Hindawi
Shock and Vibration
Volume 2018, Article ID 7849327, 8 pages
https://doi.org/10.1155/2018/7849327

Research Article

An Optimization Method for Maximizing the Low Frequency Sound Insulation of Plate Structures

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Received 9 March 2018; Revised 9 May 2018; Accepted 17 May 2018; Published 27 June 2018

Academic Editor: Radoslaw Zimroz

A combined approach based on finite element method, boundary element method, and genetic algorithm (FEM-BEM-GA) is proposed for optimizing the low frequency sound (LFS) insulation performance of plate structures. This approach can identify the optimal structural parameters (especially concerning the effects of arbitrary boundary conditions) so as to maximize the structural overall LFS insulation. The basic ideas of this approach are as follows: (1) the sound transmission loss (TL) analysis of a plate with arbitrary boundary conditions is conducted by the coupled FEM-BEM method; (2) the single-number rating method (such as low frequency sound transmission class) is used to assess the plate's overall LFS insulation; and (3) the genetic algorithm (GA) is employed for searching the optimal solutions of the multiple-parameter optimization problem. The proposed approach is subsequently illustrated by numerical studies. The results show the effectiveness of consideration of the effects of boundary condition in the plate's LFS insulation optimization and demonstrate the feasibility and effectiveness of this approach as a structure design tool.

1. Introduction

There are numerous types of noise around buildings that seriously influence people's living quality [1]. Among these noises, low frequency noise is a major component of many occupational and community noises which is emitted by numerous sources in the society [2–4]. The lack of attenuation of low frequency noise by walls, windows, and other structures and its pervasive ambient levels make low frequency noise a factor of critical importance to people's living quality and health. An widely accepted frequency range for low frequency sound (LFS) is from 20Hz to 250Hz which covers 12 one-third octave bands [4]. The noise within this frequency range can cause not only audible annoyance but also nonaudible annoyance (such as vibration/rattle annoyance) [5]; and it even has negative impacts on people's health and well-being [6].

The study of plate structures can serve as a first step in understanding and manipulating the dynamic and acoustic behavior of more complicated constructions [7]. Examples include the walls and windows of buildings, factory machinery casings, parts of vehicle shells, and the hulls and bulkheads of ships. These structures however often result in poor sound insulation, especially at low frequency [8]. The structural parameters, including plate material, size, thickness, and boundary condition, are the key factors that determine the plate's sound insulation performance. Particularly, the effects of arbitrary boundary conditions have recently received great attention. Both analysis and experimental studies [9, 10] have demonstrated that boundary condition significantly affects the plate's sound insulation, especially in the low frequency domain. Although the plate's sound insulation (especially the LFS insulation) is highly dependent on the plate's actual boundary condition, according to the authors' best knowledge, no optimization technique is yet available for maximizing the sound insulation of plate structures by considering the effects of arbitrary boundary conditions. This kind of methods however has many potential advantages because it only requires the modification of boundary supports and does not need to make any change to the main body of the structure.

The purpose of this study is to develop an optimization method for maximizing the plate's LFS insulation. This method is supposed to be capable of considering arbitrary

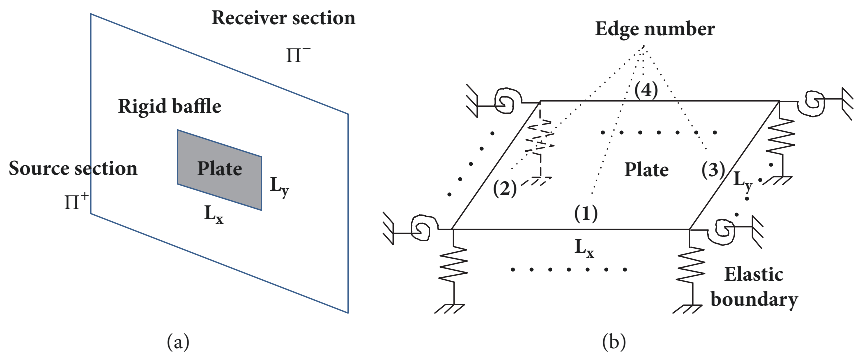

FIGURE 1: Schematic illustration of a baffled rectangular plate structure: (a) a plate mounted on an infinite rigid baffle; (b) elastic boundary supports along the edges.

plate parameters simultaneously as variables (especially concerning the effects of arbitrary boundary conditions). To this end, a finite element method, boundary element method, and genetic algorithm (FEM-BEM-GA) combined method is proposed, in which the coupled FEM-BEM model can accurately predict the low frequency sound transmission loss of the plate with arbitrary boundary conditions while the genetic algorithm (GA) can efficiently handle the multiple-parameter optimization problems. The single-number rating of low frequency sound transmission class is used as the objective function in the optimization.

