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Substructure isolation and damage identification using free responses

HOU JiLin[1], JANKOWSKI Łukasz[2] & OU JinPing[1,3*]

[1] School of Civil Engineering, Dalian University of Technology, Dalian, 116024, China;
[2] Smart-Tech Centre, Institute of Fundamental Technological Research Polish Academy of Sciences, Warsaw, Poland;
[3] School of Civil Engineering, Harbin Institute of Technology, Harbin, China

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Structural health monitoring (SHM) has become a hot and intensively researched field in civil engineering. Thereinto, damage identification play an important role in maintaining structural integrity and safety. Many effective methods have been proposed for damage identification. However, accurate global identification of large real-world structures is not easy due to their complex and often unknown boundary conditions, nonlinear components, insensitivity of global response to localized damages, etc. Furthermore, global identification often requires lots of sensors and involves large number of unknowns. This is costly, rarely feasible in practice, and usually yields severely ill-conditioned identification problems. Substructuring approach is a possible solution: substructuring methods can focus on local small substructures; they need only a few sensors placed on the substructure and yield smaller and numerically much more feasible identification problems. This paper proposed an improved substructure method using local free response for substructure damage identification. The virtual supports are constructed by Substructure Isolation Method (SIM) using the linear combination of the substructural responses. The influence of the global errors is isolated by adding the virtual supports on the main degree of freedoms (DOFs) of the substructure. Through the correlation analysis, the substructural modes are selected and used for damage identification of the substructure. A plain model of cable stayed bridge is used for the verification of the proposed method.

structural health monitoring (SHM), damage identification, substructure, cable stayed bridge, free response

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1 Introduction

As an important part in structural health monitoring, structural damage identification [1,2] provides reliable theoretical guidance for the assessment of the structural health and safety. Currently, related studies mainly employed the structural dynamic information-based damage identification method [3,4]. Such damage identification method can directly analyze the change of signal characteristic parameters using signal processing methods, such as wavelet analysis and Hilbert-Huang transformation (HHT) [5]. Besides, it can also realize the damage identification by optimizing the parameters of finite element model (FEM) using the information such as structure mode (frequency and mode shape) [6], flexibility matrix [7], time domain response [8] and frequency response [9], stress spectrum [10,11] and displacement [12]. At present, structural damage identification method has been profoundly studied. However, since civil engineering structures are large and complex, the damage of the global structure can't be easily and accurately identified especially when only a few sensors are arranged.

*Corresponding author (email: oujinping@dlut.edu.cn)

In civil engineering structures, multiple parameters are required to be identified and the dynamic information actually measured by the sensors are limited. Therefore, the accurate identification on structural damage was restricted. Such restriction can be effectively solved by substructuring method [13] or changing the structure via modifying the stiffness or mass. The damage of the structure is identified using modal perturbation after adding mass or stiffness to the structure [14]. Known mass [15] is added to the structure and conducted damage identification using the orthogonal property of structure eigenvalue. However, mass and stiffness components were difficult to be installed to the large complex structures in civil engineering.

SIM [16] can effectively change the structure forms. It is capable of isolating the substructures from the global structure by constructing virtual supports through linearly combining the dynamic response of local structure. In the present study, substructure isolated method is improved using free response by considering that sensors could be constructed into virtual supports, which can be applied to analyze the complicated substructures. Then the improved method is introduced using plane cable-stayed bridge model. According to the characteristics of cable-stayed bridge model, each bridge tower and corresponding beam are taken as a substructure. Virtual supports are constructed on the main degree of freedoms (DOFs) of the boundary of substructure to reduce the influences of the global structure on the substructures. The accurate structural damage identification is performed finally.

2 SIM

2.1 SIM

For substructure isolation, a key equation, the constraining equation of isolated substructure, is shown as eq. (1). This equation has been detailed deduced in previous study [16]. Thus in this study, the deduction process will not be repeated. In the following, we simply introduce the construction process of each matrix in the equation

$$\boldsymbol{D}_s=\boldsymbol{D}-\boldsymbol{C}\boldsymbol{A}^{+}\boldsymbol{B}. \tag{1}$$

