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Structure damage localization of the slab track by adding virtual masses

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Abstract

In this paper, a damage localization method based on additional virtual mass and dynamic test of simple harmonic excitation is proposed. Firstly, when additional masses are added to the structure, a large number of virtual structures can be constructed; then the virtual construction formula is derived in order to obtain the dynamic response of virtual structures without adding real mass. After dynamic test of simple harmonic excitation, the dynamic response of virtual structures can be obtained using the acceleration response and virtual construction formula. Furthermore, when the applied harmonic excitation frequency is close to the natural frequency of the structure, the structural response can reach a maximum by adding advisable mass and the mass value can be calculated. When the local structure is damaged, the extreme value and the corresponding position of the additional mass are found by adding mass at different positions in the structure. Thus, the approximate location of the damage is determined according to the results. Finally, the numerical simulation of the elastic foundation beam model simplified by track structure is carried out, and the results show that the damage can be localized.

Keywords: structural health monitoring, damage identification, slab track, virtual mass

1 Introduction

Structural health monitoring (SHM) is an effective way to realize the fast warning and then to ensure the structural safety (An et al. 2017). Structural damage identification is one of the most important parts and foci of SHM. The dynamic response of the structure is the basic dynamic information of the structure. When the structure is damaged, the dynamic response will also change. At present, the damage identification method based on dynamic information is widely used. It is often identified with structure mode (frequency and mode shape) (Zhou et al, 2013), flexibility matrix (Duan et al, 2005), time domain response (Kolakowski et al, 2008) and frequency response (Lin and Zhu, 2006). However, it takes a lot of energy to get much dynamic information though dynamic tests, which is time consuming and inconvenient.

Aiming at the problem that the dynamic information is not enough, Nalitolela et al. (1992) presented a model updating method by adding physical masses or stiffeners on the structure and utilizing modal information of the perturbed structures. Cha and de Pillis (2001) added known physical masses to the structure and then identify damage using the orthogonal conditions of the system eigenvalue problem. Dems and Mróz (2010) identified the damage using additional control parameters such as mass, support, load or thermal loading combined with modal, static and thermographic analysis. Dinh et al. (2012) improved the structural parameter identification method using the state-space transformation of the eigenvalue problem. Deng et al. (2013) updated the finite element model of the fixed-free beam by adding a series of known masses and the updated results is consistent with the experience.

However, there are some difficulties in adding real mass, such as oversized mass value, limited operating space and installation difficulty. Based on the above all, the method of additional virtual mass (Hou et al. 2013) was proposed and validated by numerical simulation. It can realize that the frequency response after adding virtual mass can be obtained according to the force and acceleration frequency response measured.

The remainder of this paper is organized as follows. The second section provides the proposed damage identification method. The third section describes the numerical research object. The fourth section describes the numerical simulation of the elastic foundation beam model simplified by track structure. The final section gives the conclusions.

2 The additional virtual mass method

Assuming that the mass, damping and stiffness matrix of the undamaged structure are $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ respectively, if an additional mass is applied to a substructure of the original structure and the motion equation of the modified structure model in the frequency domain can be expressed as:

$$(\boldsymbol{M}+\Delta\boldsymbol{M})\ddot{\boldsymbol{X}}^{V}(\omega)+\boldsymbol{C}\dot{\boldsymbol{X}}^{V}(\omega)+\boldsymbol{K}\boldsymbol{X}^{V}(\omega)=\boldsymbol{B}\boldsymbol{F}(\omega) \tag{1}$$

After measuring the response of the corresponding degree of freedom (Dof) of the structure, Eq. (2) can be obtained as follow and the detailed process of derivation can be found in the previous work (Hou et al. 2013):

$$H_{pp}(\omega,m)=\frac{Y(\omega)}{F(\omega)+mY(\omega)} \tag{2}$$

where $H_{pp}(\omega,m)$ is the acceleration frequency response of the substructure when the virtual mass is added on the p-th Dof; $Y(\omega)$ and $F(\omega)$ are the frequency domain response and excitation of the structure, which are obtained by the Fourier transforms of the measured time domain response $a(t)$ and structural excitation $f(t)$ of the real structure respectively. For each additional mass m, the response of the corresponding virtual structure can be calculated using Eq.(2) based on the measured excitation and response of the real structure.

