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Optimization and mechanism of acoustic absorption of Alberich coatings on a steel plate in water

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ABSTRACT

The acoustic absorption of Alberich coatings is generally a topic attracting persistent interests. The present paper optimizes acoustic absorption of two types of Alberich coatings on a steel plate immersed in water using a differential evolution algorithm combined with a finite element method. Both the coatings contain cylindrical cavities of mixed sizes. We compare the optimized absorption for different arrangement, i.e., the both coatings on different surfaces or only on the outer surface of the steel plate. The results show that the different coatings on both surfaces of the steel plate can achieve better sound absorption from 1.3 kHz to 10.0 kHz. The power dissipation density and the displacement pattern are used to analyze the broadband absorption mechanism induced by the acoustic resonance and the acoustic coupling between the optimized coatings. The results validate the idea that it can effectively enhance the low-frequency and bandwidth of the absorption by laying different coatings on both surfaces of the steel plate.

1. Introduction

It is important to enhance low-frequency and bandwidth of absorption of a coating for improving acoustic stealth performance of underwater objects [1]. Generally, a rubber layer embedded with periodic arrays of cavities, known as an Alberich coating [2–5], is often used on underwater structures. Other scatterers including locally resonant structures [6–9] and micro scatterers [10,11] may also be embedded in the coatings. Ivansson [12,13] used the layer-multiple-scattering method to analyze the acoustic characteristic of the coating, which contains cylindrical cavities with axes in a lateral direction and in a single period. It showed that the monopole resonant frequency of the cylindrical cavity was lower than that of the spherical cavity with the same radius. Hence compared with spherical cavity, the cylindrical cavity can reduce the coating thickness. Ivansson demonstrated that the rubber layer with cylindrical cavities and superellipsoidal cavities can provide significant reflection reduction from 8 kHz to 22 kHz by mixing cavities with different size. The energy dissipation mechanism of the rubber slab with one layer of cylindrical cavities was analyzed [14,15], and both the physical and structural parameters of the rubber slab were optimized by a genetic algorithm (GA) for favorable absorption from 1.5 kHz to 10 kHz. However, most of the current studies focused on the coating placed on the surface of a rigid or half-infinite steel plate, different coatings on both surfaces of a steel plate immersed in water have less been investigated.

Panigrahi et al. [16] used the finite element method (FEM) to investigate the echo reduction and transmission loss of different coatings on both surfaces of a steel plate. The results showed that both coatings on different or the outer surface of the steel plate could affect the acoustic echo reduction and transmission characteristic, however, the acoustic absorption optimization of different coatings on both surfaces of a steel plate and then the mechanism was not considered.

Inspired by Panigrahi's work, the acoustic absorptions of different Alberich coatings on both surfaces or only outer surface of a steel plate immersed in water are optimized and compared. Here the difference evolution (DE) algorithm [17–19] together with FEM [20,21] are developed for the acoustic absorption optimization. Then the power dissipation density (PDD) and the displacement pattern (DP) are derived to reveal intuitively the broadband absorption mechanism of the acoustic resonance and their coupling between the coatings.

2. Model and optimization method

2.1. Theoretical model

Fig. 1 shows a sketch model of an absorption structure of two coatings on a steel plate (the thickness h_s = 10mm) under the Cartesian coordinate system. There are two arrangements of coatings, i.e., both

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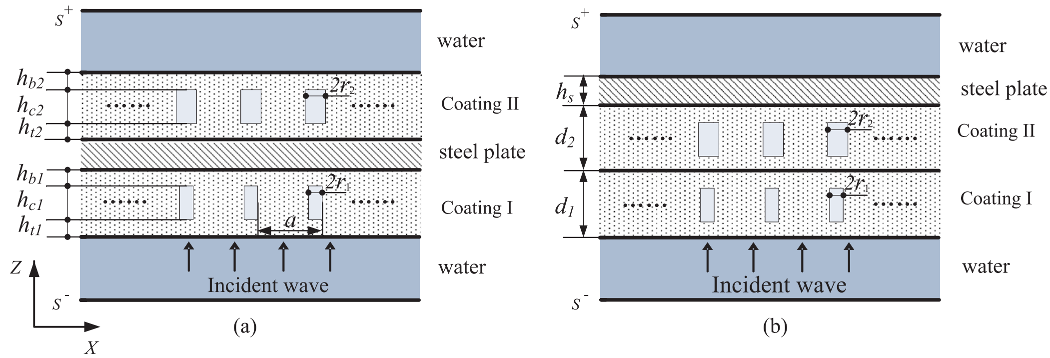

Fig. 1. (a) Coatings on both surfaces of a steel plate (Config. 1), (b) both coatings on outer surface of steel plate (Config. 2).

