &= X_0 + R\cos(\omega t + \varphi), \\ Y(t) &= Y_0 + R\sin(\omega t + \varphi), \\ Z(t) &= Z_0, \end{aligned} \quad (21)$$

Where X_0, Y_0, Z_0 are the coordinate of the centre of the trajectory (circle), R is the circle radius, and φ is the phase, all constants. If the source has an ellipsoidal trajectory, given by the equations:

$$\begin{aligned} X(t) &= X_0 + a\cos(\omega t + \phi), \\ Y(t) &= Y_0 + b\sin(\omega t + \phi), \\ Z(t) &= Z_0, \end{aligned} \quad (22)$$

where a and b are the ellipse semi-axes and if is considered two sources, is possible to estimate the time variation of the noise field produced by the two sources. In the figures 7 – 13, is shown the evolution of the noise field for a couple of noise sources, which have a same ellipsoidal trajectory (22), for a=10 m, b= 5 m, ω_1= 0.628 rad/s, ω_2=1.445 rad/s, ${}_1$=1, ${}_2$=0. The center of the ellipse is in the origin of the axes. The sources noise level are L_1= 135 dB and L_2= 125 dB. Sources high are 2 m.

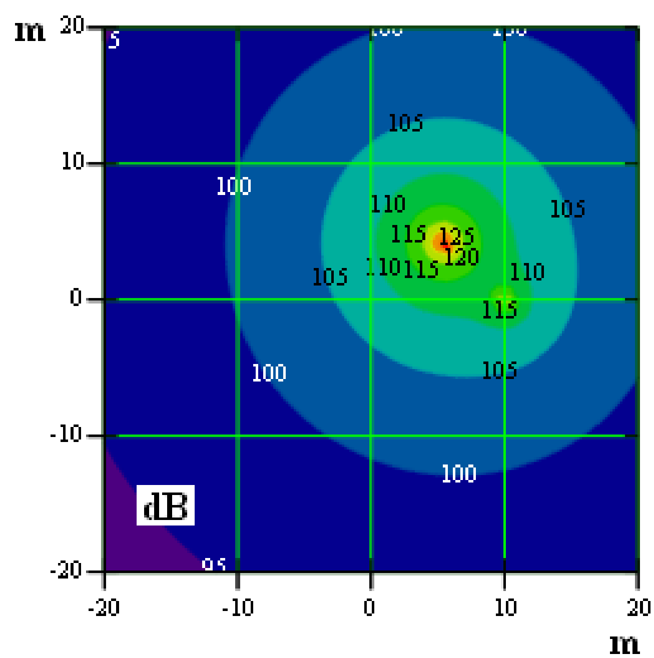

Fig. 7 Noise field at the time t=0.0 s.

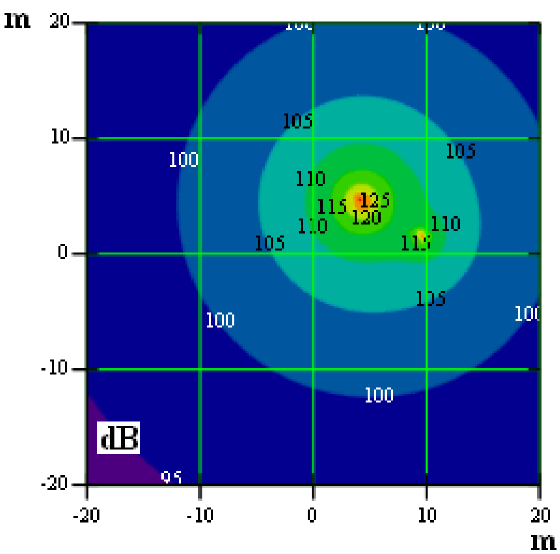

Fig. 8 Noise field at the time t=0.2 s.