2. Sound Transmission Loss (TL) Analysis Model

Consider a rectangular plate of length L_x, width L_y, and thickness h, with arbitrary elastic boundary supports along the four edges, as shown in Figure 1. The plate is supposed to be mounted on an infinite rigid baffle, which separates the fluid medium (air medium) into source section Π^+ and receiver section Π^-. Arbitrary incident sound waves varying harmonically are incident to the plate in the source section, and the vibration of the plate induced by the incidence waves then radiates sound waves into the receiver section.

The vibroacoustic behavior of the plate can be determined by the coupled finite element and boundary element method (FEM-BEM), in which the plate vibration response is given as [11]

$$\{U\} = \left[-\omega^2 \{M\} - j\omega \{\zeta\} + \{K\} - 2 \{\mathcal{T}\} \{H\} \{\mathcal{R}\}\right]^{-1} \cdot \{\mathcal{T}\} \{P_0\}, \quad (1)$$

and the sound pressures on the plate surfaces are given as

$$\{P^+\} = \{P_0\} + \{H\} \{\mathcal{R}\} \{U\}, \quad (2)$$

$$\{P^-\} = -\{H\} \{\mathcal{R}\} \{U\}. \quad (3)$$

$\{U\}$ is the global nodal displacement vector of the plate. $\{P^+\}$ and $\{P^-\}$ are the radiated sound pressures on the front (in section Π^+) and back (in section Π^-) plate surfaces, respectively. $\{P_0\}$ is the vector representing the pressure of the incidence sound wave. $\{M\}$, $\{\zeta\}$, and $[K]$ are the mass, damping, and stiffness matrices of the plate structure. $\{H\}$ is a square matrix formed by the "collocation" procedure. $\{\mathcal{R}\}$ is a global transformation matrix converting the nodal displacement vector to the transverse deflection vector. $\{\mathcal{T}\}$ is a global transformation matrix converting the fluid pressure to point forces that act on the nodes of the plate. The damping matrix $\{\zeta\}$ is supposed to be proportional to the stiffness matrix $\{K\}$ and is written as $\{\zeta\} = \sigma\{K\}$, where $\sigma = 2\xi/\omega_0$, ξ is the damping factor, and ω_0 is the fundamental natural frequency of the plate structure.

Particularly, in order to consider arbitrary elastic boundary supports, the stiffness matrix $\{K\}$ of the whole plate structure is decomposed into plate and boundary supports [11], which is expressed as $\{K\} = \{K_p\} + \{K_b\}$. $\{K_p\}$ and $\{K_b\}$ are the stiffness matrices for the plate and boundary supports, respectively. The arbitrary elastic boundary supports are modeled as a combination of translational and rotational springs, with k_t and k_r being the translation stiffness and rotational stiffness, respectively. The element stiffness matrix of $\{K_b\}$ can then be expressed as

$$\{K_b\}_e = \int \left(k_t \{N_w\}^{\mathrm{T}} \{N_w\} + k_r \left\{ \frac{\partial N_w}{\partial \vec{n}_b} \right\}^{\mathrm{T}} \left\{ \frac{\partial N_w}{\partial \vec{n}_b} \right\} \right) d\Gamma_b, \quad (4)$$

where $\{N_w\}$ is the shape function vector for the plate element and $\vec{n}_b$ is the normal unit vector of the element boundary contour Γ_b. It is noted that the elastic parameters (k_t and k_r) along the contour can arbitrarily be varied to reproduce simply supported ($k_t = \infty$ and $k_r = 0$), clamped ($k_t = \infty$ and $k_r = \infty$), free ($k_t = 0$ and $k_r = 0$), and guided edges ($k_t = 0$ and $k_r = \infty$), or, more important, any intermediate situation (i.e., general boundary condition). Moreover, these parameters can spatially vary along each edge to represent arbitrary nonuniform elastic restraint.

