A NEW IMPACT TESTING METHOD FOR EFFICIENT STRUCTURAL FLEXIBILITY IDENTIFICATION

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ABSTRACT: Traditional multi-reference impact testing (MRIT) has the merit to produce not only structural modal parameters but also structural flexibility, however it requires a number of instruments mounted on the whole structure leading to expensive cost and much experiment time. A new impact test method is proposed in this article for faster and more efficient flexibility identification of bridges. In the proposed method, the investigated structure is subdivided into smaller substructures that will be tested independently, and test data of all substructures are integrated by taking the interface measurement as reference for flexibility identification of the whole structure. The new impact testing method requires limited instrumentation thus it can be performed rapidly and efficiently. Especially, the signal processing procedure developed in the proposed method is able to identify the full flexibility matrix of the whole structure from the sparse FRF matrixes of the substructures. Numerical and experimental examples are investigated to demonstrate the effectiveness of the proposed method by comparing its results with those from the traditional MRIT method for structural flexibility identification and deflection prediction.

Keywords: impact testing, substructure, data processing, flexibility identification, reference.

1. INTRODUCTION

Structural health monitoring (SHM) plays an important role in safety evaluations of bridges by deploying smart sensors on structural major components [1-2]. From bridge owners' point of view, they expect the SHM technology accurately identifies structural characteristics, locates and quantifies structural damages, evaluates structural safety condition, and predict the residual life of the investigated structure. By taking the above requirements as goals, significant efforts have been made by researchers and engineers from aspects of sensors, experiments, signal processing, and finite element updating to facilitate the applications of the SHM technology on real structures [3-7]. The vibration-based SHM technology has progressively become a mainstream way for structure safety evaluation after over thirty years' development. For instance, ambient vibration test has been widely applied for modal identification of long span bridges. By deploying sensors (accelerometers, strain gauges etc.) on the investigated structure, structural responses under ambient excitations (traffic, wind,

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temperature etc.) are measured and structural characteristics are identified by processing the ambient test data [8-10]. The state-of-the-art and state-of-the-practice report of the SHM technology edited by ASCE St-Id committee collected ten bridge monitoring case studies, almost all of which adopted ambient vibration test as the main experiment tool [11]. Despite its wide application, the ambient-vibration-test- based SHM still have a far way to meet the bridge owners' requirements. It successfully identifies structural modal parameters (frequency, damping and mode shapes), however it fails to directly locate and qualify structural damage. Even though the finite element updating technology provides a possible way to connect ambient test and structural damage detection, there are still a lot of challenging problems when applying it for safety evaluation of real structures, e.g., the non-unique problem in the FE calibration [12].

Compared to the ambient vibration test mainly identifying structural modal parameters, the force-controlled vibration test has the merit to identify not only structural modal parameters but also more detailed structures features, like flexibility. Multi-reference impact testing (MRIT) has been reported for safety evaluation of short/middle span bridges [13-14]. By measuring both impacting forces and structural responses, MRIT is able to identify structural flexibility, from which structural deflections under any static load can be predicted. Case studies of several short/middle bridges have illustrated that the predicted deflections from the impact test data were comparable with those from corresponding static truck load tests [13]. It is known that structural deflection is generally used as a index for safety evaluation as defined in bridge maintenance codes, thus the investigation of the flexibility identification from the impact testing is promising. However, a large number of sensors are required to be deployed on the whole structure in the traditional impact testing method. It leads to expensive experiment cost (sensors, cables, data acquisition system, and labor), and much test time during which the investigated bridge has to be closed. Inspired by the sub-structuring idea which has been widely applied in structural identification, a new impact testing method is proposed in this article for more efficient structural flexibility identification. It subdivides the investigated structure into smaller substructures that will be tested independently. Then test data of all substructures will be integrated at last to identify the flexibility matrix of the whole structure from the sparse frequency response function matrix. The proposed experiment method only requires limited instrumentations and rapidly conducts impact testing of large structures.

Moreover, the proposed experiment method is potential to solve the key problem existing in the structural mobile testing, a novel area developed in recent years. The mobile testing system integrates impact device, limited number of sensors, and data acquisition, and automatically moving on the investigated bridge to sequentially perform impact tests on localized portions of the larger structure [15]. The challenge of the structural mobile testing lies on the difficulty to integrate independent impact test datasets into a global dataset describing the behavior of the structure. The signal processing procedure developed in the proposed method will offer a solution to overcome that difficulty, namely, identify the full structural flexibility matrix of the whole structure from the sparse frequency response function (FRF) matrixes of the substructures.

This article is structured as follows. The idea of the proposed method will be first presented in Section 2. How to integrate the impact test data of all substructures to identify the flexibility matrix of the whole structure will be focused, which includes modal parameter identification through the complex mode indicator function (CMIF) method, mode shape matrix extension by using the interface

measurement, and the full flexibility matrix identification. In Section 3, a numerical example will be investigated to demonstrate how to use the proposed method for structural flexibility identification. Experiment studies of a grid structure in the laboratory will be performed in Section 4 to further verify the effectiveness of the proposed method. Conclusions will be draws in Section 5.