3 The numerical research object

With the rapid development of high-speed railway in China, the slab track structure has been widely applied.The slab track structure is mainly composed of rail, fastener system, track slab, CA mortar and concrete supporting layer. When the slab track structure components are connected reliably as a whole, the track structure can be simplified to an elastic foundation beam model (Figure 1). According to the physical parameters of each part in the slab track structure, the physical parameters of the composite beam are calculated by the theory of material mechanics. Finally, the physical parameters' values of the elastic foundation beam model are shown in Table 1. The length of track structure model should be discussed emphatically here. As the track structure can be considered infinitely long, the boundary condition of the original structure is changed when only part of it is intercepted and analyzed. When the model length is different, it will lead to the change of natural frequency and other structural dynamic information. In order to reduce the influence of boundary condition, the model length of this paper is as long as 48m. However, only half of the middle length is analyzed in damage identification,which makes the model close to the actual structure as much as possible. At last, the damage of foundation is simulated by reducing the spring stiffness.

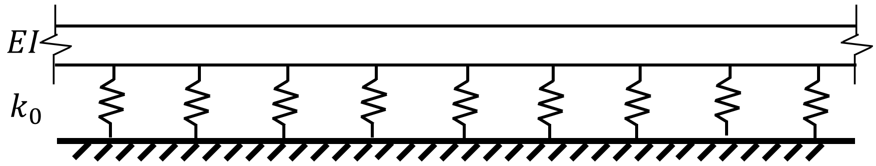

Figure 1. The elastic foundation beam model

Table 1: The physical parameters of the elastic foundation beam model

physical parameter	E(GPa)	A(m^2)	I(m^4)	ρ(kg/m^3)	k(MPa/m)
value	32.78	1.71	0.563	2500	76

4 Damage identification in numerical simulation

The elastic foundation beam model is established by MATLAB, and it is divided into 200 elements. After calculating, the first four order frequencies of the undamaged model can be obtained as follows: f_1=15.66Hz;f_2=16.59Hz;f_3=20.13Hz;f_4=27.48Hz . In this paper, the first order frequency is selected to identify the damage. The damage factor of the track structure is μ , which represents the ratio of residual stiffness to original stiffness after damage.

When the frequency of the harmonic excitation is determined, the frequency response function (FRF) and the acceleration response of the damaged structure can be obtained. Then the response of the damaged structure with additional virtual mass can be constructed by Eq. (2). Therefore, when different masses are added to one position on the model, the curve of additional mass values and the response of virtual structure is displayed in order to find the mass value when the response is maximum. This step can be carried out for every position along the structure to be analyzed, and corresponding mass value of every position is got. Eventually, the relationship between the location and the mass value of additional virtual mass is illustrated by a figure. When the mass is added to the damaged location, the additional mass value will be minimum at this time. Therefore, the position where the additional mass value is the minimum is the approximate position of the damage.

4.1. Damage case 1: single damage

Assuming that only one spring has stiffness reduction of 40%, the damage factor μ is 0.6. Moreover, the location of the damage is the spring at the node of 80. The frequency of harmonic excitation is selected according to the frequency of damaged model. Here, $f_s = 14.8\text{Hz}$.

According to the results of numerical simulation, the curve of additional mass values and the response of virtual structure is shown in Figure 2 as an example. Here, the masses of different values are added at the node of 60. In addition, the curve between the location and the mass value of additional virtual mass is shown in Figure 3. It can be seen from the figure that the minimum of the mass is about located at the node of 80 which is same as the location of the damage.

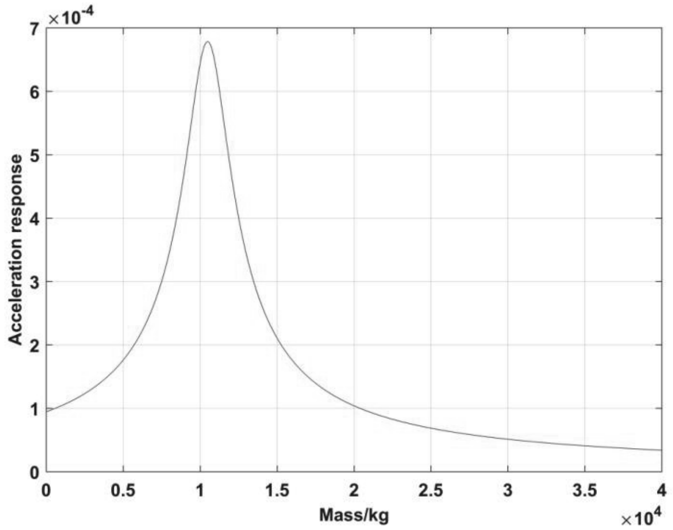

Figure 2. The curve of additional mass values and the response of virtual structure at node of 60