The sound transmission loss (TL) of the plate can then be defined as

$$\mathrm{TL} = 10 \log_{10} \left(\frac{W^+}{W^-} \right), \quad (5)$$

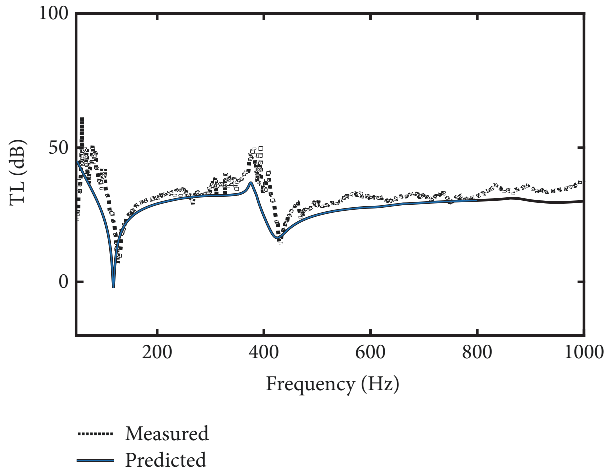

FIGURE 2: Comparison of the predictions and measured data.

where W^+ and W^- are the sound power at the front plate surface (in the source section Π^+) and the radiated sound power at the back plate surface (in the receiver section Π^-). They can be expressed as

$$W^{\pm} = \frac{1}{2}(j\omega\Delta S) \times \mathrm{Re}\left[\{P^{\pm}\}^{\mathrm{T}}(\{\mathscr{R}\}\{U^{\pm}\})^{*}\right], \qquad (6)$$

where ΔS is the area of the plate element, $\{U^+\} = -\{U^-\} = \{U\}$, and the superscript asterisk denotes the complex conjugate.

Combining (1)-(6), the sound transmission loss of the plate with arbitrary elastic boundary conditions can be determined.

The accuracy of this TL model has been validated by the experiment [11]. The TL measurements were conducted on an aluminum (Al) plate structure. The Al plate is 1mm thick and is installed in a steel frame with actual radiated area of 24cm by 24cm. The plate is with uniform elastic boundary supports along the four edges and the actual boundary parameters are $\overline{k}_t = 3201$ and $\overline{k}_r = 13.28$, estimated by the boundary condition identification (BCI) method [11]. $\overline{k}_t$ and $\overline{k}_r$ are the dimensionless forms of k_t and k_r [10, 11]. Figure 2 shows a comparison of the measured and calculated TL results of the plate structure [11]. The predicted results agree well with the experimental data, which demonstrates the effectiveness of the TL prediction model in studying the low frequency sound (LFS) insulation of plate structures with elastic boundary supports.

3. Single-Number Rating Indicators for Low Frequency Sound Insulation

TL is a powerful descriptor that gives comprehensive information about the sound insulation performance and allows the engineers to efficiently analyze this performance at different frequency ranges. In practice, a simpler characterization, namely, by one single number, is also demanded, especially for the purpose of easy ranking of structures and verification of the compliance with legal requirements [12].

Tokita and Nakanura Thresholds are validated to be good indicators of the potential for low frequency noise annoyance [5]. These thresholds present the sound pressure levels at which subjective response to direct exposure to low frequency sound changes as functions of frequency from one characterization to another. Based on the Tokita and Nakanura Thresholds, a single-number rating method called low frequency sound transmission class (LFSTC) is recently developed [13], which is useful for assessing the structural sound insulation in the low frequency range (20Hz~250Hz). The rating indicator, $\mathrm{LFSTC_{O\&N}}$, is defined by this single-number rating method, which is developed based on the "oppression and noisy" threshold and is suitable for the case when high level LFS is present. The $\mathrm{LFSTC_{O\&N}}$ is employed in this paper to assess the plate's overall LFS insulation. The classification procedure of LFSTCO&N is easy to understand and implement, which is quite similar to that given in the international standard (ASTM E413-10 [14]). The reference contour used for calculating $\mathrm{LFSTC_{O\&N}}$ is given in Table 1 (in 1/3 octave bands). More details about this method can be found in [13].

