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Technical Note

Flexural vibration reduction of hinged periodic beam–foundation systems

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ABSTRACT

The hinged connection and periodic structure are introduced to the classic beam–foundation systems, so called as hinged periodic beam–foundation systems, to reduce the flexural vibrations. The cell-hinged, segment-hinged and identically hinged periodic beam–foundation systems are proposed. The frequency dispersion relation and frequency response of these systems with soil foundation are calculated and analyzed. The study shows that, the existence of hinges helps greatly to obtain lower and wider band gaps (BGs) with stronger attenuation. Finally, a combination beam–foundation system composed by the cell-hinged and identically hinged periodic structures is proposed to obtain super wide BG.

1. Introduction

Lots of harmful vibrations from soil foundation induced by earthquake, blasting, machine, traffic, pile driving, etc. would cause resonance, failure, disturbance of sensitive equipment and discomfort to people [1]. These vibrations generally have low frequency ranges. For example, the frequency range of earthquake is lower than 20 Hz, that of the railway induced vibrations which cause disturbance of sensitive equipment and discomfort to people is 1–80 Hz, while its re-radiated noise has the frequency range of 16–250 Hz [2]. How to effectively eliminate and control these vibrations is the continuously considered problem. Several countermeasures have been presented, such as adjusting the frequency contents of sources [3], adding dampers on sources or structures [4], installing wave barriers on propagation path between sources and receivers [5]. Concerning the wide applications such as railroad tracks [6–8], highway pavements [9–11] and continuously supported pipelines [12–14], how to eliminate the vibrations of beam–foundation systems is a meaningful topic.

In recent years, the phononic crystals (PCs) which have periodically arrayed composite materials have caused much attention [15–18]. Researchers have been attracted mainly because of the existence of band gaps (BGs), within which there can be no propagation of elastic waves in PCs. The feature is of interest for potential applications such as acoustic insulation [15] and vibration control [19,20], etc. The introduction of periodic structures to beam–foundation systems is a possible way to eliminate and control vibrations in such systems, by using the BG properties.

In our previous research [21], the periodic beam–foundation systems from introducing the periodicity into beams are presented. Yu et al. also studied such systems [22]. The results show good BG properties. Note that the relevant studies usually focus on the rigid connected periodic beam–foundation system while the influence of the connection method in beam–foundation system is rarely discussed. We notice that in the two dimensional lattice grids and one dimensional homogeneous beam, the BG range and other properties could be changed with hinged connections, compared with the rigid connected case [23–25]. Thus, we try to introduce the hinged connection and PCs simultaneously into one dimensional case, in order to give more choice for BG design in applications.

The beam–foundation system makes it possible to replace rigid connections into hinges. Because for beam–foundation systems, unlike the normal beam, the support of foundation gives extra constraints, which makes the connection type affect the normal usage of systems little. Replacing the rigid connections by hinges in certain periodic mode supplies a new idea to introduce periodicity into the rigid connected periodic beam–foundation systems or normal beam–foundation systems for vibration elimination and control, following the studies of the common rigid connected periodic beam–foundation system [22,23]. Generally,

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beam–foundation systems could be simplified as the model of beams on elastic foundations. Winkler model [26,27] is an appropriate elastic foundation model and often adopted. The model could describe many structures such as railroad tracks, highway pavements, continuously supported pipelines, by using different foundation parameters.

In this note, we first define three kinds of hinged periodic beam–foundation systems to eliminate and control flexural vibrations. Then the frequency dispersion relation and frequency response of these systems with soil foundation are calculated and analyzed. Finally, from the combination of different hinged structures, a multi-hinged periodic beam–foundation system with super wide BG started from 0 Hz can be proposed conveniently.

2. Models of hinged periodic beam–foundation systems

Fig. 1(a) shows a homogeneous Euler–Bernoulli beam on a Winkler foundation. The length, width and height of the beam are l, b and h. In the Winkler model, only one parameter c is needed to represent the stiffness of foundation [26,27]. Fig. 1(b) shows a cell of the rigid connected periodic beam anchored on a Winkler foundation. The beam consists of an infinite repetition of alternating segment with different material and length arrayed along the x direction. The periodic length is a. Fig. 1(c) shows a similar model as that in Fig. 1(b). The difference is that the former rigid connections between different cells are replaced by hinges. So we get the cell-hinged periodic beam–foundation system. Besides the cell-hinged case, all of the rest rigid connections shown in Fig. 1(c) could also be replaced by hinges. Then we get the segment-hinged periodic beam–foundation system which is shown in Fig. 1(d). Actually, these two hinged beam–foundation systems contain two kinds of periodicities or more, which are the periodicity of material arrangement and the hinged position. If the periodicity of material arrangement is considered only, the rigid connected periodic beam–foundation system is obtained. While we just consider the periodicity of hinged position, we get the identically hinged periodic beam–foundation system, which is shown in Fig. 1(e).