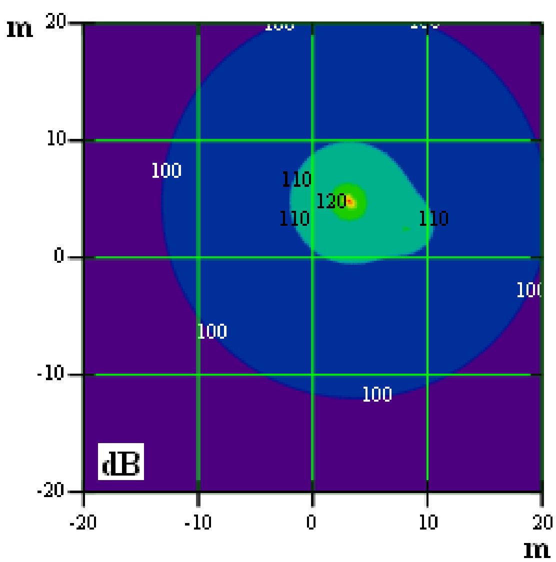

Fig. 9 Noise field at the time t=0.4 s.

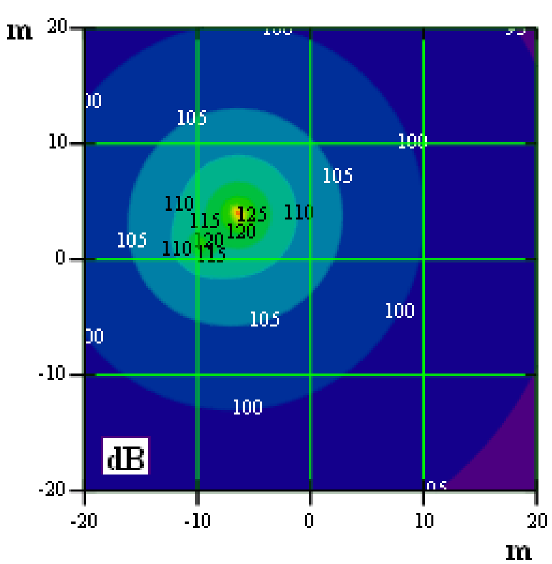

Fig. 10 Noise field at the time t=2.0 s.

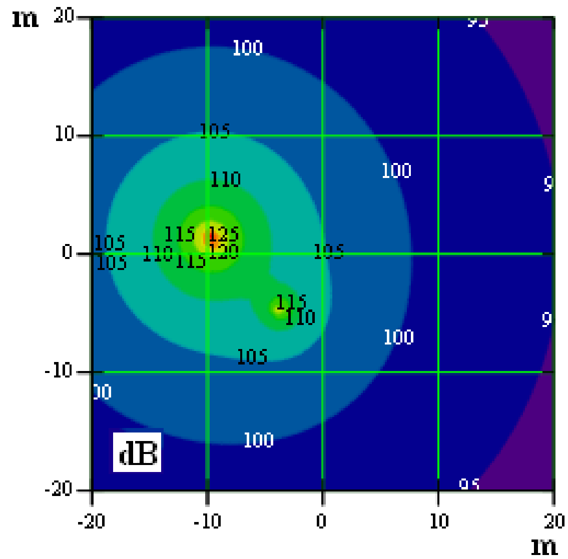

Fig. 10 Noise field at the time t=3.0 s.

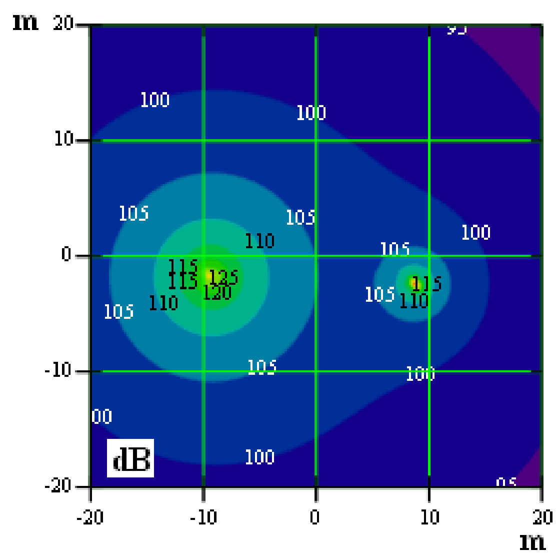

Fig. 12 Noise field at the time t=4.0 s.