The well-known C-weighted metric is another good indicator of the potential for low frequency noise annoyance [5]. The C-weighted metric is considered to be applicable to most industrial sources of steady low frequency noise [15] and is used by World Health Organization (WHO) as an important indicator for providing guidance on the health effects of low frequency noise [16]. The rating indicator, $\mathrm{LFSTC_C}$, is also defined in this paper to assess the plate's overall LFS insulation, which is based on the reference contour of C-weighted metric (also given in Table 1). The classification procedure of $\mathrm{LFSTC_C}$ is the same as that of $\mathrm{LFSTC_{O\&N}}$.

4. Optimization Methodology

The objective is to identify the optimal plate parameters (especially the optimal boundary parameters) so as to maximize the LFS insulation of the plate. This is a multiple-parameter optimization problem, which requires the optimization method to be capable of considering multiple plate parameters simultaneously as variables. Even if only the boundary condition is set as the design variable, there can be multiple boundary parameters for a practical plate and each boundary parameter can take on an infinite number of different values. This makes it impossible to apply an exhaustive search to the task of structural optimization. Therefore, global search algorithms that can search intelligently for the optimal solution within the search space are needed. In this study, a genetic algorithm (GA) is employed and combined with the coupled FEM-BEM method for the development of structural optimization strategy.

4.1. Genetic Algorithm. Genetic algorithms (GAs) are heuristic search techniques based on principles present in natural evolution. Compared to other stochastic methods, GAs have a distinct advantage that it is extremely easy to parallelize the algorithm since the calculations of each iteration are independent of one another [17]. The general procedure of a GA consists of four bioinspired operators, including

Table 1: Reference sound insulation contours for calculation of single-number ratings.

Frequency (Hz)	20	25	31.5	40	50	63	80	100	125	160	200	250
Values of Reference for $LFSTC_{O\&N}$ (dB)	-17	-10	-3	4	0	-3	-7	-3	0	4	2	0
Values of Reference for $LFSTC_C$ (dB)	-6	-4	-3	-2	-1	-1	-1	0	0	0	0	0

initialization, crossover, selection, and mutation. This procedure is inspired by the processes of natural selection and genetics and creates "environments" where the best quality individuals tend to pass on their data to the next generation. The quality of the population can therefore increase over time. In the search process, the fitness function (objective function) is a key concept which is used for the assessment of the fitness of individuals (i.e., the quality of individuals).

4.2. FEM-BEM-GA Combined Optimization Approach. The flowchart of the optimization strategy is given in Figure 3, which can be described as follows: (1) Input the known variables of the plate. (2) Input the constraints of the design variables. (3) Run the FEM-BEM-GA combined method to search the optimal values of the design variables. In this combined method, the low frequency sound transmission loss of the plate with arbitrary elastic boundary conditions is calculated by the coupled FEM-BEM method. The GA is applied to search the optimal structural parameters so as to maximize the LFS insulation of the plate. The single-number rating indicator (such as $LFSTC_{O\&N}$ and $LFSTC_C$) is employed to assess the plate's overall LFS insulation and is used as the fitness function in GA.

5. Illustrative Examples

The proposed method is applied to the LFS insulation optimization of two plate cases. The element number used in the coupled FEM-BEM model is 100 (10×10). The subscript n of $\overline{k}_{tn}$ and $\overline{k}_{rn}$ represents the edge number (see Figure 1). In the following illustrative examples, the single-number ratings, $LFSTC_{O\&N}$ and $LFSTC_C$, are used as the fitness functions. The optimization algorithm is run 5 times independently in each case to ensure finding the best results; and in each run the initial population in GA is set to be 100 and the optimization algorithm terminates if no improvement in the best solution is observed for 10 consecutive generations.

5.1. Case 1 (Boundary Condition Optimization). The known parameters, design constraints, optimization target, and final optimization results are shown in Table 2. The plate's boundary condition along Edges 1 and 4 is set to be clamped; and the boundary parameters of the other two edges (Edges 2 and 3) are taken as design variables. For comparison, the single-number rating indicators, $LFSTC_{O\&N}$ and $LFSTC_C$, of the same plate with two classic boundary conditions, SSSS (simply supported on all edges) and CCCC (clamped on all edges), are also calculated (see Table 2).

