inter•noise 96
25th Anniversary Congress – Liverpool

INCE: 38.5

A BEM-OPTIMIZATION FOR NOISE CONTROL IN ENCLOSURES

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1. INTRODUCTION

A software tool for design optimization was developed in this study for solving noise control systems in enclosures with mixed continuous and non-continuous design variables and appropriate constraints. *Either* the optimum amplitude, phase, and location of the secondary source for active noise control (ANC) *or else* the optimal resistance, reactance, and location of acoustical material for passive noise control (PNC) were simultaneously determined by minimizing the total acoustic potential energy of the control volume in the cavity. The boundary element method (BEM) was utilized for computing sound fields in the enclosure. An optimizer based on sequential quadratic programming (SQP) [1] was selected for its accuracy, efficiency, and reliability. In coping with the non-continuous design variables, the optimizer was linked with a modified branch and bound procedure (BBP) [2] because of practical applications. An irregularly shaped car cabin is modeled to show the usefulness of the software for preliminary design of noise control systems in enclosures.

2. BOUNDARY ELEMENT ACOUSTICAL ANALYSIS

The indirect boundary element method (IBEM) [3] is applied to formulate the acoustical field in interior spaces. The method is a numerical implementation of Huygen's principle in acoustics. The final matrix form for the system of equations is generally written as $\mathbf{A}\sigma + \mathbf{P}\psi_p + \mathbf{S}\psi_s = \alpha$, where σ, ψ_p, and ψ_s are strength vectors of fictitious, primary, and secondary sources, respectively. Vector α contains the values of the boundary conditions. Matrices **A**, **P**, and **S** are derived from types of boundary condition applied to nodes. If σ is solved, the acoustic pressure at interior or boundary locations of the enclosure can be calculated through proper manipulations.

3. DESIGN OPTIMIZATION MODEL

The general mathematical model for the nonlinear single objective constrained optimization problem can be stated as finding a n-vector $\mathbf{x} = (x_1, x_2, ..., x_n)$ of design variables to minimize the objective function $f(\mathbf{x})$, subject to the constraints, $h_i(\mathbf{x}) = 0$, i = 1 to p and $g_i(\mathbf{x}) \leq 0$, i = 1 to m, and bounds on design variables, $\mathbf{x}_l \leq \mathbf{x} \leq \mathbf{x}_u$.

In this study, the total acoustic potential energy [4,5]of the control volume is minimized by choosing the optimal secondary sources (ANC) or acoustical treatments (PNC) for attenuating primary sources within a given set of constraints. The sole equality constraint implies that the codes' sum ($\sum\lambda_i$)of candidate regions (ANC) or acoustical patching (PNC) must be equal to the number (n) of secondary sources or pieces of acoustical materials [4,5]. As a result of practical considerations, space allowances for sound sources and maintaining the specified sound pressure level (SPL) at particular locations can be selected as inequality constraints [4,5]. For the ANC optimization, design variables are the location (x,y,z) and the strength (ϕ,θ) of the secondary source. However, location (x,y,z), and impedance (R,X) of acoustical materials can be selected as design variables for the PNC optimization.

4. COMPUTER SIMULATIONS

A car cabin with dimensions as Ref. 6 is used as an illustrative example to verify the utility of the BEM-based optimization technique for ANC in a practical situation where an irregularly shaped boundary occurs. A primary source of volume velocity 1 m^3/s is positioned at P_1 of (0.5,0.14,0.34) in correspondence with the single transmission path of noise source. A secondary source S_1 is then introduced to attenuate the sound field in the neighborhood (control volume) of the driver's and passengers' heads. Three regions (See Fig. 1) are reserved for installing the ANC system. The design bounds and constraints are $0.1 \leq x \leq 4.4$m, $0.14 \leq y \leq 2.14$m, $0.04 \leq z \leq 1.64$m, $0 \leq \phi \leq 1$ m^3/s, $-180° \leq \theta \leq 180°$, $\lambda_1+\lambda_2+\lambda_3 = 1$, and SPL at positions of the heads height $\leq$ 80 dB. Optimal results are shown in Table 1. Regardless of whether the exciting frequency of the primary is a near-resonance of the cabin or not, the optimal placement of the secondary source most frequently approaches a position in a region close to the primary source (i.e. Region 1) as indicated from simulation results. A reasonable explanation for some of the results presented in this study is that a corner is more likely to be near (if not at) an anti-nodal point for most acoustic modes of a rigidly boundary cavity. Hence, it is expected that optimal secondary source locations would tend to approach the primary source position in situations where these two conditions are satisfied: (1) the primary source is at one of the corners, and (2) the excitation frequency is away from a resonance. Under these circumstances many acoustic modes are excited and the best way of coupling the secondary source in anti-phase with the primary field is to come close to the primary source.

