Active noise control effect on penetration of urban noise from 3-D spaces into enclosures

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Abstract

A new acoustic model of attenuation of environmental noise by an electro-acoustic active noise control (ANC) unit is suggested here. It analyses noise escape from an enclosure to the environment through openings and vice versa, in the cases where the ANC is on and off. The simulation is based on solving the sound field by BEM. The BEM has to satisfy specific boundary conditions over a rigid boundary and the opening (window). The particle velocity defines the primary (original) source and the secondary sources (of the ANC). The sensitivity of the system were examined, and the positions of the error sensors of the ANC at the opening zone were optimised in order to improve the performance of the system. Also, the locations and complex amplitudes of the secondary sources were obtained by satisfying the conditions at the opening. The theory and the numerical results are concluded in the paper by a set of graphical presentations of the resulting sound fields. It is concluded that the efficiency of the optimised positioning of the error sensors is much higher than the efficiency of the non-optimised location. Many illustrations that demonstrate the sensitivity of the model are given. They help presenting a new method for optimal geometrical design of ANC system for both external and internal control of noise penetration from the inside of an enclosure, via the opening, to the environment outside the building, and vice versa. The topics of the paper include: development of formulation for the problem; Parameters analysis that determines the efficacy of the problem; and search for optimal positioning of the electro-acoustic components of the ANC.

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1 Introduction

The research aims at simulation of active noise control (ANC) of environmental noise that penetrates through window, from the room to the environment and vice versa.

It is based on construction of a set of intentional sources that reduce by destructive interference the amount of noise radiated through the window. The superposition is done so as to satisfy desired boundary conditions in points over the area of the window. By this superposition, secondary sources of amplitudes adjusted to the boundary conditions at the window, add to the primary source in a way that attenuates noise beyond the opening. The advantage of the suggested method is that the treatment is confined to the area of penetration of noise, and thus, does not involve the geometry, the acoustics and the other properties of the protected domain.

A modified mathematical model, suitable for the internal and external problems of noise radiation through openings was developed here, including the relevant numerical solution, built in MATLAB environment. It enables a profound analysis of the effect of various parameters that influence the performance of the ANC, using simulation of reality. The results were compared with those published in the literature, and some books and papers that helped build such a strategy and simulation are [1-16].

The program presented here is unique. Yet, parts of the problem could be tested by SYSNOISE®. A general view of the acoustic set is shown in figure 1.

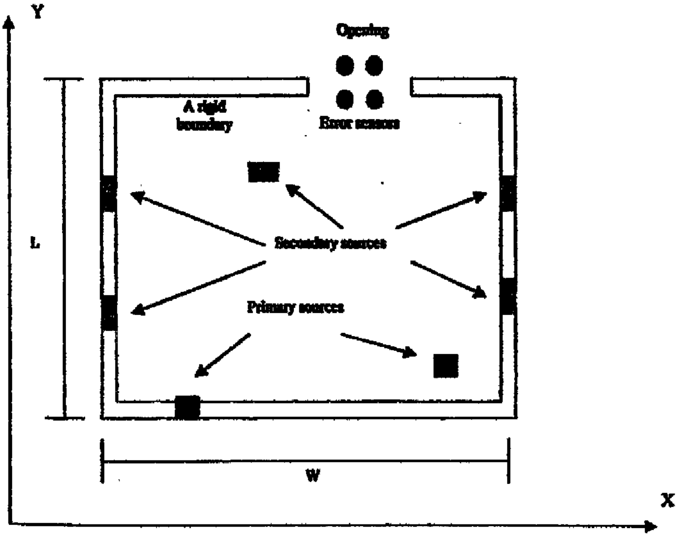

Figure 1: A geometrical scheme of the problem

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2 Formulation

See list of symbols at the end of the paper. A list of symbols is given in the introduction to [17]. See also [6].