It is proved that when the boundary parameter's value ($\overline{k}_t$ or $\overline{k}_r$) is larger than 1×10^{10}, increasing the value of this boundary parameter does not affect the plate's TL results anymore [9, 13]. For simplicity, unless stated otherwise, the infinite large value of boundary parameter is represented by 1×10^{10}. For example, the boundary condition of clamped supported can be represented as $\overline{k}_t = 1 \times 10^{10}$ and $\overline{k}_r = 1 \times 10^{10}$.

From Table 2, for $LFSTC_{O\&N}$, it can be seen that the optimal boundary parameters are found which can maximize $LFSTC_{O\&N}$ ($LFSTC_{O\&N}$ =45 dB). As a result of this optimal boundary condition, increases of 10 dB and 8 dB in $LFSTC_{O\&N}$ are obtained in comparison with those of SSSS and CCCC boundary conditions, respectively. For $LFSTC_C$, it also can be seen that the optimal boundary parameters are found which can maximize $LFSTC_C$ ($LFSTC_C$ =42 dB). As a result of this optimal boundary condition, increases of 9 dB and 8 dB in $LFSTC_C$ are obtained in comparison with those of SSSS and CCCC boundary conditions, respectively.

5.2. Case 2 (Boundary Condition and Thickness Optimization). The known parameters, design constraints, optimization target, and the final optimization results are shown in Table 3. The plate's boundary parameters along the four edges are taken as design variables, as well as the plate's thickness. It is assumed that the plate is with uniform boundary supports along the four edges and that the thickness is an integer multiple of 1 mm. Such situations are common in practical applications. For comparison, the $LFSTC_{O\&N}$ and $LFSTC_C$ results of a reference plate (the same plate but with 15 mm thickness, i.e., the upper limit of thickness constraint) with SSSS and CCCC boundary conditions are also calculated (see Table 3).

For $LFSTC_{O\&N}$, it can be seen that the optimal boundary parameters and thickness are found which can maximize $LFSTC_{O\&N}$ ($LFSTC_{O\&N}$ =31 dB). As a result of these optimal structural parameters, increases of 6 dB and 3 dB in $LFSTC_{O\&N}$ are obtained in comparison with those of the reference plate with SSSS and CCCC boundary conditions, respectively. For $LFSTC_C$, it also can be seen that the optimal boundary parameters and thickness are found which can maximize $LFSTC_C$ ($LFSTC_C$ =32 dB). As a result of this optimal boundary condition, increases of 7 dB and 4 dB in $LFSTC_C$ are obtained in comparison with those of the reference plate with SSSS and CCCC boundary conditions, respectively.

6. Discussion

6.1. Computation Time of Optimization. A normal personal desktop computer manufactured in year 2015, with 8 GB of memory and Intel (R) Core (TM) i7-4790 processor (8 cores, 3.6 GHz), was used for running the simulation cases. During the whole calculation process, the average usage of

TABLE 2: Known parameters and optimization of Case 1.

(a)

Known parameters	Density	Young's modulus	Poisson's ratio	Damping factor	Lx	Ly	h
	7800kg/m^3	216GPa	0.28	0.01	1m	1m	12mm

(b)

Constraints	Edge No.	1		2		3		4	
	Boundary parameter	$\bar{k}_{t1}$	$\bar{k}_{r1}$	$\bar{k}_{t2}$	$\bar{k}_{r2}$	$\bar{k}_{t3}$	$\bar{k}_{r3}$	$\bar{k}_{t4}$	$\bar{k}_{r4}$
	Variable Range	∞	∞	$0\sim10^4$	$0\sim10^3$	$0\sim10^4$	$0\sim10^3$	∞	∞

(c)

Target	Maximize $\mathrm{LFSTC}_{\mathrm{O\&N}}$	
Results	Optimal Boundary condition	$\bar{k}_{t1}=\infty,\ \bar{k}_{t2}=2123.76,\ \bar{k}_{t3}=3.91,\ \bar{k}_{t4}=\infty,$ $\bar{k}_{r1}=\infty,\ \bar{k}_{r2}=300.64,\ \bar{k}_{r3}=0,\ \bar{k}_{r4}=\infty$
	Optimal $\mathrm{LFSTC}_{\mathrm{O\&N}}$	45dB

Note: for comparison, the $\mathrm{LFSTC}_{\mathrm{O\&N}}$ results of the same plate with two classic boundary conditions, SSSS (simply supported on all edges) and CCCC (clamped on all edges), are 35 dB and 37 dB, respectively.

