Applied Acoustics 129 (2018) 108–115

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Optimization of geometrical parameters for periodical structures applied to floating raft systems by genetic algorithms

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ARTICLE INFO

Article history:
Received 16 June 2017
Received in revised form 13 July 2017
Accepted 18 July 2017
Available online 26 July 2017

Keywords:
Vibration isolation
Periodic structure
Geometric optimization
Genetic algorithms
Floating raft

ABSTRACT

This paper presented a theoretical study of the vibration control of a floating raft system using periodic structures. The band gap properties of the periodic structures, the power flow and the power transmissibility of the floating raft system were investigated by using the transfer matrix method. To minimize the power flow through periodic structures in a floating raft system, the geometrical parameters of the periodic structures were optimized by using a genetic algorithm. The numerical results demonstrated that the optimum periodic structure can provide broader stop band regions. The stop band regions of the optimum periodic structure contained all the harmonic frequencies of the force excitation in the floating raft system. The numerical results validated that the proposed optimization approach is sufficiently capable for the design of periodic structures. The proposed optimization approach has potential use for the development of vibration and shock isolation systems such as floating raft systems.

1. Introduction

The floating raft systems, a kind of two-stage vibration isolation system, have been widely applied to ships and submarines to improve acoustic stealth performances [1,2]. Rotatory machines such as: diesel engines, pumps, and electric generators were installed on floating raft systems. Noise and vibration of rotatory machines were generally dominated by peaks at the rotational frequency, blade pass frequency, and their various harmonics in the frequency spectra. Therefore, in the design of noise and vibration systems, more concerns were focused on these frequencies.

Comprehensive efforts have been made in the investigation of the propagation of waves in periodic structures that consisted of several identical structural components [3–5]. Waves transmitted in periodic structures have shown the existence of stop band and pass band regions in the frequency spectra [6–8]. Sound and vibration were forbidden in the stop bands of infinite periodic structures. This is of interest for applications such as frequency filters, noise absorbers, vibration absorbers, and high-precision mechanical systems [9–13]. Therefore, periodic structures can be applicable to noise and vibration control for their outstanding isolation effectiveness in the stop band regions. The stop band regions can be tailored to match the frequency bands that contained harmonics frequencies of vibration excitations, attenuating noise and vibration in these frequency bands [14]. To decrease power flow and power transmissibility of floating raft systems, periodic structures were introduced to floating raft systems. A genetic algorithm (GA) was utilized to tailor the stop band regions of periodic structures in this study.

GAs are a kind of population-based search and optimization methods that mimic the process of natural evaluation. They have been successfully applied to various optimization problems which are difficult to be solved by conventional methods [15]. GAs have also been applied to a wide range of applications in noise and vibration control area, such as optimization of noise barriers [16], mufflers [17–19], supporting structures [20], and acoustical sandwich panels [21]. GAs have noticeable advantages of handling optimization problems which exist large numbers of parameters, multiple criteria, and parameters in discrete data series. Moreover, GAs are especially capable for optimization problems with many local optimal, which are unreliable for direct optimum methods (i.e. steepest ascent) [22]. The advantages of GAs are especially capable for solving the optimization problem in this study. Therefore, a GA was utilized in the design approach for periodic structures.

2. Theory

As shown in Fig. 1, a floating raft system consisted of five substructures: two identical machines (substructure 1), eight identical isolators (substructure 2), an intermediate raft (substructure 3),

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http://dx.doi.org/10.1016/j.apacoust.2017.07.018

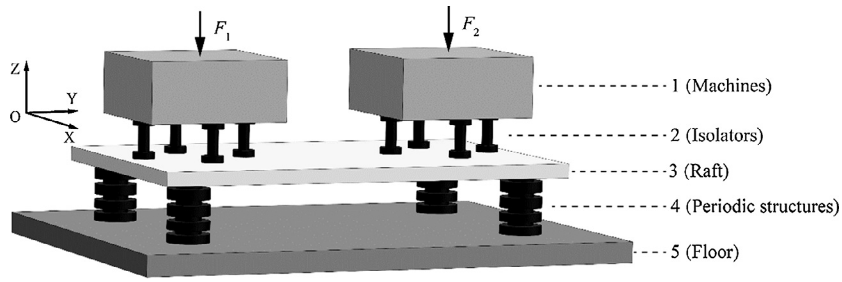

Fig. 1. A schematic diagram of the floating raft system.

four identical periodic structures (substructure 4), and a simply supported flexible floor (structure 5) were considered in this study.

2.1. Model of the periodic structures

It is assumed that each periodic structure in the floating raft consisted of $N1$ unit cells. Each unit cell consisted of $N2$ layers. The one-dimensional (1-D) model of a unit cell is shown in Fig. 2. The transfer matrix method was used to calculate the band gaps and wave transmission characteristics of 1-D periodic structure models because of its simplicity and convenience [23].