Assuming that substructure boundary has n DOFs, thus n sensors are needed to be placed on the boundary of the substructure; in addition, l sensors are placed in the interior of the substructure. The excitation applied on the boundary or the outside of the substructure are defined as constraining excitation. Since substructure boundary contains n DOFs, n groups of different constraining excitations are required to be applied on the boundary or outside of the substructure (the differences refer to different excitation positions or directions). Under the ith group impulse excitation, denote by $\boldsymbol{a}_{ji}$ the corresponding impulse response of the jth sensor on the boundary of the substructure; denote by $\boldsymbol{c}_{ki}$ the impulse response of the kth sensor in the interior of substructure; $\boldsymbol{a}_{ji}$ and $\boldsymbol{c}_{ki}$ are defined as "constraining response". Usually, the constraining response is mainly used to constrain the boundary response of the substructure. If w is the sampling time point, $\boldsymbol{a}_{ji}$ and $\boldsymbol{c}_{ki}$ are w dimensional column vectors. Constraining response $\boldsymbol{a}_{ji}$ and $\boldsymbol{c}_{ki}$ (i,j=1,2, $\cdots$,n; k= 1,2, $\cdots$,l) are arranged as the impulse response matrixes ($\boldsymbol{A}$ and $\boldsymbol{C}$) respectively. Thus $\boldsymbol{A}$ and $\boldsymbol{C}$ are "constraining response matrix", where $\boldsymbol{A}=[\boldsymbol{A}_{ji}]$, $\boldsymbol{C}=[\boldsymbol{C}_{ki}]$; $\boldsymbol{A}$ is a nw dimensional square matrix; $\boldsymbol{C}$ is the matrix of row lw and column nw; $\boldsymbol{A}_{ji}$ and $\boldsymbol{C}_{ki}$ are w dimensional matrix as well as an impulse response matrix. Figure 1 shows the construction form of impulse response matrix $\boldsymbol{A}_{ji}$. Namely, $\boldsymbol{A}_{ji}$ *is* constructed by delaying the arrangement of impulse response a_{ji}. Therefore, constraining response matrix is a block matrix composed by Toeplitz matrix. Similarly, matrix $\boldsymbol{C}$ can also be constructed.

The excitation applied to the interior of substructure is defined as "basic excitation"; m groups of different basic excitations are applied to the interior of substructure; the jth group of excitation is noted as $\boldsymbol{f}_j$; under excitation $\boldsymbol{f}_j$, the responses of n sensors on the substructure boundary is recorded as $\boldsymbol{b}_j$, and the responses of the l sensors in the interior of the substructure is noted as $\boldsymbol{d}_j$. $\boldsymbol{b}_j$ and $\boldsymbol{d}_j$ are defined as "basic response". Meanwhile, $\boldsymbol{b}_j$ and $\boldsymbol{d}_j$ are nw and lw dimensional column vectors of the responses measured by the sensors in corresponding boundary and the interior of substructure arranged according to the order of the number of sensors. The matrix $\boldsymbol{B}=[\boldsymbol{b}_1,\boldsymbol{b}_2,\cdots,\boldsymbol{b}_m]$ and $\boldsymbol{D}=[\boldsymbol{d}_1,\boldsymbol{d}_2,\cdots,\boldsymbol{d}_m]$ constructed by basic responses $\boldsymbol{b}_j$ and $\boldsymbol{d}_j$ are "basic response matrix" , where $\boldsymbol{B}$ is the matrix of nw row and m column, $\boldsymbol{D}$ is the matrix of lw row and m column. Basic response matrix is mainly designed to obtain the information that reflects the basic dynamic characteristics of substructure.

Substituting matrix $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ into constraining eq. (1), the matrix $\boldsymbol{D}_s$ obtained is the response of the isolated substructure. In matrix $\boldsymbol{D}_s$, the response $\boldsymbol{d}_{s,j}$ of the *jth* column is equivalent to the response of the *jth* sensor in the interior of virtual isolated substructure to the basic excitation $\boldsymbol{f}_j$. Then basing on the characteristics of excitation $\boldsymbol{f}_j$, the damage identification of the substructure can be realized using the isolated substructure model and suitable optimization method.

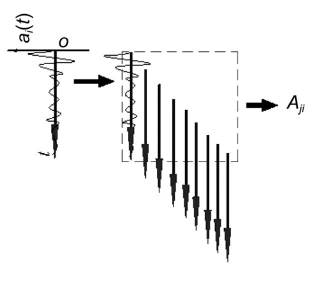

Figure 1 Impulse responses matrix.

2.2 The SIM method based on free response

The accurate construction of isolated substructure requires a strong irrelevance between constraining response and basic response. For the current SIM method using impulse response, the excitation positions regard to each group of response are different. Therefore, the irrelevance between all sets of response is ensured. In the SIM method based on time series response, the excitation needs to be applied to the exterior of substructure to keep the irrelevance of responses. However, to utilize the SIM method to the large civil engineering structures, two problems are presented as follows.

1) Excitation. The method of applying excitation commonly used in real engineering includes artificial excitation (modal force hammer), ambient excitation and free response. Generally, modal force hammer can merely excite the response of local structure. However, when substructure is complex or large, the response cannot be excited; ambient excitation shows effect on almost all over the global structure, including the substructure. Thus the requirement in the time series method, that is, excitation cannot be presented in the interior of substructure, is unable to be satisfied; although free response meets the requirement above, the sections of free response show strong correlations. Thus free response is rarely used to construct isolated substructure.