(d)

Target	Maximize $\mathrm{LFSTC}_{\mathrm{C}}$	
Results	Optimal Boundary condition	$\bar{k}_{t1}=\infty,\ \bar{k}_{t2}=1.16,\ \bar{k}_{t3}=5965.05,\ \bar{k}_{t4}=\infty,$ $\bar{k}_{r1}=\infty,\ \bar{k}_{r2}=0.20,\ \bar{k}_{r3}=397.95,\ \bar{k}_{r4}=\infty$
	Optimal $\mathrm{LFSTC}_{\mathrm{C}}$	42dB

Note: for comparison, the $\mathrm{LFSTC}_{\mathrm{C}}$ results of the same plate with two classic boundary conditions, SSSS (simply supported on all edges) and CCCC (clamped on all edges), are 33 dB and 34 dB, respectively.

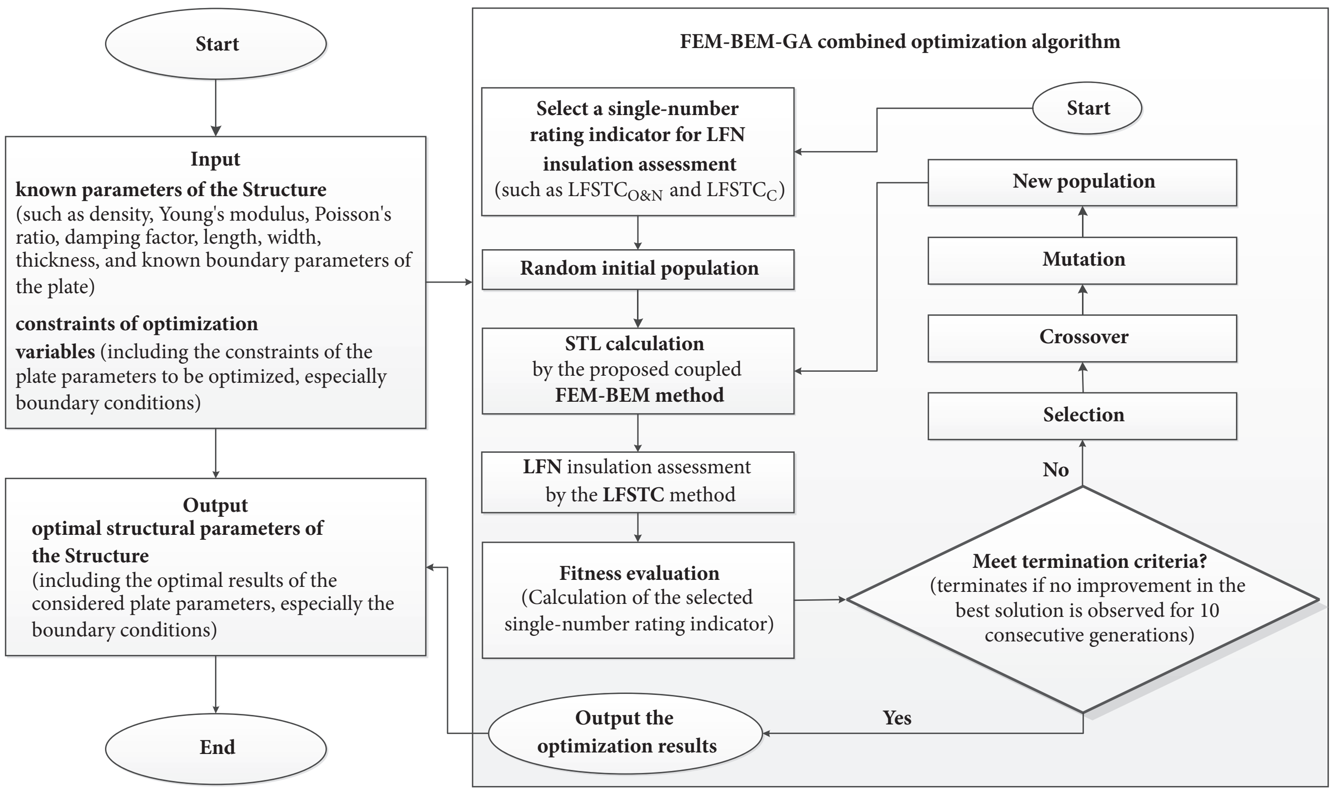

Figure 3: Flowchart of optimization strategy.