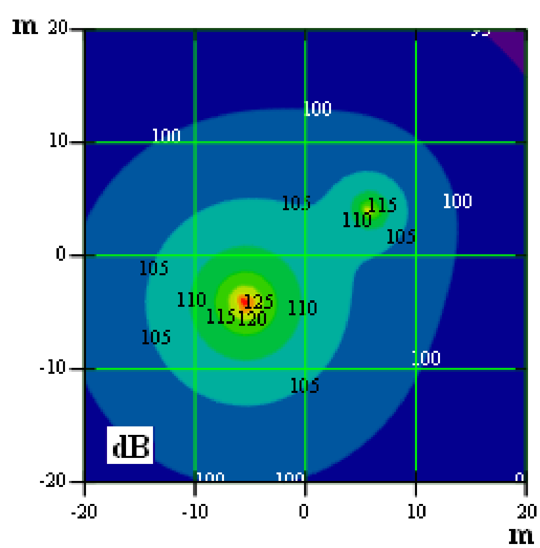

Fig. 13 Noise field at the time t=5.0 s.

This model simulates, for example, the noise produce by the automobile race.

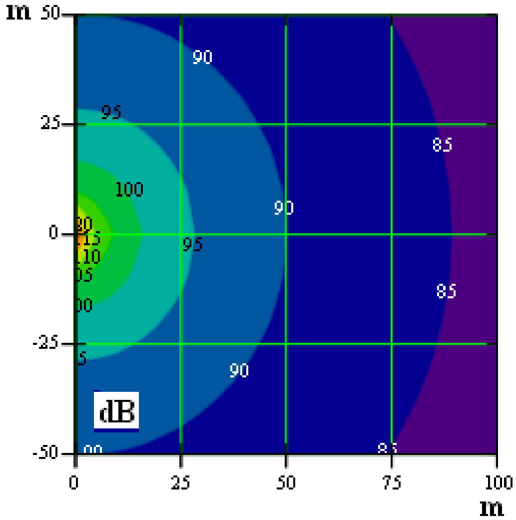

Fig. 14 Noise field at the time t=0.0 s.

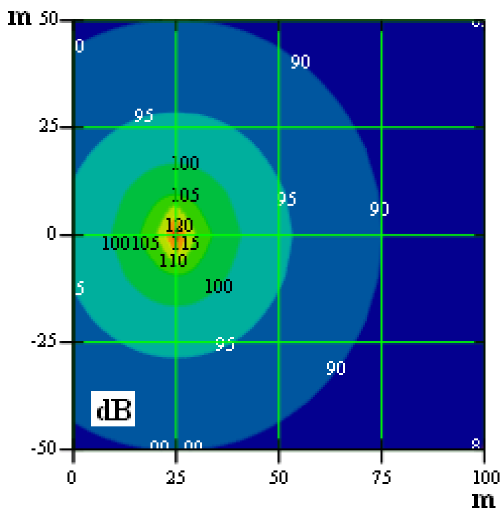

Fig. 15 Noise field at the time t=1.0 s.

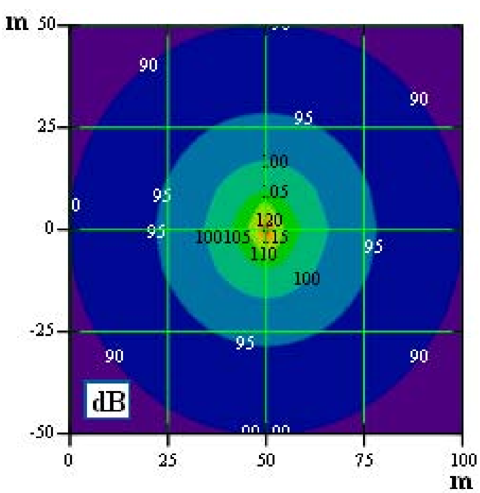

Fig. 16 Noise field at the time t=2.0 s.