the coatings on the both surfaces of the steel plate, as shown in Fig. 1a (this configuration is hereafter referred as Config. 1), and both coatings on the outer surface of the steel plate, as shown in Fig. 1b (this configuration is denoted by Config. 2). The whole structure can be considered as a multilayered fluid–solid structure perpendicular to Z-axis. A plane longitudinal incident wave perpendicular to the XY plane is from the semi-infinite water (SIW) and transmits to the other SIW. Both of the SIW domains are cut cross by the surface s^- and s^+ respectively for finite domain analysis. Both Coating I and coating II are made of rubber matrix embedded with single layer cylindrical cavities (the axis is parallel to Z axis) which are arranged infinitely in a quadrate lattice with a grating spacing (or lattice constant) of a_1 in XY plane. The total thickness of the coating I is d_1, the height and the radius of the inner cavities are h_{c1} and r_1 respectively, the distance between the lower surface of cavity and incident surface of coating I is h_{t1} (called the thickness of cover plate), the distance between the upper surface of cavity and transmitted surface of coating I is h_{b1} (the thickness of ground plate). The total thickness of the coating II is d_2, the corresponding height and the radius of the inner cavity are h_{c2} and r_2, the thickness of the cover and the ground plates are h_{t2} and h_{b2}, respectively.

2.2. Optimization method

The absorption coefficient of the coatings is a nonlinear function of the structural and material parameters, so it is difficult to obtain an ideal acoustic absorption by parametric analysis. Here the DE algorithm [17–19] is chosen for multiple objective optimization of Alberich coatings. Compared with traditional optimization methods, DE algorithm has obvious advantage in solving large-scale nonlinear problems. The general process of the DE algorithm is the same as most evolutionary algorithms, including mutation, crossover and selection etc., and the flow chart is shown in Fig. 2.

In DE algorithm the goal is to find a global minimum for all in the search-space. The objective function is defined for the acoustic absorption of the two configurations (in Fig. 1) as

$$F(x) = \max_{f\in[f_1,f_2]} [1-\alpha(f;x)], \tag{1}$$

where $\alpha(f;x)$ is the absorption coefficient of coatings, $x = (x_1, x_2, x_3\cdots\cdots x_n)$ is the n-dimensional parameter vector, where each element represents a specific design variable, including structural and material parameters; $x\in\mathbb{K}$, $\mathbb{K}$ stands for the range of design variable and depends on the application conditions; $[f_1, f_2]$ denotes the design frequency range. The paramount importance is to set the parameters of DE algorithm, in this paper, a population for each generation is set to $8n$ (n denotes the number of design variables), the evolutional generation is set as 20, and it shows a good convergence.

During the acoustic absorption optimization, it uses the FEM [20,21] to calculate of the absorption coefficient of the coatings. Due to the periodicity of structure, we can simplify the absorption analysis of an infinite panel to one unit according to the Bloch theory. The energy reflectance r and transmittance t are respectively calculated on the fluid domain boundaries s^- and s^+ (Fig. 1). For the energy conservation, the absorption coefficient is defined as

$$\alpha = 1-r-t \tag{2}$$

3. Optimal design

3.1. Optimized structural parameters

First of all, the structural parameters of the two configurations in Fig. 1 are optimized for improving the acoustic absorption. The material parameters used in present paper are listed in Table 1. Coating I and coating II use the same matrix rubber. The loss factors of the longitudinal and shear modulus of the rubber are 0.05 and 0.5 respectively. In optimization there are nine parameters, including the lattice constant of coatings and the other structural parameters of the both coatings (including the radius and height of the cavities, the thicknesses of the cover and ground plates). The total thickness of coating I and coating II

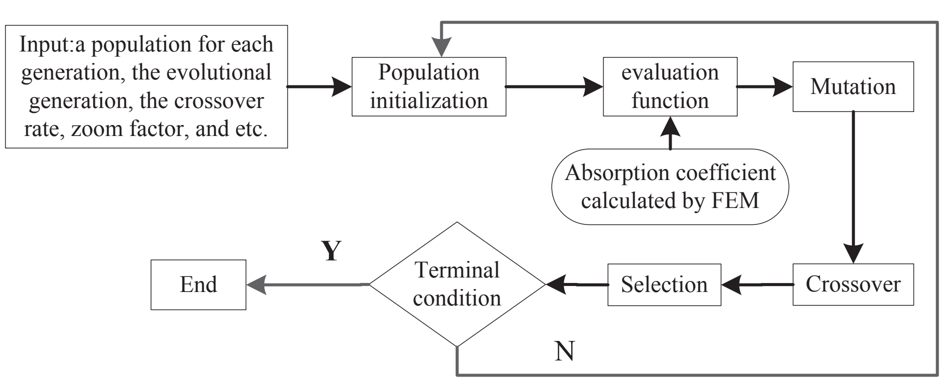

Fig. 2. Scheme of DE algorithm.