Active Noise Control In Non-Diffuse Three-Dimensional Enclosures With High Modal Density: Theoretical Studies

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1. INTRODUCTION

In this paper, the active control of low-frequency noise in rooms is investigated. A novel design method called the Image-GA method is proposed. In this method, a noise field is modeled using the image-source method (Guo and Hodgson, 1999), and Genetic Algorithms (GAs) and the quadratic optimization method are combined to optimize locations of control loudspeakers and error microphones. The introduction of the image source model allows the consideration of different acoustical characteristics of walls. Generally speaking, global control is very difficult, if not impossible, to realize in a large enclosure. The local control strategy, which can only assure sound cancellation at error microphones, is not very useful in practice. Considering that workers usually work only in a certain area of a workroom, a new control strategy called "locally-global" control, using the reduction of the acoustical potential energy in the target area as the cost function, is proposed. Numerical investigations were reported in this paper. Experimental results will be reported in next paper.

2. METHOD

2.1 Image-source model

In a free field, the sound pressure emitted by a point source can be expressed as

$$p(\mathbf{X},\mathbf{X}') = q\frac{i\omega\rho_0 e^{-ikR}}{4\pi R} = qZ_R \tag{1}$$

where q is the complex source strength, Z_R is the complex acoustical transfer impedance from the source position to the receiver position, ω is the angle frequency, k is the wavenumber, ρ_0 is the air density, $\mathbf{X}$ is the source position (x,y,z), $\mathbf{X}'$ is the receiver position (x',y',z'), and R is the distance between the source and the receiver.

When a rigid wall is present, the sound at a receiver position will be the sum of the direct sound and reflections from the wall. To model a reflection, one may assume there is an image source located symmetrically on the other side of the wall. Thus, the sound pressure becomes the sum of the noise from the original and image sources.

For a room with low sound absorptive walls, the sound pressure can also be calculated using Eq. (1). In this case, the acoustical transfer impedance can be written as

$$Z_R(\mathbf{X},\mathbf{X}') = \frac{i\omega\rho_0}{4\pi}\sum_{p=0}^{1}\sum_{r=-\infty}^{\infty} \beta_{x1}^{|n-q|}\beta_{x2}^{|n|}\beta_{y1}^{|l-j|}\beta_{y2}^{|l|}\beta_{z1}^{|m-s|}\beta_{z2}^{|m|}\frac{e^{-ik|\mathbf{R_p}+\mathbf{R_r}|}}{|\mathbf{R_p}+\mathbf{R_r}|} \tag{2}$$

2.2 Placement optimization of control loudspeakers

The strong ability of Genetic Algorithms in dealing with complicated problems has been shown in many research areas. Therefore, Genetic Algorithms are employed here as a tool to find the optimal placement of the control loudspeakers and error microphones.

For each searched configuration of control loudspeakers, the control output is optimized using the quadratic optimization method. As is known, the minimization of the sound field at discrete error sensor locations does not guarantee the best results in terms of sound reduction throughout the enclosure. Therefore, some global error criterion is preferred. In a small enclosure such as vehicle cabins, global control can be relatively easy to realize because of the low modal density in the low-frequency range. However, for a large-sized room, the modal density will be high even over the low-frequency range. This makes it very difficult to realize sound attenuation throughout the enclosure with a limit number of control sources. Actually, in a large workroom, workers usually work in a certain area. Hence, one may use the acoustical potential energy in the area as an error criterion. This control strategy can be called "locally–global" control.

Since a linear system is considered, the acoustic potential energy can be expressed as the sum of the primary and secondary sources

$$E_p = \mathbf{q_c^H A_E q_c} + \mathbf{q_c^H b_E} + \mathbf{b_E^H q_c} + \widetilde{E} \tag{3}$$

By minimizing the acoustical potential energy, one can obtain the vector of optimum control source outputs. The difference between the acoustic potential energy levels before and after control is used as the cost function in the Genetic Algorithms to evaluate the fitness of the control source configuration. The higher the difference, the higher is the fitness value assigned to the configuration. At the end of the search, one optimum configuration, or at least a sub-optimum one, will be obtained.

2.3 Placement optimization of error microphones

After the optimum configuration of control sources is obtained, the optimum position of the error microphones are searched in the target area using Genetic Algorithms. For each searched configuration, the optimum control output is calculated by minimizing the sum of the squared sound pressures at the error microphones

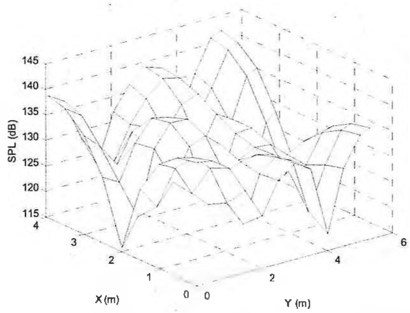
Then the reduction of acoustic potential energy in the target area under this optimum control output is used as the cost function in Genetic Algorithms. At the end of the search, the optimal, or at least a sub-optimal, configuration of error microphones can be found.

3. NUMERICAL RESULTS AND ANALYSIS

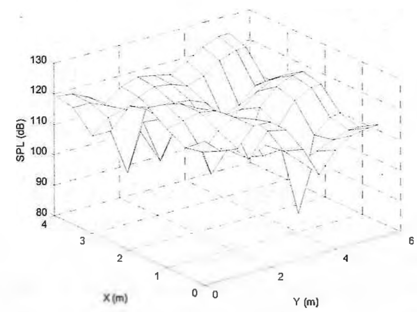
In the numerical investigation, a 2 by 2 control system was designed for a room of 5.3 m long, 3.95 m wide and 2.72 m high. The reflection coefficients were assumed to be, respectively, 0.938 for the four walls, 0.99 for the floor, and 0.812 for the ceiling. One point source placed in one of the corners at (0,0,0) generates noise at 100Hz. The source strength is $0.5m^3/s$. The control area is set to be the whole plane at z=1.60m, the typical height of human ears. The element dimension is 0.5 m, both in the x direction and in the y direction. Theoretically, an infinite number of image sources should be used in the calculation. However, in practice, a finite number has to be used. The image number was determined using the criterion in the literature (Guo and Hodgson, 1999), which is 60 in the research.

As is known, when a control source is placed within a half-wavelength distance from a noise source, global control can be realized. However, this is impossible in many practical situations. To make this research more meaningful and general, the clearance constraint of half-wavelength in at least one direction was imposed. Without this clearance constraint, after optimization, the control sources tend to be located at the same position as the noise source.

The optimum positions for the control sources are (2.42, 0.85, 0.91) and (1.15, 2.22, 0.54). The two error microphones are optimally placed at (2.29, 1.20, 1.60) and (1.91, 3.42, 1.60). Figures 1 (a) and (b) show the sound field before and after control, respectively. From this figure, one can see that a significant sound reduction is achieved at most positions using the optimally designed 2 by 2 control system. The reduction of acoustical potential energy in the target area is 13.3 dB. However, after control, the sound pressure level increases at a few positions which had relatively low noise levels before control. This often happens when the global control strategy is used in control system design.



(a) Before control



(b) After control

Figure 1: Control performance of the optimal control system

4. Conclusions

In this paper, active control of low-frequency noise in three-dimensional rooms was investigated. A novel design method called the Image-GA method and a new control strategy called "locally-global" control were proposed. The numerical results show that, through optimal design, significant sound reduction can be achieved in the target area. The experimental validation will be reported in next paper.

REFERENCES:

Guo, J. and Hodgson, M. (1999), "Investigation of active noise control in non-diffuse sound fields", Proceedings of ACTIVE 99, 621-632.

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