2) Virtual support. The responses of all DOFs on the boundary of the substructure need to be monitored when using SIM method. However, when the substructure boundary is complex or certain DOFs are hard to be measured, the virtual supports for isolating the substructure can hardly be constructed.

To solve the problems above, SIM method is improved as follows:

1) Substructure boundary. Since the response of substructure needs to be monitored when using SIM method, substructure division position should be set on the positions with weak structural stiffness or simple connection forms as far as possible.

2) Virtual support. When substructure boundary is complex or some DOFs cannot be easily measured, virtual supports are mainly placed on the directions of the main DOFs of substructure boundary. In such way, the connection between global structure and substructure is weakened and the accuracy of substructure identification can be improved.

3) Constraining response. The responses obtained by exciting substructure boundary using modal force hammer are taken as constraining response. Since substructure boundary is located in the positions with weak stiffness, modal force hammer can excite the vibrations near substructure boundary. The initial state of the constraining response is zero here. Constraint matrixes ***A*** and ***C*** are block lower triangular matrixes. Their arrangement form can be found in previous study [错误!未定义书签。].

4) Basic response. Free response is taken as basic response. However, it can be known from eq. (1) that the boundary response of the basic response is limited as zero using the linear combinations of constraining response when using SIM method. Since the initial state of constraining response is zero, the response of substructure boundary of the basic response at initial time point is also required to be zero. Generally, free response can't ensure that all boundary responses of substructure measured at certain time point are zero. Therefore, the boundary response at the initial time point is made to be zero through linearly combining several groups of free responses. Then the responses experiencing linear combination can be taken as basic responses. It should be noted that the response at initial time point is zero does not mean that the initial state of structure is zero, but means that the response at time point of zero is just be zero.

To sum up, in the present study, the free response of the global structure is taken as basic response; the response of the substructure boundary excited by modal force hammer is used as constraining response; virtual supports are arranged on the directions of the main DOFs of the substructure boundary to relieve the effect caused by the global structure to substructures. Substructure damage identification is thereby realized. In the following section, a numerical simulation is used to explain the proposed method via a simplified plane cable-stayed bridge model.

3 Numerical example

3.1 FEM of cable-stayed bridge

Figure 2 shows the simplified plane FEM model of a cable-stayed bridge. This model is composed by three main towers with respective height of 17, 21 and 17 m, and four spanned beams with respective length of 21, 56, 56 and 21 m. The flexural stiffness of the main beam is 1.333×10^8 N/m^2, the axial stiffness is 1.600×10^9 N, line mass is 2.650×10^3 kg/m; the flexural stiffness of the three main towers are 2.000×10^9 N/m^2, axial stiffness is 2.400×10^{10} N, line mass is 3.975×10^4 kg/m; the axial stiffness the cable is 8.2467 N/m^2, line mass is 2.4819 kg/m. The natural frequencies of the first 6 orders of the cable-stayed bridge are shown in Table 1.

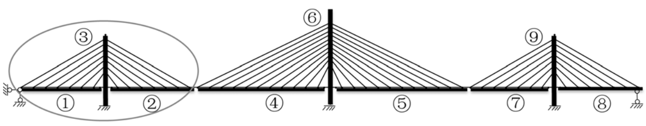

Figure 2 Numbering.

Table 1 The identified natural frequency (Hz)

Order	1	2	3	4	5	6
Natural frequency	0.251	0.354	0.418	0.501	0.522	0.748

The cables of the cable-stayed bridge show obvious substructure characteristics. In general, such substructure characteristics can be identified using the dynamic information of each cable independently. Thus in the present study, the parameters of the cables are assumed to be known, and only the damages on main tower and main beam are to be identified. The whole bridge is divided into 9 parts. The numbers of the 9 parts are shown in Figure 2. Figure 3 shows the assumed damage extent of each part. The left spanned main tower in Figure 2 is determined as the substructure needed to be identified. And the first three damage extents are set as the parameters required to be identified.

3.2 The analysis of substructural modes

To isolate substructure, virtual supports are constructed by limiting the response of the sensor on the boundary to be zero. In Figure 2, the boundary of substructure presents three DOFs, namely, vertical displacement, horizontal displacement, and rotational displacement. However, the DOF of rotational displacement is difficult to be measured or measurement accuracy is low. Thus substructure cannot be easily isolated from the global structure. In such situation, virtual supports are installed at the directions of the main DOFs of substructure boundary. The influences brought by the global error structure to substructure are thereby weakened and damage identification is realized finally. Since vertical acceleration is the main vibration mode of the bridge, the virtual supports are constructed using the method, see Figure 4. The two vertical supports limit the vertical displacement of substructure boundary. Meanwhile, the rotational displacement is also limited to some extent. Because of that substructure cannot be completely isolated from the global structure using virtual supports, the model of the global structure should still be used in the mode calculation of the structure. Figure 5 shows the first 4 orders modes of the FEM model with the virtual supports (Figure 4).