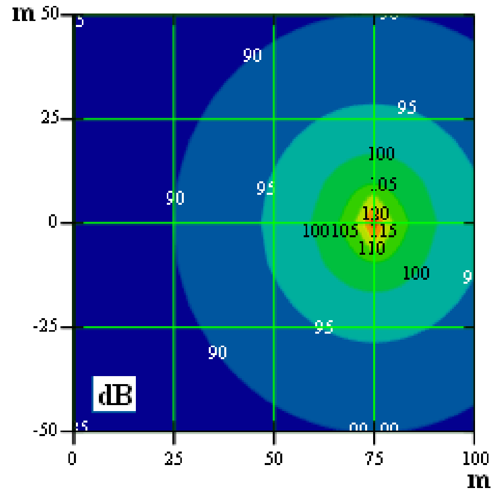

Fig. 17 Noise field at the time t=3.0 s.

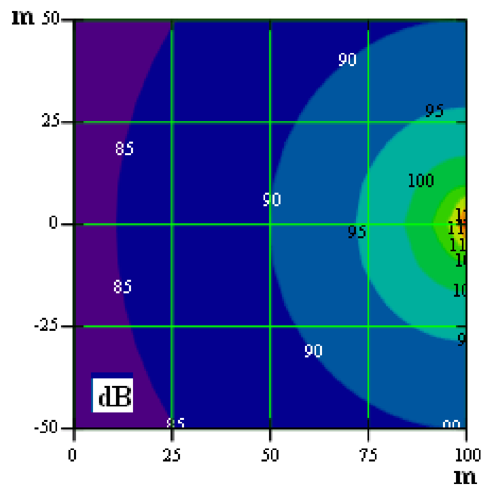

Fig. 18 Noise field at the time t=4.0 s.

The traffic noise produce by the source on the right trajectory can be simulating using the equation (20). The noise fields made by a vehicle which is moving on the Ox axes, with a constant speed 25 m/s, for different time, are shown in the figure 14 – 18.

Using these formulae is possible to simulate the noise field generated by a source that is in an accelerated movement. In aim to simulate a source in accelerated movement, is consider a constant acceleration for a source that has a right trajectory: $X=at^2/2$, $Y(t)=0$, $Z(t)=2$ m, if $t<30$ s, and $Z(t)=20$ m, if $t \geq 30$ s. This simulation is the beginning for the aircraft taxiing. For this reason is consider that the source power increase with the aircraft speed, for example, $L(t)= 108+0.4at$, where a is the acceleration, which is constant in this example. For $a= 2$ m/s, the distribution of the noise field in track zone, is shown in the figure 19, for time: $t= 0$ s, $t= 10$ s, $t= 30$ s, and $t= 40$ s.

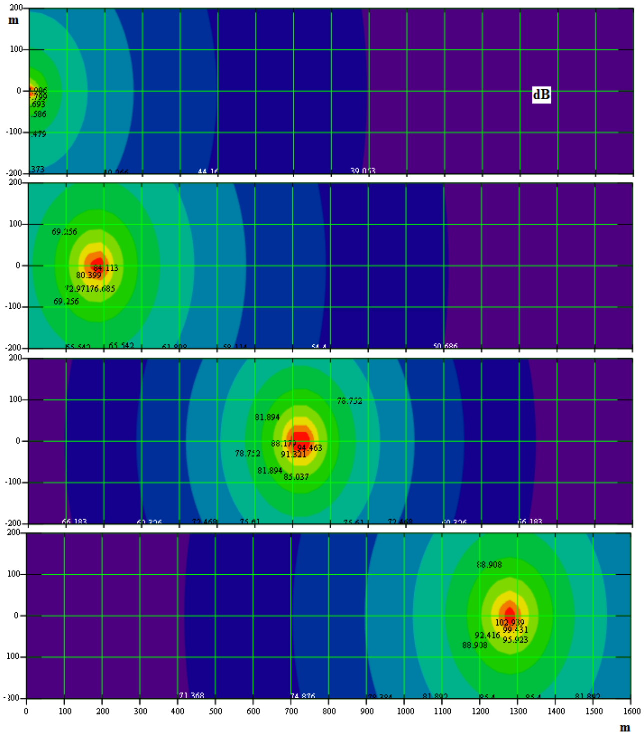

Fig. 19 Noise field of a source in accelerated movement.