The wave equation:

Newton's equation of motion: $$-\mathrm{grad}(p) = \rho\frac{\partial v}{\partial t}. \tag{1}$$

The kinematics relation: $$\mathrm{div}(v) = \frac{\partial \delta}{\partial t}. \tag{2}$$

The thermodynamic relation: $$p = -K\delta. \tag{3}$$

The adiabatic relation: $$PV^{\gamma} = \text{const.} \tag{4}$$

The wave equation: $$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = \frac{\rho}{K}\frac{\partial^2 p}{\partial t^2}. \tag{5}$$

The omni-directional source:

The wave equation in spherical coordinates:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial p}{\partial r}\right) = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}. \tag{6}$$

The solution for the harmonic wave equation:

$$p(r,t) = p(r/r_0)\exp(-i\omega t) = -ik\rho c S_\omega g_\omega(r/r_0)\exp(-i\omega t). \tag{7}$$

Green's function:

$$g_\omega = \frac{1}{4\pi R}\exp(ikR);\quad R^2 = (x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2. \tag{8}$$

Figure 2 depicts the electro-acoustic elements of the problem and the geometrical relations between them, the boundary S of the domain divided into elements and the control point i. These relations enable the definition of the integral form that calculates the influence of the acoustic sources (primary and secondary) and the enveloping surface on the sound pressure at any point i.

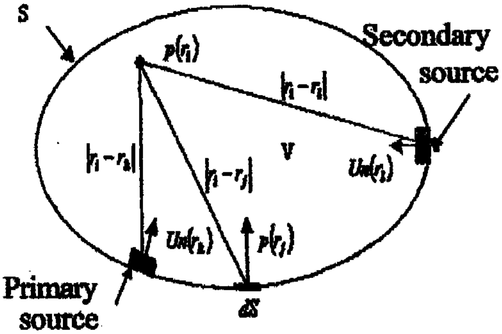

Figure 2. Geometrical relations between the sources, control point and the boundaries of the examined domain,

Formulation for the contribution of the primary source to the pressure in the room –internal problem:

1. The sound pressure obtained at each point, i, over the internal surface of the room: $$\sum_{J=1}^{N} p(r_j)\int_{S_j} \frac{\partial G(r_i, r_j)}{\partial n} dS. \qquad (9)$$
2. The influence of K primary sources on the ith point: $$\sum_{k=1}^{K} U_n(r_k)\int_{S_k} j\omega\rho_0 G(r_i, r_k)dS. \qquad (10)$$
3. The influence of L secondary sources on the ith point: $$\sum_{l=1}^{L} U_n(r_l)\int_{S_l} j\omega\rho_0 G(r_i, r_l)dS. \qquad (11)$$
4. Green's function: $$G(r_i, r_j) = \frac{\exp(-jk|r_i - r_j|)}{4\pi|r_i - r_j|}. \qquad (12)$$

The boundary conditions:

1. The normal particle velocity over the rigid boundary is zero.
2. The acoustic pressure for the external problem over the area of the window is equal to that of the internal problem.
3. The particle velocity of the external problem at the window is obtained by calculating the pressure gradient of the internal problem.

   Formulation for a primary source:

   The internal problem:

The sound pressure obtained at each point, i, over the internal surface of the room:

$$\frac{1}{2}p(r_i) = \sum_{j=1}^{N} p(r_j)\int_{S_j} \frac{\partial G(r_i, r_j)}{\partial n} dS + \sum_{k=1}^{K} U_n(r_k)\int_{S_k} j\omega\rho_0 G(r_i, r_k)dS. \qquad (13)$$

The sound pressure obtained at the area of the window:

$$p(r_w) = \sum_{j=1}^{N} p(r_j)\int_{S_j} \frac{\partial G(r_w, r_j)}{\partial n} dS + \sum_{k=1}^{K} U_n(r_k)\int_{S_k} j\omega\rho_0 G(r_w, r_k)dS. \qquad (14)$$

The sound pressure at each point in the room, calculated after solving the sound pressure at each point of the surface of the room:

$$p(r_i) = \sum_{j=1}^{N} p(r_j)\int_{S_j} \frac{\partial G(r_i, r_j)}{\partial n} dS + \sum_{k=1}^{K} U_n(r_k)\int_{S_k} j\omega\rho_0 G(r_i, r_k)dS. \qquad (15)$$

The external problem:

The sound pressure obtained at each point, i, over the internal surface of the room:

$$\frac{1}{2}p(r_w) = \sum_{j=1}^{N} p(r_j)\int_{S_j} \frac{\partial G(r_i, r_j)}{\partial n} dS + \sum_{k=1}^{K} U_n(r_w)\int_{S_k} j\omega\rho_0 G(r_i, r_w)dS. \qquad (16)$$

The particle velocity obtained over the surface of the window by calculating the sound pressure gradient of the internal problem:

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$$\frac{\partial p}{\partial n} = -j\rho\omega U_n(r_w) = \frac{p(r_w) - p(r_{i\_w})}{\Delta Y}. \tag{17}$$

Sound pressure at each point outside the room, using the known surface sound pressures:

$$p(r_i) = \sum_{j=1}^{N} p(r_j) \int_{S_j} \frac{\partial G(r_i, r_j)}{\partial n} dS + \sum_{k=1}^{K} U_n(r_w) \int_{S_k} j\omega\rho_0 G(r_i, r_w) dS. \tag{18}$$

Formulation for the active control:

The sound pressure obtained at each point, i, of the internal surface of the room:

$$\begin{aligned} \frac{1}{2} p(r_i) = {} & \sum_{j=1}^{N} p(r_j) \int_{S_j} \frac{\partial G(r_i, r_j)}{\partial n} dS + \\ & + \sum_{k=1}^{K} U_n(r_k) \int_{S_k} j\omega\rho_0 G(r_i, r_k) dS + \sum_{l=1}^{L} U_n(r_l) \int_{S_l} j\omega\rho_0 G(r_i, r_l) dS. \end{aligned} \tag{19}$$

The sound pressure obtained at the sensors that are located in the window area:

$$\begin{aligned} \frac{1}{2} p(r_m) = {} & \sum_{j=1}^{N} p(r_j) \int_{S_j} \frac{\partial G(r_m, r_j)}{\partial n} dS + \\ & + \sum_{k=1}^{K} U_n(r_k) \int_{S_k} j\omega\rho_0 G(r_m, r_k) dS + \sum_{l=1}^{L} U_n(r_l) \int_{S_l} j\omega\rho_0 G(r_m, r_l) dS. \end{aligned} \tag{20}$$

The boundary conditions at area of the window are:

$$p(r_m) = 0; \quad \text{or} \quad p(r_m) = 0 \text{ and } \frac{\partial p(r_m)}{\partial n} = 0. \tag{21}$$

3 Optimisation and criteria

3.1 The aim of the optimisation

Optimisation aims at the location and number of error sensors, primary and secondary sources, so as to obtain maximum reduction of noise radiation through the opening. An optimal choice of the active control system should be considered, following design needs.

Optimisation constitutes a search for modified active control systems by a preferred location for the primary and the secondary sources, while putting the error sensors in optimal places.

Verification of conclusions by solving the optimal location for each case enables a more reliable solution by considering all the possible locations, within a given margin of error.

3.2 Computerised criteria for minimisation of noise penetration

The program for the optimisation of the sensors location scans possible states for an ideal placement. The criterion is minimum total acoustic power at the area of the window. This criterion considers the sound pressure and particle velocity (potential and kinetic energies) all over the area of the window:

$$\mathrm{Lwindow\_sum}_j = 10\log_{19}\left[\sum_{i=1}^{n}10^{0.1\mathrm{Lpi}} + \sum_{i=1}^{n}10^{0.1\mathrm{Lvi}}\right]\mathrm{dB}.$$

$$L_{pi} = 10\log_{19}\left[\left(\frac{p_{\mathrm{window\_i}}}{p_0}\right)^2\right]\mathrm{dB};\ L_{vi} = 10\log_{19}\left[\left(\frac{i\rho\omega v_{\mathrm{window\_i}}\times \mathrm{delta}}{p_0}\right)^2\right]\mathrm{dB}. \qquad (22)$$

The test of sensitivity to the location of the sources includes relative distance between the primary and secondary sources and the opening. The results appear in the conclusions.