CPU and memory was less than 45% and 35%, respectively. The average time of calculating TL (see (1)-(6)) is about 0.01s per frequency. The average time of calculating the fitness function for each combination of design variables is about 3.21s, including the time of calculating TL for the whole frequency range of interest (10Hz-300Hz) and the time for calculating $\mathrm{LFSTC}_{\mathrm{O\&N}}$ (or $\mathrm{LFSTC}_{\mathrm{C}}$).

Even if only one boundary parameter is set as the design variable, it can take on an infinite number of different values; therefore it is impossible to apply an exhaustive search for the optimization. Even if only integer numbers are considered for the design variables, the number of possible combinations is still very large. Taking Case 2 as an example, this number can be estimated as $(10^{10} - 10^3) \times 10^{10} \times (15 - 5) \approx 1 \times 10^{21}$. It also takes almost infinite time (about 3.21×10^{21} s) for performing an exhaustive search and therefore cannot be solved without using intelligent search algorithms.

Table 4 shows the computation time of the two cases (in Section 5) by using the proposed optimization method. It can be seen that the time of running the optimization algorithm (i.e., the whole procedure of Figure 3) is about 20~26 minutes. The proposed method indeed can significantly reduce the searching time and make the optimization much more efficient and applicable.

6.2. Performance of Optimization. The examples given in Section 5 demonstrate the boundary condition has significant effects on the plate's LFS insulation and is worthy of consideration in structural optimization. The optimal results obtained based on both $\mathrm{LFSTC}_{\mathrm{O\&N}}$ and $\mathrm{LFSTC}_{\mathrm{C}}$ indicators show the following: (1) For a given plate, the LFS insulation performance can be effectively improved even if only modifying the plate's boundary parameters (such as $\mathrm{LFSTC}_{\mathrm{O\&N}}$ and $\mathrm{LFSTC}_{\mathrm{C}}$ of Case 1). This is useful in practical applications especially when the design constraints do not allow modifying the body and appearance of the given structure (such as the plate's material, size, shape, mass, and surface property). (2) The plate with a proper boundary condition could have even better LFS insulation performance than that of the thicker plate. In such case, it is possible to design a plate with both better LFS insulation and smaller thickness (smaller mass) within the design constraints (such as $\mathrm{LFSTC}_{\mathrm{O\&N}}$ of Case 2).

It can also be noted from the examples that different fitness functions (i.e., different rating indicators, $\mathrm{LFSTC}_{\mathrm{O\&N}}$, and $\mathrm{LFSTC}_{\mathrm{C}}$) lead to different optimal results. The optimal values of plate parameters are highly dependent on the selected LFS insulation indicators. Users can choose freely the LFS insulation rating indicator ($\mathrm{LFSTC}_{\mathrm{O\&N}}$ or $\mathrm{LFSTC}_{\mathrm{C}}$) according to their actual needs.

6.3. Applications of Optimization. With the development of elastic material and structural assembly technology, it is proved that elastic plate boundary conditions can be realized in practical applications. For example, the plate structure with elastic mounting can be achieved by placing elastic materials along the border of the plate [18]. Lower-density elastic materials, such as Getzner Sylomer and Sylodyn, are of a type suitable for use in an elastic boundary setup [18, 19]. The

Table 3: Known parameters and optimization of Case 2.