The governing equation for the longitudinal wave propagated in the Z direction (as shown in Fig. 2) of the lth layer of a unit cell can be given as

$$\frac{\partial^2 u_l(z,t)}{\partial^2 t} = \frac{E_l}{\rho_l}\frac{\partial^2 u_l(z,t)}{\partial^2 z}, \tag{1}$$

where u_l denotes the displacement of the lth layer in a unit cell, ρ_l and E_l denote the density and Young's modulus of the material of the lth layer, respectively. The solution of Eq. (1) can be written as a superposition of forward and backward travelling waves with a harmonic time dependence

$$u(z,t) = \left[A_+^{(l)} e^{jk_p^{(l)} z} + A_-^{(l)} e^{-jk_p^{(l)} z}\right] \times e^{-jwt}, \tag{2}$$

where j denotes the imaginary unit; w denotes the angular frequency; $A_+^{(l)}$ and $A_+^{(l)}$ denote amplitudes of the forward and backward travelling waves, respectively; $k_p^{(l)} = \sqrt{w^2 \rho_l / E_l}$ denotes the wave number of the longitudinal wave in the lth layer of a unit cell.

The stress can be given as

$$\sigma(z,t) = E_l \frac{\partial u(z,t)}{\partial z}. \tag{3}$$

The transfer mobility model of the lth layer of a unit cell can be given as

$$\begin{bmatrix} u_{l+1} \\ \sigma_{l+1} \end{bmatrix} = \mathbf{TM}_{layer(l)} \begin{bmatrix} u_l \\ \sigma_l \end{bmatrix}, \tag{4}$$

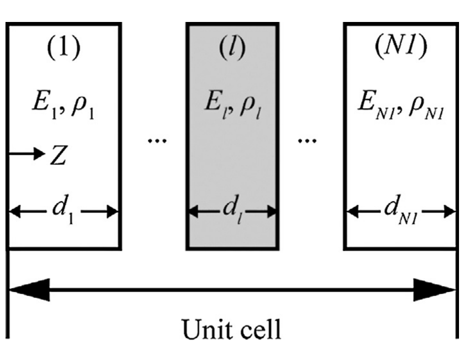

Fig. 2. A schematic diagram of a unit cell in a periodic structure.

$$\mathbf{TM}_{layer(l)} = \begin{bmatrix} \cos\left(k_p^{(l)} l_l\right) & -\frac{\sin(k_p^{(l)} l_l)}{E_l A_l k_p^{(l)}} \\ E_l A_l k_p^{(l)} \sin(k_l l_l) & \cos\left(k_p^{(l)} l_l\right) \end{bmatrix}, \tag{5}$$

where A_l and l_l denotes the cross-sectional area and the thickness of the lth layer.

The transfer mobility matrix between two connected unit cells can be given as

$$\begin{bmatrix} u_{p+1} \\ \sigma_{p+1} \end{bmatrix} = \mathbf{TM}_{cell} \begin{bmatrix} u_p \\ \sigma_p \end{bmatrix}, \tag{6}$$

$$\mathbf{TM}_{cell} = \prod_{l=1}^{N1} \mathbf{TM}_{layer(l)}. \tag{7}$$

The transfer matrix of the periodic structure can be given as

$$\mathbf{TM}_{ps} = (\mathbf{TM}_{cell})^{N2}. \tag{8}$$

The relationship between displacements and stress of two adjacent unit cells can be given as

$$\begin{bmatrix} u_{p+1} \\ \sigma_{p+1} \end{bmatrix} = \lambda \begin{bmatrix} u_p \\ \sigma_p \end{bmatrix}, \tag{9}$$

where $\lambda = e^{\mu} = e^{a+bj}$ denotes the propagation constant. Combining Eqs. (6) and (9), free wave propagated in the periodic structure can be described by the eigenvalue problem

$$\mathbf{TM}_{cell} \begin{bmatrix} u_p \\ \sigma_p \end{bmatrix} = \lambda \begin{bmatrix} u_p \\ \sigma_p \end{bmatrix}, \tag{10}$$

where $\lambda_1 = e^{\mu_1} = e^{a_1+b_1 j}$ and $\lambda_2 = e^{\mu_2} = e^{a_2+b_2 j}$ are eigenvalues of the transfer mobility matrix of a unit cell in the periodic structure. The real parts a_1 and a_2 describe the exponential decay rate of the longitudinal waves, whereas the imaginary parts b_1 and b_2 describe the phase transfer of the longitudinal waves through each unit cell [6]. If $a = 0$, the free waves propagate without attenuation, and the corresponding frequency bands are pass bands. If $a \neq 0$, the free waves propagate with attenuation, and the corresponding frequency bands are stop bands.

2.2. Model of the floating raft system

The transfer matrix models of the five substructures can be given as

$$\begin{Bmatrix} \mathbf{V}_i^t \\ \mathbf{V}_i^b \end{Bmatrix} = \mathbf{M}_i \begin{Bmatrix} \mathbf{F}_i^t \\ \mathbf{F}_i^b \end{Bmatrix} = \begin{bmatrix} \mathbf{m}_{11}^{(i)} & \mathbf{m}_{12}^{(i)} \\ \mathbf{m}_{21}^{(i)} & \mathbf{m}_{22}^{(i)} \end{bmatrix} \begin{Bmatrix} \mathbf{F}_i^t \\ \mathbf{F}_i^b \end{Bmatrix}, \quad i = 1 \sim 5, \tag{11}$$

where $\mathbf{V}_i^t$ and $\mathbf{F}_i^t$ denote the velocity and force vectors at connection points on the top interface of the ith substructure, respectively; $\mathbf{V}_i^b$ and $\mathbf{F}_i^b$ denote the velocity and force vectors at connection points on the bottom interface of the ith substructure, respectively; $\mathbf{M}_i$