Inverse Prediction of Sound Insulation to a Wall with Apertures

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Abstract

With concerning a wall with apertures, which means there exists sound leak, the sound insulation of the wall is impaired severely. Under the meeting of the insulation requirement, inverse sound insulation prediction approach can be utilized to determine the minimum insulation of the solid wall and maximum area of apertures or cracks. The prediction, therefore, will provide the guidance to obtain the allowable value of aperture area for installation of ducts and electrical outlet box on the wall.

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1. Introduction

A sound leak is the passage of sound energy through the apertures or cracks in the structure of a building. Common apertures in buildings are due to: cracks in the wall of a house, Unsealed gaps around power outlet, openings around pipes where they penetrate wall and cracks around the edges of doors and windows etc,. Although the area of aperture can be quite small, the sound insulation of this part is roughly zero. As a consequence, the total sound insulation of the wall is determined largely by the aperture area. Evidently, aperture and hole in the structure exhibit the characteristics that depress sound insulation. In general, walls in the building are always with more or less apertures or cracks because of the reasons of construction and building material. The higher sound insulation that is sought, the more significant it is to eliminate all sound leaks. So, a wall with apertures exhibit lower insulation than other wall without any leaks are usually the weaker sound insulating elements between rooms and therefore require careful acoustic design.

A theory of sound transmission through a wall with apertures is employed in the present paper to determine at what combinations of design variables (the sound insulation R and the area ratio between the wall and the apertures φ) could result in structure satisfying the sound insulation criterion.
2. Sound Insulation to a Wall with Apertures

As to a wall with apertures, two separate transmission paths to be considered: the structural transmission through the solid wall and the leak transmission through the apertures or slits. As to a wall with apertures or cracks, the whole area of the wall, the sound insulation of the solid wall and the area ratio between the wall and the apertures are known as $S$, $R_w$ and $\phi$, respectively. The transmission coefficient $\tau_w$ is

$$\tau_w = 10^{\frac{R_w}{10}}$$  \hspace{1cm} (1)

The area-weighted transmission coefficient of the wall is

$$\tau = \frac{(1 - \phi)S\tau + \phi S\tau_a}{S} = \frac{(1 - \phi)S\tau + \phi S}{S} = (1 - \phi)\tau + \phi$$  \hspace{1cm} (2)

The transmission coefficient of apertures $\tau_a$ equals to 1 means that the incident sound energy passes through the aperture in the wall. Then the total sound insulation of the wall is expressed as

$$\bar{R} = 10\log_{10} \frac{1}{\tau} = 10\log_{10} \frac{1}{(1 - \phi)\tau + \phi}$$  \hspace{1cm} (3)

As shown in (3), with increase of the area ratio $\phi$, the total sound insulation of a wall with apertures $\bar{R}$ will decrease rapidly. For instance, if the aperture area is 0.0001 times the wall area, the sound insulation will no more exceed 40dB no matter how perfect the wall is potentially. Or, the total sound insulation of a wall with apertures $\bar{R}$ can be calculated by the area-weighted sum of transmission coefficient as $[1]

$$\bar{R} = 10\log_{10} \left( \frac{S}{S \cdot 10^{\frac{R_w}{10}} + S_a \cdot 10^{\frac{R_a}{10}}} \right)$$  \hspace{1cm} (4)

where $R_w$ and $S_a$ are the represent sound insulation and area of apertures, respectively.

3. Inverse Prediction of Sound Insulation to a Wall with Apertures

With respect to a wall with apertures, as the whole area of the wall $S$ and the sound insulation criterion $R'$ of the wall are known simultaneously, the inverse prediction of sound insulation is employed to determine the preferable values range of the $R_w$ and $\phi$ which can reach the sound insulation criterion $\bar{R}'$.