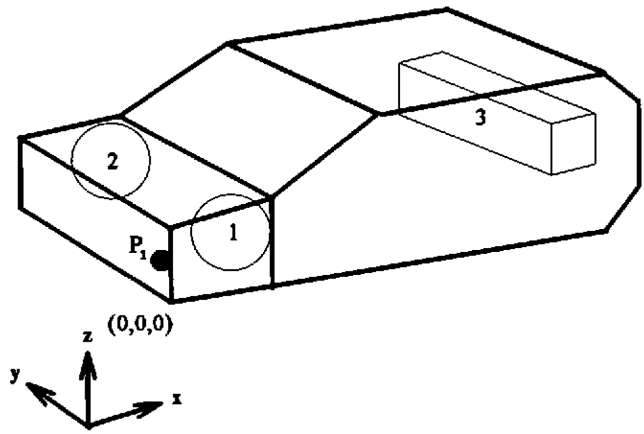

Fig. 1 Schematic diagram indicating positions of primary sources and feasible regions of secondary sources for numerical simulations.

Table 1 Optimal results of ANC for the primary source located at P_1 with a resonance/off-resonance of the cabin. The superscript in the location of the secondary source indicates that the region it belongs to.

Frequency (Hz)	Strength of secondary source (m^3/s, degree)	Location of secondary source (m, m, m)	Objective with ANC ($\times 10^{-3}$, joule)	function without ANC ($\times 10^{-3}$, joule)	Insertion loss [5] (dB)
Resonance					
39	(1.000,-180)	$(0.292,0.390,0.296)^1$	0.093	1091.9	40.6
66	(0.959,+180)	$(0.353,1.748,0.238)^2$	7.028	338.8	17.7
75	(0.776,-180)	$(0.485,0.435,0.590)^1$	0.032	444.9	41.0
84	(1.000,-180)	$(0.619,0.400,0.253)^1$	0.071	332.2	34.1
103	(0.794,-180)	$(0.485,0.433,0.590)^1$	0.835	615.9	27.4
Off-resonance					
20	(1.000,-180)	$(0.720,0.428,0.590)^1$	0.022	102.2	37.1
50	(1.000,-180)	$(0.316,0.403,0.499)^1$	0.007	23.9	36.9
70	(1.000,+180)	$(0.250,0.415,0.272)^1$	0.281	150.2	28.2
90	(0.761,-180)	$(0.438,0.390,0.590)^1$	0.037	58.2	31.5
110	(0.756,-180)	$(0.485,0.390,0.590)^1$	0.026	31.6	29.4

The aforementioned car cabin is also used to investigate the developed BEM-based optimization technique for designing acoustical treatments. Assuming the primary field of the cabin is the same as above case. Five candidate regions are selected for patching acoustical materials, i.e., ceiling, floor, left door, right door, and back panels. Design bounds of impedance are $0 \leq R \leq 1000$ and $100 \leq X \leq 2000$ Pa s/m. The constraints are $\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5 = n$, and SPL at positions of passenger heads' height ≤ 80 dB. Acoustical treatments in the resonant excitation of the car cabin with location and impedance as design variables are illustrated in Table 2 for n =1 and 2. Some remarks can be drawn from these typical simulations: (1) The optimal location for n=1 case is all of positioning in the floor region. Also, one of the optimal treatments for all of n=2 case contains the floor panel. These results can directly correlate with its importance of acoustical influence in the primary field [4]; (2) As a result of dominance of acoustical treatment in the floor region, performance of the n=2 case does not have much improvements as compared with n=1 case, except for the first two resonant excitations.

Table 2 Optimal acoustical treatments with n = 1 and 2, where C, F, L and R represent the regions of ceiling, floor, left, and right door panel, respectively.

n	Frequency (Hz)	Location	Impedance (R,X) (Pa s/m)	Objective function ($\times 10^{-3}$, joule)		Insertion loss (dB)
				Original	Optimal	
1	39	F	(0,-159)	1092	5	21
	66	F	(0,-300)	339	19	12
	75	F	(0,-100)	445	3	23
	84	F	(0,-100)	332	7	14
	103	F	(0,-100)	616	22	15
2	39	C/F	(0,-100)	1092	0.4	32
	66	C/F	(0,-100)	339	3	20
	75	C/F	(240,-100)	445	2	24
	84	C/F	(0,-100)	332	5	18
	103	F/R	(272,-100)	616	7	19

5. CONCLUDING REMARKS

Combining the BE acoustical analysis with BBP enhanced SQP optimization solver could be an effective tool for designing ANC systems or acoustical treatments in enclosures at low frequency. The car cabin of irregularly shaped boundaries was a good numerical example for illustrating the utility of the developed tool.

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