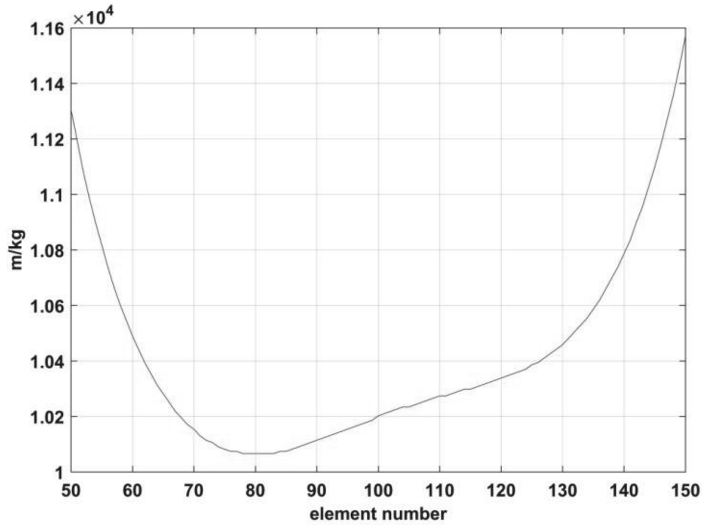

Figure 3. The curve between the location and the mass value of additional virtual mass

4.2. Damage case 2: multiple damage

Assuming that the springs in a certain length are damaged with stiffness reduction of 30%, the damage factor μ is 0.7 for each spring. Moreover, the location of the damage is the spring at the node of 120~130. The frequency of harmonic excitation is selected according to the frequency of damaged model. Here, $f_s = 14.8\text{Hz}$. This damage case is able to simulate the separation of track structure and foundation.

Similarly, according to the results of numerical simulation, the curve between the location and the mass value of additional virtual mass is shown in Figure 4. It can be seen from the figure that the minimum of the mass is about located at the node of 125, which is the middle of damage length. Compared with the damage case 1, the ordinate range of the curve is bigger and the curve is steeper at the extreme value. So, the location of the damage is more obvious. However, this method can only identify the range of damage, and can not accurately identify the boundaries of damage.

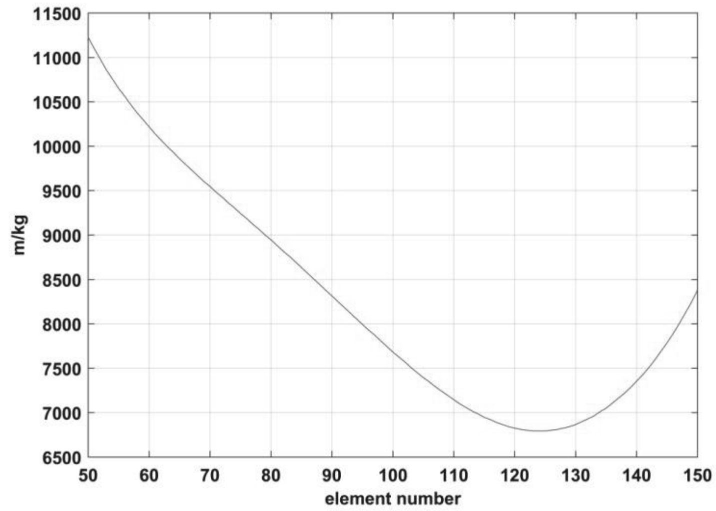

Figure 4. The curve between the location and the mass value of additional virtual mass under damage case 2

5 Conclusions

In this paper, a damage localization method based on additional virtual mass and dynamic test of simple harmonic excitation is proposed. The numerical simulation of the elastic foundation beam model simplified by track structure is carried out. The conclusions are as follows:

1) The virtual structure is easy to construct and calculate compared with adding real masses to the original structure.

2) The method proposed in this paper can be realized only with an excitation and an acceleration response measured.

3) The method can identify single damage and multiple damage of elastic foundation beam, and locate the damage approximately.

In general, the method proposed in this paper can quickly obtain multiple groups of virtual structure response with the measured dynamic information. And the damage is located according to the value of additional virtual mass. Finally, it is verified with two damage cases by numerical simulation. Besides, the elastic foundation beam model can be used to simulate the damage between track structure and foundation, which has practicability to a certain extent. However, the accuracy of this method needs improvement.

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