(a)

	Density	Young's modulus	Poisson's ratio	Damping factor	Lx	Ly
Known parameters	2500kg/m^3	65GPa	0.25	0.01	1m	0.6m

(b)

Constraints	**Boundary condition**	Boundary parameter	$\bar{k}_{t1} = \bar{k}_{t2} = \bar{k}_{t3} = \bar{k}_{t4}$	$\bar{k}_{r1} = \bar{k}_{r2} = \bar{k}_{r3} = \bar{k}_{r4}$
		Variable Range	$10^3 \sim \infty$	$0\sim \infty$
	Plate thickness	Variable Range	5~15mm (being an integer multiple of 1 mm)	

(c)

Target	Maximize $\mathrm{LFSTC_{O\&N}}$	
Results	Optimal boundary condition	$\bar{k}_{t1} = \bar{k}_{t2} = \bar{k}_{t3} = \bar{k}_{t4} = 11707.61$, $\bar{k}_{r1} = \bar{k}_{r2} = \bar{k}_{r3} = \bar{k}_{r4} = 0.37$
	Optimal plate thickness	8mm
	Optimal $\mathrm{LFSTC_{O\&N}}$	31dB

Note: for comparison, the LFSTCO&N results of the reference plate (the same plate but with 15 mm thickness) with SSSS and CCCC boundary conditions are 25 dB and 28 dB, respectively.

(d)

Target	Maximize $\mathrm{LFSTC_{C}}$	
Results	Optimal Boundary condition	$\bar{k}_{t1} = \bar{k}_{t2} = \bar{k}_{t3} = \bar{k}_{t4} = 30682.08$, $\bar{k}_{r1} = \bar{k}_{r2} = \bar{k}_{r3} = \bar{k}_{r4} = 0.91$
	Optimal plate thickness	15mm
	Optimal $\mathrm{LFSTC_{C}}$	32dB

Note: for comparison, the $\mathrm{LFSTC_{C}}$ results of the reference plate (the same plate but with 15 mm thickness) with SSSS and CCCC boundary conditions are 25 dB and 28 dB, respectively.

Table 4: Computation time of optimization.

	Objective	Average number of generations when algorithm terminates	Average time of each generation	Average computation time of the optimization algorithm (Figure 3)
Case 1	Maximize $\mathrm{LFSTC_{O\&N}}$	26	58s	1508s ≈25min
	Maximize $\mathrm{LFSTC_{C}}$	21	58s	1218s ≈20min
Case 2	Maximize $\mathrm{LFSTC_{O\&N}}$	18	82s	1476s ≈25min
	Maximize $\mathrm{LFSTC_{C}}$	21	75s	1575s ≈26min

parameters of these materials, such as their stiffness, can be obtained from their suppliers [19] or checked and corrected by the boundary condition identification (BCI) method [11].

Also, it should be admitted that, at the current stage, it is not easy to exactly set the plate boundary condition to be arbitrary optimal values in practical applications. The experimental technique for controlling the plate's boundary parameters to exactly match the optimal results is still being studied (it is also our focus). Nevertheless, the optimization idea and technique proposed in this study can serve as a fundamental step in understanding and optimizing the LFS insulation of plate structures.

7. Conclusion

A finite element method, boundary element method, and genetic algorithm (FEM-BEM-GA) combined optimization approach is developed for maximizing the low frequency sound (LFS) insulation of plate structures. In this approach, the low frequency sound transmission loss of the plate with arbitrary elastic boundary conditions is calculated by the coupled FEM-BEM method, while GA is employed for searching the optimal structural parameters so as to maximize the plate's LFS insulation. Meanwhile, the single-number rating of low frequency sound transmission class is applied to assess the plate's overall LFS insulation.

The proposed approach is illustrated by numerical studies. The results demonstrate the effectiveness of considering boundary parameters in the plate's LFS insulation optimization, as well as the effectiveness of this approach as a structural design tool. According to the authors' best knowledge, no optimization method is yet available in the literature for maximizing the LFS insulation of a plate structure by considering the effects of arbitrary boundary conditions;

therefore the proposed idea as well as the optimization model can be valuable for both academic and design practitioners.

Data Availability

Access to the data will be considered by the author upon request.

Conflicts of Interest

The author declares that they have no conflicts of interest.

Acknowledgments

The work was supported by National Natural Science Foundation of China (51578252), Program for New Century Excellent Talents in Fujian Province University (2017), and High Level Talent Innovation and Entrepreneurship Program of Quanzhou City, China (2017G039).

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