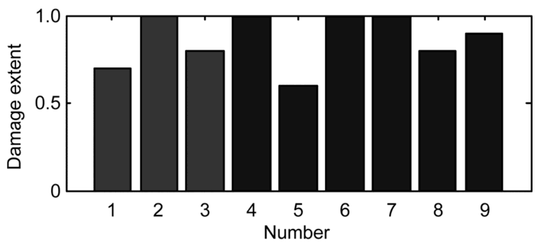

Figure 3 The damage extent.

As shown in Figure 5, virtual supports effectively separate the substructure mode from other modes of the structure. The 3rd-order mode shape in the modes of first 6 orders mainly concentrates on the modes of substructure vibration, while the 1st, 2nd, 4th, 5th, 6th order mode shapes mainly present modes of outside of the substructure. Since the identification on the substructure demands the modes that mainly focus on substructure vibration, only the 3rd-order mode in the first 6 orders modes can be used in the damage identification of the substructure. Furthermore, the proportion of the mode energy of the substructure should be judged according to eq. (2) to select the mode

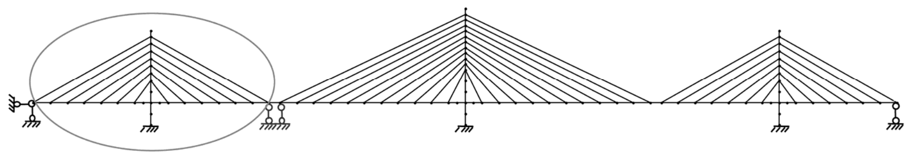

Figure 4 The virtual supports.

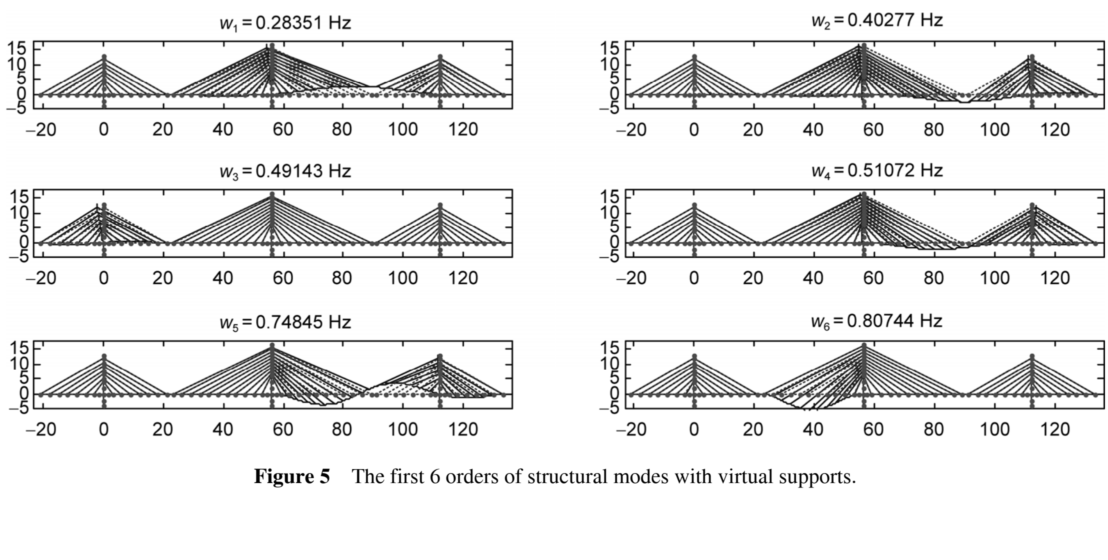

Figure 5 The first 6 orders of structural modes with virtual supports.

mainly concentrating on substructure vibration. In eq. (2), γ_i refers to the proportion of the energy of the substructure of the ith-order mode; φ_i is the mode of the ith-order structure; $\varphi_{s,i}$ represents the mode of the corresponding substructure in ith-order mode φ_i. The proportions of the substructure energy of the first 25 orders modes of the undamaged model in the energy of the whole mode are calculated using eq. (2), as shown in Figure 6. When γ_i is greater than 0.5 (Figure 6), it is considered that energy of mode φ_i mainly focuses on local substructure. The modes that mainly concentrate on substructure energy are extracted. The first 6 orders of extracted substructural modes are shown in Figure 7.

$$\gamma_i = \frac{\begin{bmatrix}\varphi_{s,i}^T & 0\end{bmatrix} K\varphi_i}{\varphi_i^T K\varphi_i}. \tag{2}$$

3.3 Basic response and free response

3.3.1 Placement of sensors

The placement of the sensors is shown in Figure 8. Two acceleration sensors are arranged on two vertical DOFs of the boundary of substructure and numbered as 1 and 2; in the interior of the substructure, 3 acceleration sensors are placed and numbered as 3, 4 and 5 respectively. Two of them are placed on the main beam and one is placed on the main tower.