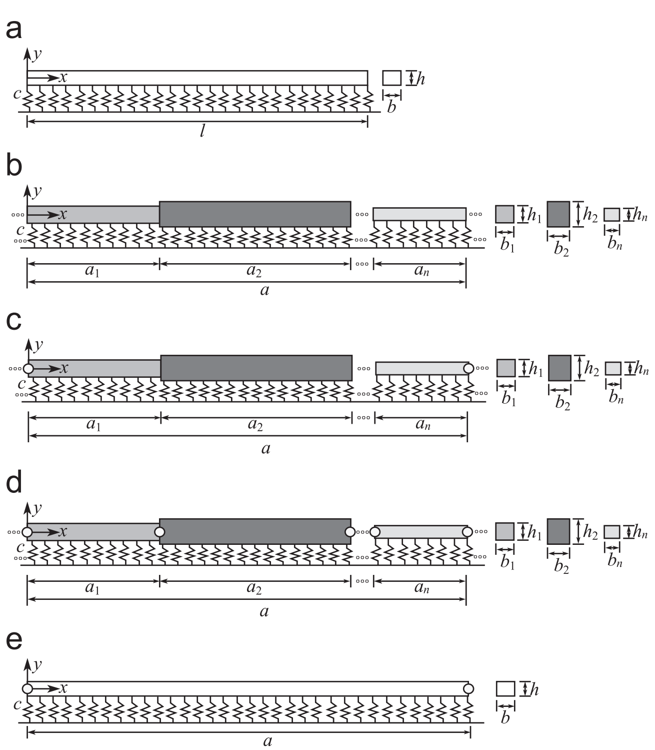

Fig. 1. (a) A homogeneous beam on a Winkler foundation. The cells of (b) the rigid connected, (c) cell-hinged, (d) segment-hinged and (e) identically hinged periodic beam–foundation systems.

Based on the transfer matrix method for the calculation of the frequency dispersion relation of the rigid connected periodic beam–foundation system [21,28], at each cross-section, the rigid connected case has four degrees of freedom (DOFs), which are the amplitude of the displacement $\nu(x)$, rotation angle $\theta(x)$, flexural moment $M(x)$ and shear force $Q(x)$. The general transfer relation can be written as

$$\mathbf{F}(a) = \mathbf{T}\mathbf{F}(0), \tag{1}$$

where $\mathbf{F}(x)=[\nu(a)\ \theta(a)\ M(a)\ Q(a)]^{\mathrm{T}}$, $\mathbf{F}(0)=[\nu(0)\ \theta(0)\ M(0)\ Q(0)]^{\mathrm{T}}$.

However, the flexural moment could not pass over a hinge and the rotation angles of the beams around a hinge are also not continuous anymore. So the DOFs become to just the displacement and shear force, for the hinged beam–foundation systems. Applying these two conditions, the transfer relation can be rewritten as

$$\mathbf{F}'(a) = \mathbf{T}'\mathbf{F}'(0), \tag{2}$$

where $\mathbf{F}'(x)=[\nu(a)\ Q(a)]^{\mathrm{T}}$, $\mathbf{F}'(0)=[\nu(0)\ Q(0)]^{\mathrm{T}}$.

The fourth-order eigenvalue problem which contains the dispersion relation of the rigid connected periodic beam–foundation system could be easily changed to the second-order eigenvalue problems which contain the dispersion relations of the cell hinged, segment-hinged and identically hinged periodic beam–foundation systems, after using the Bloch's theorem [25].

3. Results and discussion

3.1. Band gaps

We consider the periodic beam constructed from aluminum and epoxy resin on a Winkler foundation with the stiffness of $25.0 \times 10^6\ \mathrm{N/m^3}$ which could represent a soil foundation. The periodic length $a=0.15$ m. The geometrical parameters of the aluminum segment and epoxy resin segment in a cell are the same. The length and cross-section size of each homogeneous segment are 0.075 m and 0.01 m × 0.01 m respectively. So we can analyze the rigid connected, cell-hinged and segment-hinged cases. Then, we consider the aluminum beam–foundation system with the same cross-section size and lattice constant to analyze the identically hinged case. The density and elastic modulus of aluminum are $\rho_{\mathrm{Al}}=2730\ \mathrm{kg/m^3}$, $E_{\mathrm{Al}}=7.76 \times 10^{10}$ Pa, and these of epoxy resin are $\rho_{\mathrm{Ep}}=1180\ \mathrm{kg/m^3}$, $E_{\mathrm{Ep}}=4.35 \times 10^9$ Pa.

The frequency dispersion relations of flexural vibrations in the range of 0–3200 Hz for the four cases are shown in Fig. 2. The wave number $k \in [-2\pi/a, 2\pi/a]$. For the rigid connected case, there are three BGs, which are 0–180.0 Hz, 440.9–600.8 Hz and 1752.2–3023.5 Hz. For the cell-hinged case, there are also three BGs, which are 0–179.2 Hz, 179.8–479.6 Hz and 917.7–2561.9 Hz. For the segment-hinged case, there are four BGs, which are 0–164.5 Hz, 179.8–180.0 Hz, 200.0–1765.5 Hz and 2107.1–3200.0 Hz. For the identically hinged case, there are two BGs, which are 0–1085.3 Hz and 2440.4–3200.0 Hz.

We also calculate the frequency response of the flexural vibration for the 6-cell periodic structures of the four cases based on the finite element method, which is also shown in Fig. 2, to verify the theoretical results. We apply the harmonic displacement impulse which sweeps over 0–3200 Hz to one end of the beam, and then get the frequency response at the other end. The distinct attenuation frequency ranges correspond to the BGs. The rigid connected, cell-hinged and segment-hinged cases all give three BGs. For the rigid connected case, they are 0–184.9 Hz, 411.7–591.9 Hz and 1686.9–2984.8 Hz. For the cell-hinged case, they are