In practical sound insulation design of a wall with apertures, determination in the option range for sound insulation of the wall which satisfies with the insulation criteria is the key. Many optimization algorithms have been proposed for this kind of programming solution. While each technique has its own advantages and disadvantages, including various degrees of efficiency, none of them are suitable for all problems. The choice of a particular algorithm for any solution depends on the specific problem and the user. In this paper, in aim of achieving the inverse prediction of sound insulation, a globe search procedure is developed based on combining the sound insulation model for the structure with the artificial immune algorithms (AIA), and convergence to a global optimum is guaranteed.

AIA are biologically inspired optimization techniques, which imitate immune systems of an organism to solve the combinatorial optimization problems $[2-4]$. By efficient search method, such as recognizing, selection, mutation and crossover operations in antibodies at each iterative, the optimized solution to the problem is obtained.

The inverse prediction is assumed a combinatorial optimization problem as antigens, whereas, the feasible solutions $(R_w, \phi)$ of the problem are regarded as antibodies, this immune systems will undergo the procedures as recognizing, selection, mutation and crossover operations in antibodies as it is processing. As a consequence, it is assumed that each antibody corresponds to a set of acoustical parameters $(R_w, \phi)$
that are candidates for the solutions of the objective function. Two variables of the objective function are \( R_w \) and \( \phi \) which are constituted of antibodies’ coding string. Under constrain of requirement of sound insulation, the inverse sound insulation is a process that determine the preferable acoustical parameters of the wall, and, can be realize by the AIA. Therefore, the mean distance value of opt between \( R^* \) and \( R \) is selected as the objective function

\[
\text{opt} = \frac{1}{m} \sum_{i=1}^{m} |R_i(R_w, \phi) - \bar{R}_i| \tag{5}
\]

Each antibody, therefore, can be expressed as real strings that involve the two variables. The initial antibody population is generated within definition range of the independent variables randomly. While value of objective function \( \text{opt} \rightarrow 0 \), then \( R_i \rightarrow R_i^* \), the distance between \( R_i \) and \( R_i^* \) reaches its minimum. The affinity between antibody \( v \) and antigen, which indicates the intensity of the combination between the objective function and the solution

\[
ax_v = \frac{1}{1 + \text{opt}_v} \tag{6}
\]

where \( \text{opt}_v \) is the objective function of antibody \( v \). The affinity has the value between 0 and 1. Moreover, small affinity value presents strong affinity. The N-S flow chart of immune algorithm for inverse prediction of sound insulation to a wall with apertures is shown as Fig. 1.

| Input area of a wall with aperture \( S \) and the sound insulation criterion \( \bar{R} \) |
|---|
| Randomly produce solid sound insulation of the wall \( R_w \) and the area ratio between the wall and the apertures \( \phi \) as initial solution (antigen) |
| Set up sound insulation model to a wall with aperture |
| Recognition of antigen |
| Production of initial antibodies |
| Calculation of sound insulation |
| \( S_1 = (1 - \phi) \cdot S \), \( S_2 = \phi S \cdot \tau = 10^\frac{R_w}{10} \) |
| \( A = S_1 \tau + S_2 \times 1 \cdot \quad B = S_1 + S_2 \) |
| \( T = \frac{A}{S} \cdot \bar{R} = 10 \log_{10} \frac{1}{T} \) |
| Computation of affinities |
| Selecting superior antibodies into memory cells |
| Selecting antibodies into next generation based on \( e_v \) |
| Reproduction of antibodies by mutation and crossover |
| Until Termination is satisfied |

Figure 1. N-S flow chart of calculating sound insulation to a wall with apertures
The probability of an antibody \( v \) will be selected to the next generation is obtained by its expectation rate \( e_v \). Based on the definition of the affinity, \( e_v \) is given by\(^{[4]}\)

\[
e_v = \frac{a_v}{c_v}
\]

(7)

where \( c_v \) is the density of antibody \( v \). \( c_v \) is calculated as the total number of the antibodies, which are considered being similar to antibody \( v \).

To accelerate convergence toward the optimal solution, some antibodies that have high affinities to the antigen are selected into the memory cells and may be used to produce parts of the initial antibodies. Furthermore, in the inverse prediction of sound insulation, the solutions that content some requirements and have an acceptable deviation are needed other than the optimized ones. So the antibodies that satisfied with the requirement at each process also will be stored into the memory cells.