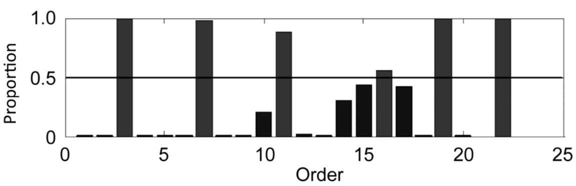

Figure 6 The proportion of substrucutural modal energy.

3.3.2 Basic response

The bridge structure is applied with moving loads. Due to the roughness of the road surface, the bridge is in free vibration when the moving loads are away. Then a section of free response is selected. Considering the effect of 5% Gaussian white noise, this free response section is denoised using wavelet method. The denoised response was shown in Figure 9. The sampling frequency is 1000 Hz.

Two sensors are placed on the boundary of the substructure. Since basic response require the initial boundary response of the substructure to be zero, three sections of response are selected from the measured response in Figure 9. The time range of the three response sections are [0.06, 10.06], [0.50, 10.50] and [0.85, 10.85] respectively. The original value of the response of the two sensors on the boundary of the first substructure section is [2.0594×10^{-1}, 2.2488×10^{-1}], while that of the second and the third substructure section are [1.2254×10^{-1}, 1.4028×10^{-1}] and [3.4252×10^{-2}, -6.9386×10^{-2}] respectively. The three groups of original values are then linearly combined. When combination coefficient is [1, −1.7814, -3.6045×10^{-1}], substructure boundary combination results in zero. When the response of the 5 sensors regard to the three response sections are combined by coefficient of [1, −1.7814, -3.6045×10^{-1}], the boundary response (Figure 10) and internal response (Figure 11) of substructure after combined could

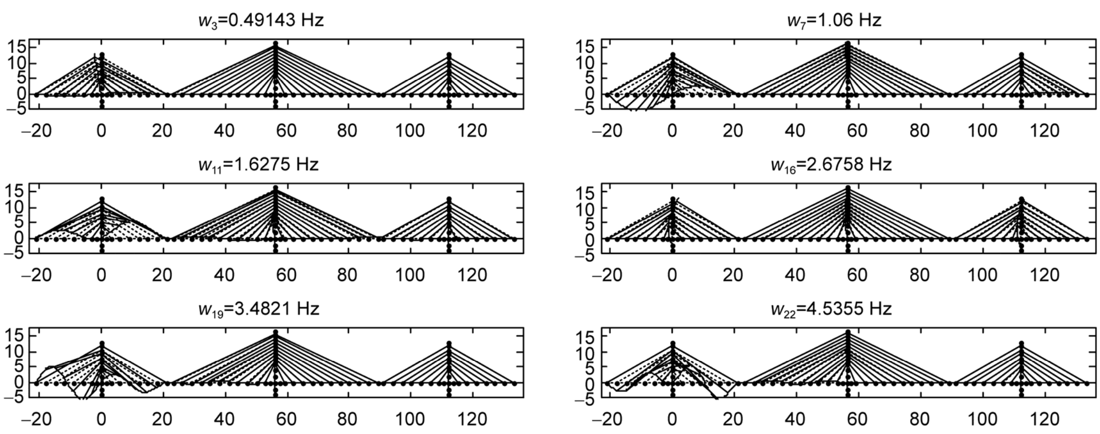

Figure 7 The first 6 structural domain mode with virtual supports.

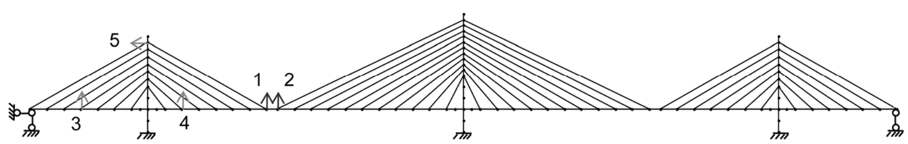

Figure 8 Sensor placement.

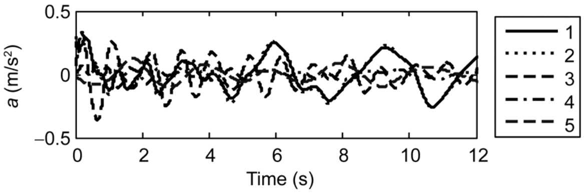

Figure 9 The denoised free response.