3.3 Example

Figure 3 gives a scheme of the case of a harmonic primary source that radiates noise at the frequency of 340 Hz, 5 error sensors and 5 secondary sources in a 2-D room. The external sound field in the vicinity of the opening when only the primary source radiates noise and the ANC is off, is presented in the upper part of figure 4. Now the optimised ANC is activated. The secondary sources are placed close to the primary source, and both of them are positioned far from the opening. The lower part of figure 4 shows the external sound field for this case in the vicinity of the opening. The reduction in this special case reaches about 50 dB, as can be observed from the figure.

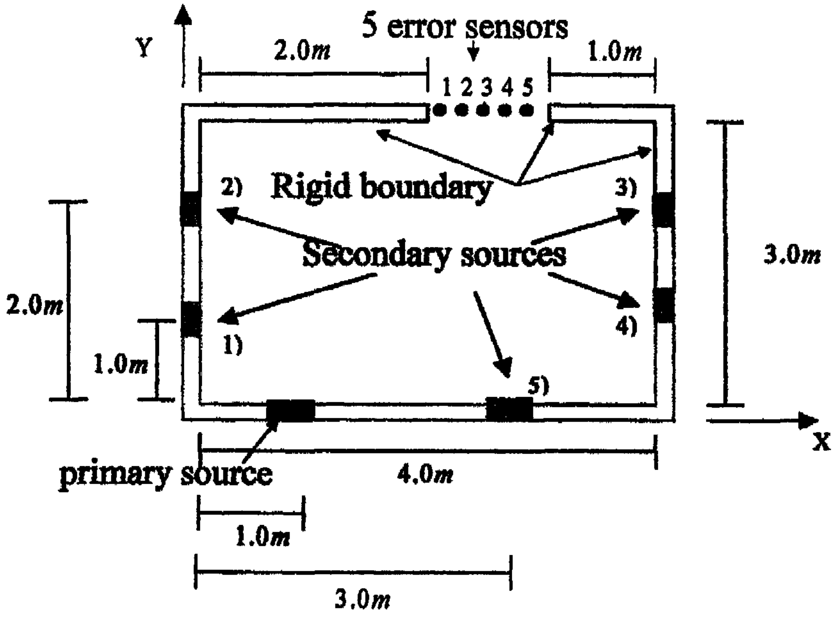

Figure 3. An active control system for the illustrated example.

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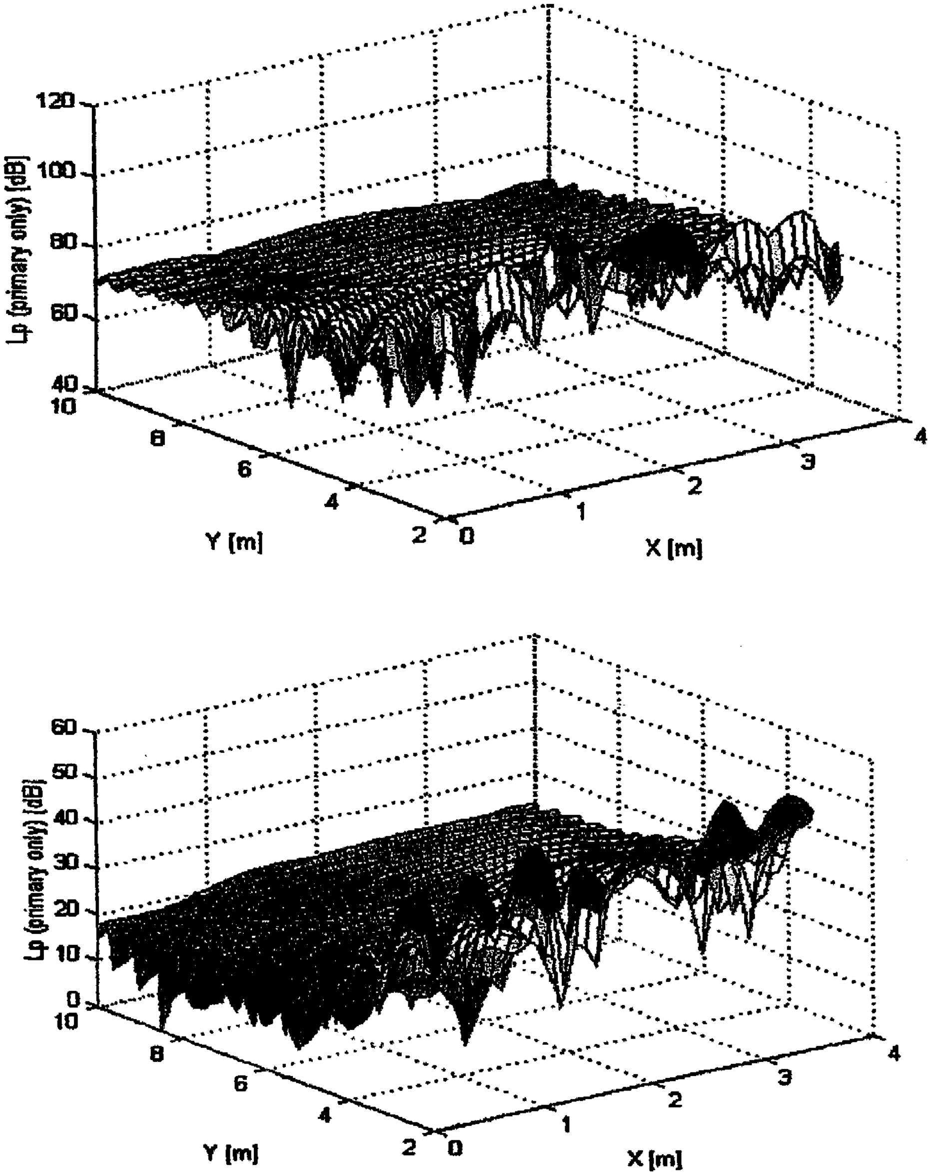