4. Example of Inverse Prediction

Suppose that the area of a wall with aperture is 12m\(^2\), the criterion of sound insulation requirement (weighted sound insulation) of the wall is \( R^* \geq 40 \) dB, and the effect of flank transmission and resonant have not been taken into account. For these reasons, The AIA was set with a population size of \( n=100 \), crossover rate \( p_c = 0.9 \), mutation rate \( p_m = 0.1 \). Due to employing the elitism, the value of the objective function for the best individuals steadily decrease with successive generations, while the affinity between antibody and antigen increase. Results of computation which adequate satisfied with \( R_{1} \rightarrow R_{I} \) are put into memory cell. Actually, after several generations, the results become stable, and additional generations do not provide more optimal solutions.

The distribution of antibodies in memory cell (with the symbol “x”) with \(|\vec{R} - R^*| < 1 \) is shown in Fig. 2, the optimal solution with the symbol “O” corresponds to: the sound insulation of solid wall \( R_w = 42.898 \) dB, the real area of aperture is limited below \( 5.8430 \times 10^{-4} \) m\(^2\); and the best affinity between antibody and antigen in each generation are also given in Fig. 2.

![Figure 2. Antibodies in memory cell and the best affinity between antibody and antigen in each generation to inverse prediction with \(|\vec{R} - R^*| < 1 \).](image-url)
For the sake of achieving higher precision at simulation, the distribution of antibodies in memory cell (with the symbol “x”) with \( |\bar{R} - R| < 0.2 \) is shown in Fig. 3, another optimal solution with the symbol “O” is given in Fig. 3 and listed in Table 1.

**TABLE I. INVERSED PREDICTION OF WEIGHTED INSULATIONS AND LEAK AREA OF WALL WITH APERTURE**

| Criterion of sound insulation requirement (dB) | Sound insulation of the solid wall by inverse prediction (dB) | Area of apertures (m²) |
|-----------------------------------------------|-------------------------------------------------------------|------------------------|
| 40                                            | 57.180                                                      | 0.0012                 |

In inverse prediction practice, it becomes evident as to how to limit the area of aperture to keep appropriate sound insulation in a structure (wall), since the double area of the aperture will require a sound insulation increase of 14.3dB in a wall. In reality, the sound insulation of a wall with apertures mainly depends upon the aperture area. The weighted sound insulation of a masonry wall might hardly attain the lowest design requirement \( (\bar{R}_w \geq 40 \text{ dB}) \), as the aperture area exceeds 0.001% of the wall area.

**TABLE II. COMPARISON BETWEEN INVERSED AND PREDICTED OF A WALL WITH APERTURES**

| Predicted weighted sound insulation \( R_i \) (dB) | Weighted sound insulation by inverse result \( R_d \) (dB) |
|-------------------------------------------------|-------------------------------------------------------|
| 40                                              | 39.918                                                 |

Therefore, the result of the comparison indicates that value of inverse insulation prediction agrees well with the expected sound insulation (design criterion).

**5. Conclusions**

In practice, this is usually not possible when the required sound insulation is fairly high and the wall with apertures; By the calculation, it was found that structural insulation improvement were to be proved inefficient, the total sound insulation lie on the attenuation to the apertures or cracks transmission, and perfect sealing wall can ameliorate essentially the total sound insulation of the room.
Subsequently, artificial immune algorithm is utilized to establish the inverse sound insulation model. The procedure of inverse prediction is consistent with the process of sound insulation design. The results of inverse sound insulation indicated value of inverse insulation prediction agrees well with the expected insulation. Furthermore, the theoretical meaning of inverse prediction is: The area of apertures can be adjusted to ensure that combined sound insulation meets the design requirement. Under the condition of meeting sound insulation requirement, the area allowable value of aperture or hole in a certain area wall which lays for socket or drainage pipe might be determined by inverse prediction.

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