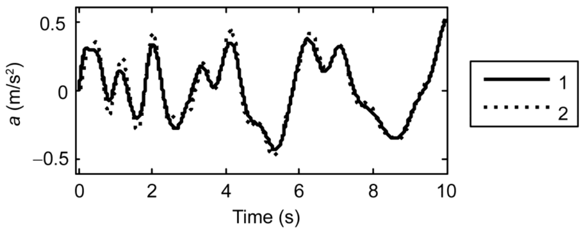

Figure 10 The combined free response of substructural boundary.

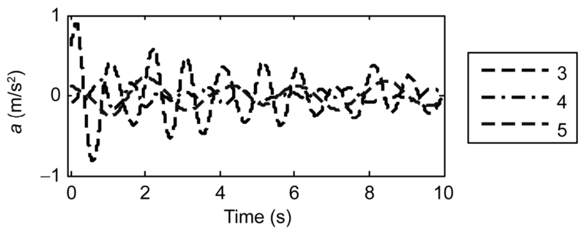

Figure 11 The combined free response of inner substructural boundary.

be obtained. The combined response is taken as the basic response for constructing the isolated substructure.

3.3.3 Constraining response

Figure 12 simulates the excitation on the FEM of the damaged bridge using force hammer. After response is added with 5% Gaussian white noise, the actual measured response is simulated. Since the two sensors on the boundary of the substructure needed to be constructed into virtual supports, two groups of excitations are required. Due to that the virtual support constructed cannot separate the substructure from the global structure totally, that was, the substructure is still one part of the global structure. Therefore, the position of excitation should be resembled with that of the sensors on the boundary. Otherwise, the response constructed using constraining function cannot be taken as free response. The force hammer excitation simulated in Figure 12 is applied as vertical excitation on the location of the sensors on the boundary. Two groups of responses are obtained. The two groups of responses are taken as constraining responses. Figure 13 shows one group of denoised responses.

3.4 Constructing the free response of isolated substructure

The constructed constraining response and the basic response are substituted into the constraining function of the SIM method, and the constraining matrix $\boldsymbol{A}$ is shown in Figure 14. The color in Figure 14 reflects the values in the matrix: the deeper the color is and the larger the value is. The responses of the two sensors on the boundary of substructure are limited to zero using the constraining function. The corresponding responses of the three sensors in the interior of the substructure, namely, the free responses of sensor 3, 4, 5 after two virtual supports are added, are shown in Figure 15.

3.5 Mode identification

The mode of the structure added with virtual supports is

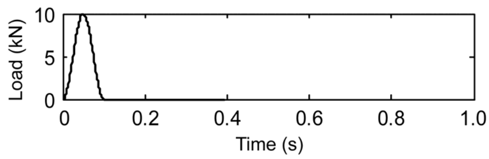

Figure 12 Excitation.

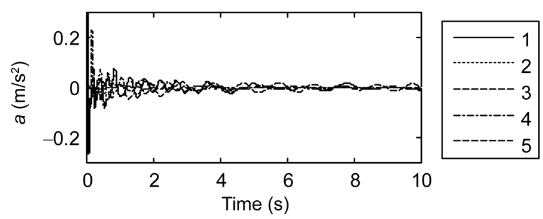

Figure 13 The 1st group of denoised response.

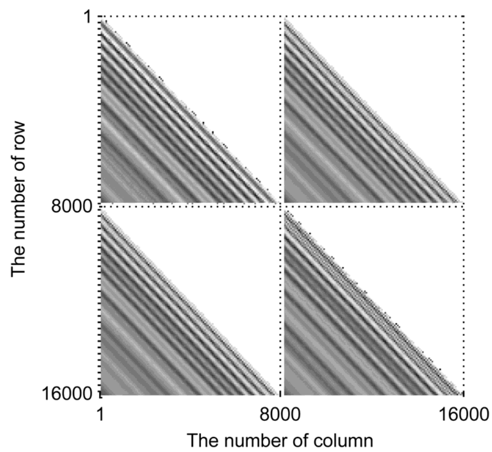

Figure 14 The matrix of constraining response.

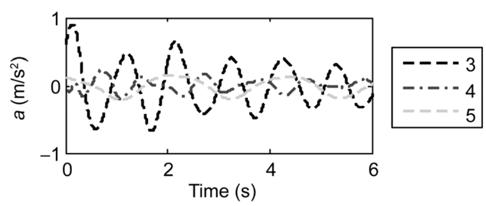

Figure 15 The constructed free response.

identified using Stochastic Subspace Identification method, see Figure 15. The frequencies of the 5 orders are shown in Table 2. Corresponding mode shapes are listed in Table 3. Table 2 presents the natural frequencies of the theoretical undamaged structure and damaged structure with virtual supports. The identified natural frequencies are in good agreement with the frequencies of theoretical damaged structure with virtual supports. This result verifies the validity of free response-based SIM method.