Figure 4. The sound field of the illustration outside the room. Upper figure: The ANC is shut and only the primary source radiates noise. Lower figure: A primary internal source and optimal ANC on.

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4 Conclusion

It can be concluded from the results of the research that location and size of the error sensors set have substantial effect on the performance of the ANC system. It means that the arrangement of the sensors location has strong influence on the ability of the control system to attenuate noise. Addition of sensors does not necessarily improve the system performance. It depends more on the location of the primary source, the secondary sources and each of the error sensors.

A wrong placement of the sensors can even enhance the noise level above the original state. It means that positioning sensors without geometrical optimisation may even cause damage.

A change in the boundary conditions at the window from zero pressure to a combined condition of zero pressure and particle velocity, and the same number of error sensors, does not necessarily lead to an improved result.

As a rule, when the secondary sources were close to the primary source and both of them far from the opening, the results were remarkably good. In fact, the system reaches its maximum efficiency this way, attenuating the acoustic power through the opening, in certain cases, by as much as 50 dB. Yet, positioning the sources in the vicinity of the opening reduces considerably the efficacy of the active control, in spite of the fact that the primary and secondary sources were close together. However, it was not possible to point out a specific tendency by increasing the distance of the ANC system from the area of the opening, when the ANC system is remote from the primary source.

The attenuation of environmental noise penetrating through an opening is much lowers than the attenuation outwards from the room. It depends on existing limitations of location design (e.g. the need to put the system close to the opening), which utterly contradicts the principle we postulated. We have found additional attenuation of about 6 dB in our tests (but, also increase of noise close to the window). Increasing slightly the distance of the system from the window improved significantly the performance of the ANC system. The result may be considered poor as compared with the result for radiation outwards, but, since passive solutions are not effective for the higher floors of a high-rise building, in such cases the active reduction by 6 dB is to be considered (where another solution is not available).

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6 Glossary

c – phase speed
f - frequency
G, g – Green's function
i-integer
j = $\sqrt{-1}$; int eger
K- adiabatic bulk modulus
k – wave number, integer
l- integer
n- normal
p – sound pressure
p_o - reference pressure
R, r – distance
S – flow rate
t- time
U – velocity of surface
V- volume
U_n –surface velocity in the direction of the normal
v – particle velocity
X ,Y; x,y,z – Cartesian co-ordinates
γ - ratio of specific heats
δ- change in a unit volume
ω - radian frequency; phase rate