Fig. 20 Map of the traffic noise superposed to the aerial map of the mapping zone.

VII. Possibilities to Consider a Theoretical Solution Which is Finite in the Source Location

In aim to improve the form of the theoretical solution, are possible more ways:

-modification of the form of the wave equation, for example, consider that the acoustic wave is governed by the Klein-Gordon equation, and sorting an dumping solution, with conditions to can give physical signification for all constant which appear in these solutions;

-consider that the acoustic wave is governing by the equation for the wave of profound water, or like in [6], [7].

A lot of exponential attenuated solution for the Klein – Gordon equation is given in [10].

VIII. Conclusions

The experimental formulae, used by the software programs for the simulation of the noise emission and the theoretical results can be used together for the simulation of the acoustic fields.

The experimental formulae can be improved structurally, but they not take into account about the frequency influence in the acoustic wave propagation. The theoretical solution naturally considers the frequency influence about the sound level. From (7) and (8) result:

$$w_c = \frac{1}{2}\rho\frac{\Psi_0^2}{r^2}\omega^2\sin^2(\omega t - kr),$$

and

$$w_p = \frac{1}{2}\Psi_0^2\rho c^2\frac{(kr\sin(\omega t - kr) - \cos(\omega t - kr))^2}{r^4}.$$

Result the next form of the wavw energy:

$$w = \frac{1}{2}\rho c^2\frac{\Psi_0^2}{r^4}\cdot$$
$$\left\{r^2\omega^2\sin^2(\omega t - kr) + c^2\left[kr\sin(\omega t - kr) - \cos(\omega t - kr)\right]^2\right\}$$

The graphic form of the dependence of the sound level of the wave frequency is shown in the figure 21.

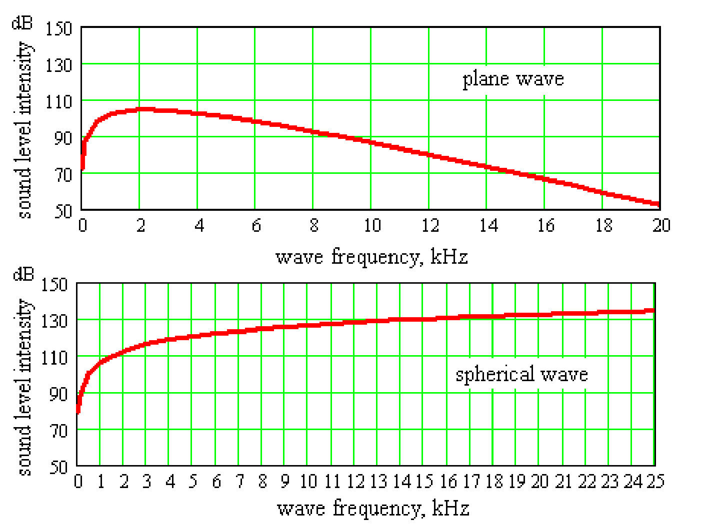

Fig. 21 The dependence of the sound level on the sound frequency.

An essential aspect of the acoustic wave propagation remains the infinite value in the source location. This problem is not very important if there is a neighborhood of the source that is not interesting for the noise mapping. But the neighborhood radius must be specified and, probably depend to the spatial extend of the real source. The infinite value of the noise level in the source location is important to avoid in the graphic representation of the noise field.