3.6 The objective function and the match of the substrucutral models

The damage extents are identified via the following objective function:

$$\Delta = \sum_i \left\| \frac{\omega_i(\boldsymbol{\mu}) - \omega_{i,m}}{\omega_{i,m}} \right\|, \tag{2}$$

where ω_i is the computed ith natural frequency of the FE model with virtual support given damage extents $\boldsymbol{\mu}$; $\omega_{i,m}$ is the identified ith frequency obtained from the constructed responses by SIM method.

From the substructure mode analysis of the FE model, it can be seen that the modes with high proportion of the substructure energy don't appear in a successive sequence. In Figure 16 the identified modes using SSI method don't have the 4th and 5th order, which indicates that not all the substructure modal can be identified successively. Therefore, it is a key step to match the identified modal with the theoretical modal in the same order. This is performed by calculating the correlation η_{ij} between the two kind of modes using eq. (3),

$$\eta_{ij} = k_1\eta_{ij}^{\omega} + k_2\eta_{ij}^{\varphi} \quad \left(k_1 + k_2 = 1, k_1 \geqslant 0, k_2 \geqslant 0\right), \tag{3}$$

where η_{ij} refers to the correlation coefficient between the jth identified mode and the ith theoretical mode; η_{ij} consists of two parts: frequency correlation η_{ij}^{ω} and mode

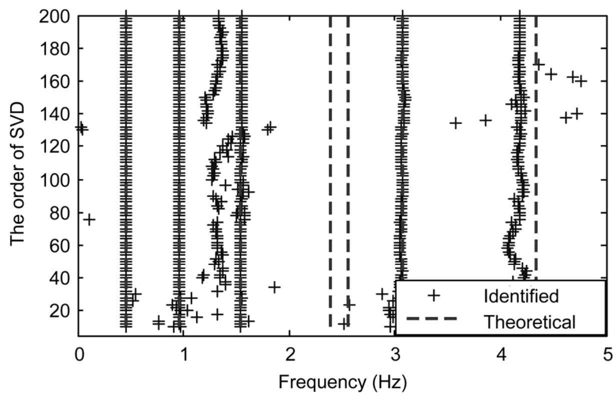

Figure 16 The identified 5 natural frequencies using SSI method.

correlation η_{ij}^{φ}, which are respectively calculated using eqs. (4) and (5),

$$\eta_{ij}^{\omega} = \frac{1}{1 + \left|\omega_i^A - \omega_j^m\right|}, \tag{4}$$

$$\eta_{ij}^{\varphi} = MAC\left(\varphi_i^A, \varphi_i^m\right) = \frac{\left\|\varphi_i^A - \varphi_j^m\right\|^2}{\left\|\varphi_i^A\right\|\left\|\varphi_j^m\right\|}. \tag{5}$$

The coefficients k_1 and k_2 refer to the respective weight of the frequency and modal shape in the relevance calculation, which are non-negative reals and with the sum of 1. Here it takes the frequency and modal shape with equal importance, i.e. k_1=k_2=0.5. Via eq. (3), the correlations η_{ij} between the jth identified mode and all the theoretical substructure mode are computed, then the nth order of the theoretical modal with the biggest value $\eta_{nj}(i = n)$ is picked as the matched mode of the jth identified mode, as shown in eq. (6)

$$n \Rightarrow \eta_{nj} = \max\left(\eta_{1j}, \eta_{2j}, \cdots, \eta_{mj}\right). \tag{6}$$

Using the identified frequencies (Table 2) and the modal shapes (Table 3), as well the intact theoretical FE model, the frequency correlations are computed and shown in Figure 17 in the form of matrix. Similarly the mode correlation matrix is computed and shown in Figure 18. Theoretically, the diagonal element in the correlation matrix should have bigger value. However in mode correlation matrix, some correlation between the modes of different orders also has big value, see Figure 18, which shows that the 1st order of identified modal shape respectively has high correlation with the 1st, 4th, 9th orders of the theoretical modal shape. However the frequency of the 1st order obviously is quite different from that of the 4th order or 9th order. So it can't match the identified modals and the theoretical modals by only using the correlation of the modal shapes.

Figure 19 shows the obtained correlation matrix which

Table 2 The identified natural frequency (Hz)

Order	1	2	3	4	5
Intact	0.491	1.060	1.628	3.482	4.536
Damaged	0.454	0.966	1.545	3.070	4.336
Identified	0.454	0.962	1.555	3.075	4.184

Table 3 The identified mode shape

Sensor	1	2	3	4	5
3	0.343	1.000	1.000	0.930	0.356
4	–0.108	–0.224	0.810	1.000	1.000
5	1.000	–0.064	–0.004	–0.061	–0.037

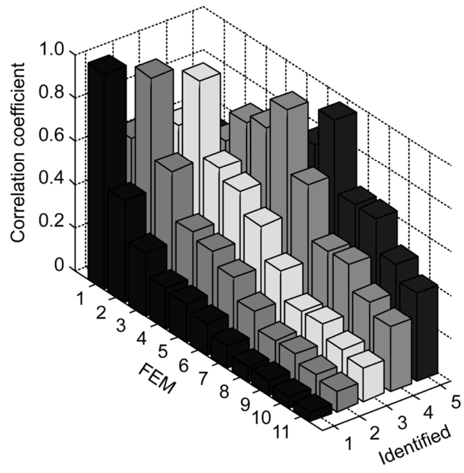

Figure 17 The correlation matrix of natural frequency.

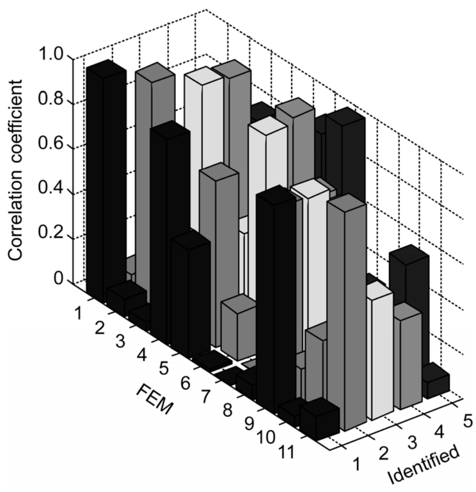

Figure 18 The correlation matrix of mode shape.

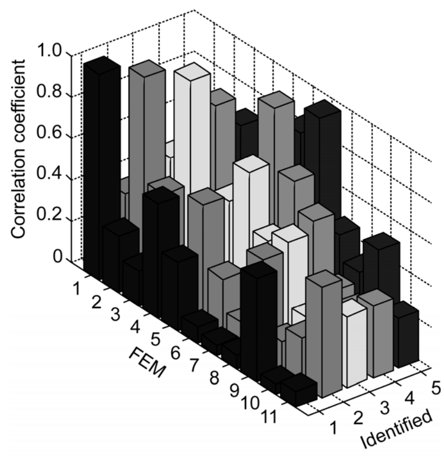

Figure 19 The combined correlation matrix.

considers the frequency and modal shape with equal importance, i.e. $k_1=k_2=0.5$, via eq. (3). It can be seen that that correlation matrix has its diagonal elements with bigger values, which proves that the identified modes and the theoretical modes are matched accurately. Then the damage can be identified using eq. (2) by minimizing the distance between the identified frequencies and the theoretical frequencies to given damage extents.

3.7 Damage identification

The two virtual supports placed on the boundary of the substructure weaken the influences caused by the errors which is outside the substructure. Therefore, we can assume approximately that the outside of the FEM substructure is undamaged. Then the three damage extents of the substructure are identified using the modes identified in Tables 2 and 3. The identification results are shown in Figure 20. It can be seen that the identification results satisfy the accuracy requirement. The effectiveness of the proposed method is verified.

4 Conclusion

This study put forward a free response-based isolated substructure damage identification method. It further verifies the effectiveness of the method proposed using a plane cable-stayed bridge model. The following conclusions are obtained:

1) All the constructed matrices, including the constraining matrix and basic matrix, are constructed by the measured response of real structure in practical application. So there are only noise errors and no modeling errors in the matrix.

2) Basic response is linearly constructed using free response. Constraining response is artificially excited using hammer excitation. Although this is a strict limitation on types of training excitation, the frequency spectrum of the excitations should de wide. So hammer excitation meets that criteria, which is easy to be applied in real application. Meanwhile, the construction accuracy of the virtual supports is improved and the range of application of the method proposed is expanded.

3) Virtual supports are placed on the main DOFs of the substructure boundary. The modes mainly reflecting the substructure vibration are selected to reduce the influences brought by the global structure to the substructure. The accuracy of the substructure damage identification is thereby improved. Besides, it overcomes the limitation on monitor

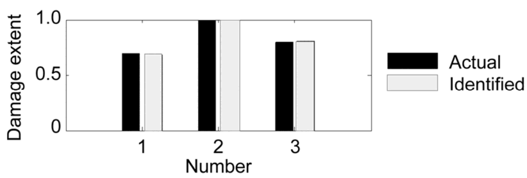

Figure 20 The identified damage extent of substructure.

ing the DOFs of the boundary of the substructure induced by SIM method.

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