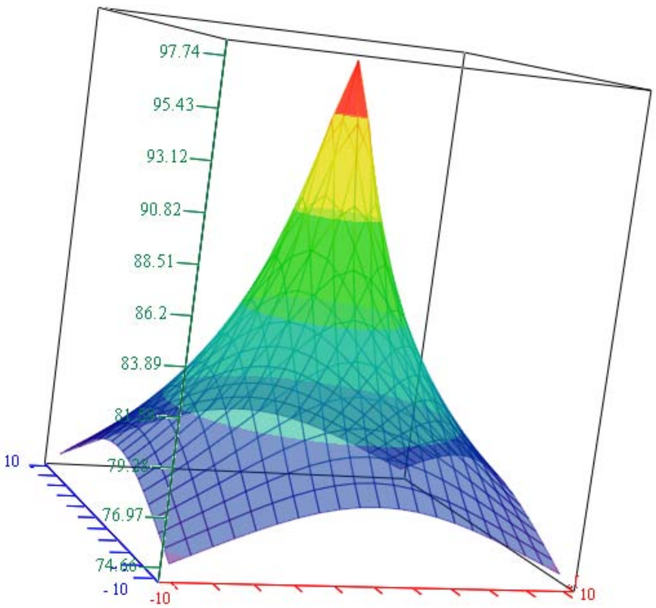

Fig. 22 Noise field mapping for a tractor U-650.

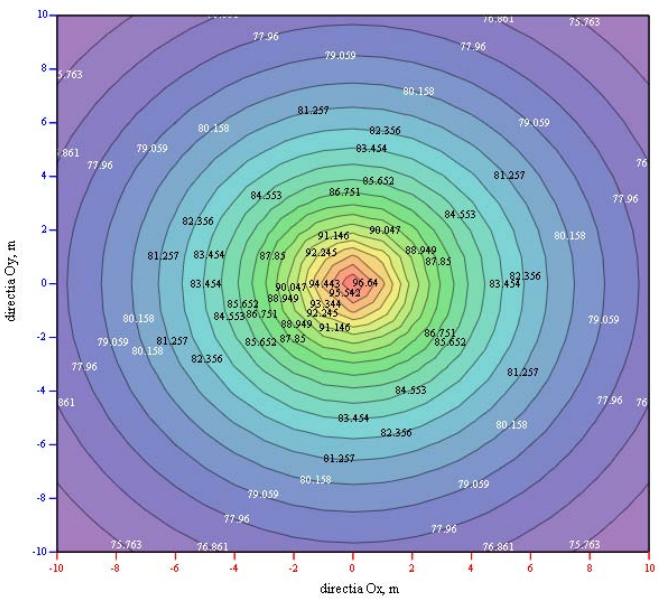

Fig. 23 Noise field mapping for a tractor U-650.

In the graphic representation, many times the vertical asymptote is not visible, but that because the computer mashing of the spatial domain. Otherwise, the computer refuses to calculate the values of the noise field because the grid point is very near to the source location (vertical asymptote of the field). This aspect is visible in the figure 22 and 23, two possible graphical field representations.

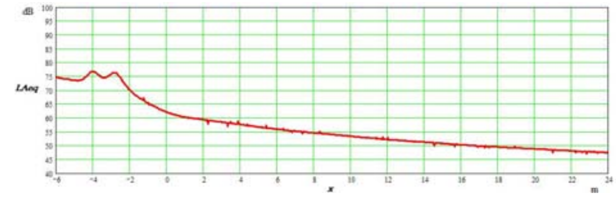

Fig. 24 Radial noise level distribution simulate for a combine.

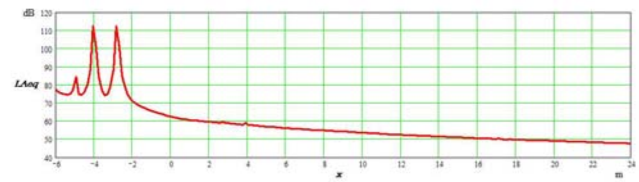

Fig. 25 Radial noise level distribution simulate for a combine.

Same problem is shown in the figure 24 and 25, where appear the radial distribution of the noise level, simulate for a combine using sixteen point sources. The peaks are, really, vertical asymptotes for the noise field.

Many time, in practices is using some methods, which give constant value for the noise field, where the simulate noise value overtake a certain value, physically impossible to exist.

All these aspects must be solved, on the each way (theoretically or experimental), or using a mixed way. But this is a subject for another paper. In this paper I suggest only some extension and reformulation for the experimental formulae, and some direction for the obtaining of an attenuated wave function, which has not infinite value in the source location or in another location.

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