2. MOBILE SUBSTRUCTURE IMPACT TESTING AND RELATED DATA PROCESSING

The idea of the proposed method is subdividing the whole structure into smaller substructures, sequentially performing impact tests on the substructures, and integrating all test data through the substructure interface measurements to identify the full flexibility matrix of the whole structure. To illustrate the idea of the proposed method, a simple 5-DOF lumped mass structure as shown in Figure 1 is considered. Traditional impact test requires five accelerometers to be deployed on the whole structure. In contrast, the structure is divided into two substructures that are tested independently in the proposed method (Figure 1), in which only three accelerometers are required. The merit of the proposed method requiring fewer sensors is not clear for this simple structure, but considering a real bridge with a number of DOFs it will be obvious. The signal processing procedure developed below will integrate the substructures' test data for the whole structural identification, which is a critical step to guarantee the success of the proposed method.

From the traditional impact test data, a full frequency response function (FRF) matrix $H \in \Re^{\mathrm{N_o} \times \mathrm{N_o}}$ is identified, where the symbol $\in \Re$ means the dimension of a matrix, and $\mathrm{N_o}$ denotes the number of outputs of the whole structure. However, when using the impact test data of the substructures A and B (Figure 1), only a sparse FRF matrix including two sparse sub-FRF matrixes $\mathrm{H^A}$ and $\mathrm{H^B}$ is identified:

$$H = \begin{bmatrix} & H_{12} & & & \\ H_{21} & H_{22} & H_{23} & & \\ & H_{32} & & & H_{35} \\ & & & & H_{45} \\ & & H_{53} & H_{54} & H_{55} \end{bmatrix} \tag{1}$$

A suit of data pre-processing methods (like filtering, windowing, and averaging) are generally used to improve data quality, and a few methods are available to estimate FRF matrix from impact test data [10]. A number of data processing methods like the CMIF method, the PolyMAX method, the PTD method, and the SSI method are able to identify structural modal parameters from the estimated FRF matrix [13, 16]. The CMIF method is adopted here for structural modal parameter identification. For the substructure A,

$$H(\omega_k)^A = U^A \times S^A \times V^{AT} \tag{2}$$

Equation (2) is the Singular Value Decomption (SVD) of the FRF matrix $H^A \in \Re^{N_o^A \times N_i^A}$ at a spectral line ω_k, N_o^A and N_i^A are output and input node number, respectively, $S^A \in \Re^{N_i^A \times N_i^A}$ is the singular value matrix, $U^A \in \Re^{N_o^A \times N_i^A}$ and $V^A \in \Re^{N_i^A \times N_i^A}$ are left and right singular vectors, respectively. The singular value matrix itself is a diagonal matrix with real, nonnegative values stored in descending

order [13]. The CMIF plot is that of the singular values as a function of frequency. The general equation connecting the measured FRF matrix and the modal parameters is

$$H(\omega_k)^A = \varphi^A \times \frac{1}{\mathrm{j}\omega_k - \lambda_r^A} \times L^{A^T} \tag{3}$$

where $\lambda_r^A \in \Re^{2N\times 2N}$=eigenvalue of mode r, N=number of the conjugate modes, $\varphi^A \in \Re^{N_o^A \times 2N}$=modal vector, $L^A \in \Re^{2N\times N_i^A}$=modal participation factor, and the symbol ^{T} denotes transposition. The SVD formulation of the FRF marix in Equation (2) and the formulation of the FRF matrix in Equation (3) are equal since they represent the same FRF matrix at a given frequency. Therefore, the peak singular values at the CMIF plots are the possible pole locations of the system. The left singular vector associated with the peak singular value is the approximate modal vector of the system, being the response at the resonance. In brief, from the CMIF method, structural eigenvalues $\lambda_k^A \in \Re^{2N\times 2N}$, modal vector $\varphi^A \in \Re^{N_o^A \times 2N}$, and modal participation matrix $L^A \in \Re^{2N\times N_i^A}$ are extracted from the FRF matrix. After these modal parameters are identified, they are used to identify structural flexibility [13]:

$$f^A = H^A(\omega_k = 0) = \sum_{r=1}^{N}\left(\frac{R_r^A}{-\lambda_r^A} + \frac{R_r^{A^*}}{-\lambda_r^{A^*}}\right) \tag{4}$$

where $f^A \in \Re^{N_i^A \times N_o^A}$ = flexibility of the substructure A, and $R_r^A = L_r^A \varphi^{A^T} \in \Re^{N_i^A \times N_o^A}$ = the residue of the rth mode, and the symbol * denotes conjugation. Due to $L_r^A \in \Re^{N_i^A \times 2N}$, the dimension of the flexibility estimated so far is $N_i^A \times N_o^A$, which can only be used to estimate deflections of the nodes within the substructure when the static load locates at the impacting node in impacting test. Similarly for the substructure B, the sparse flexibility matrix $f^B \in \Re^{N_i^A \times N_o^A}$ is identified. Therefore, the sparse flexibility matrix identified so far is

$$f = \begin{bmatrix} & f_{12} & & & \\ f_{21} & f_{22} & f_{23} & & \\ & f_{32} & & & f_{35} \\ & & & & f_{45} \\ & & f_{53} & f_{54} & f_{55} \end{bmatrix} \tag{5}$$

It is seen from Equation (5) that very limited flexibility coefficients are identified so far. For instance, when a unit load is applied to node 2 of the structure as shown in Figure 1, deflections of nodes 4 and 5 within another substructure cannot be predicted as the required flexibility coefficients are unknown. The deflections of all nodes when the static force is applied on node 1 cannot be predicted. Therefore, the method to extend the sparse flexibility matrix to a full matrix is required for structural deflection prediction. A two-stage signal processing procedure is proposed below to meet this requirement.

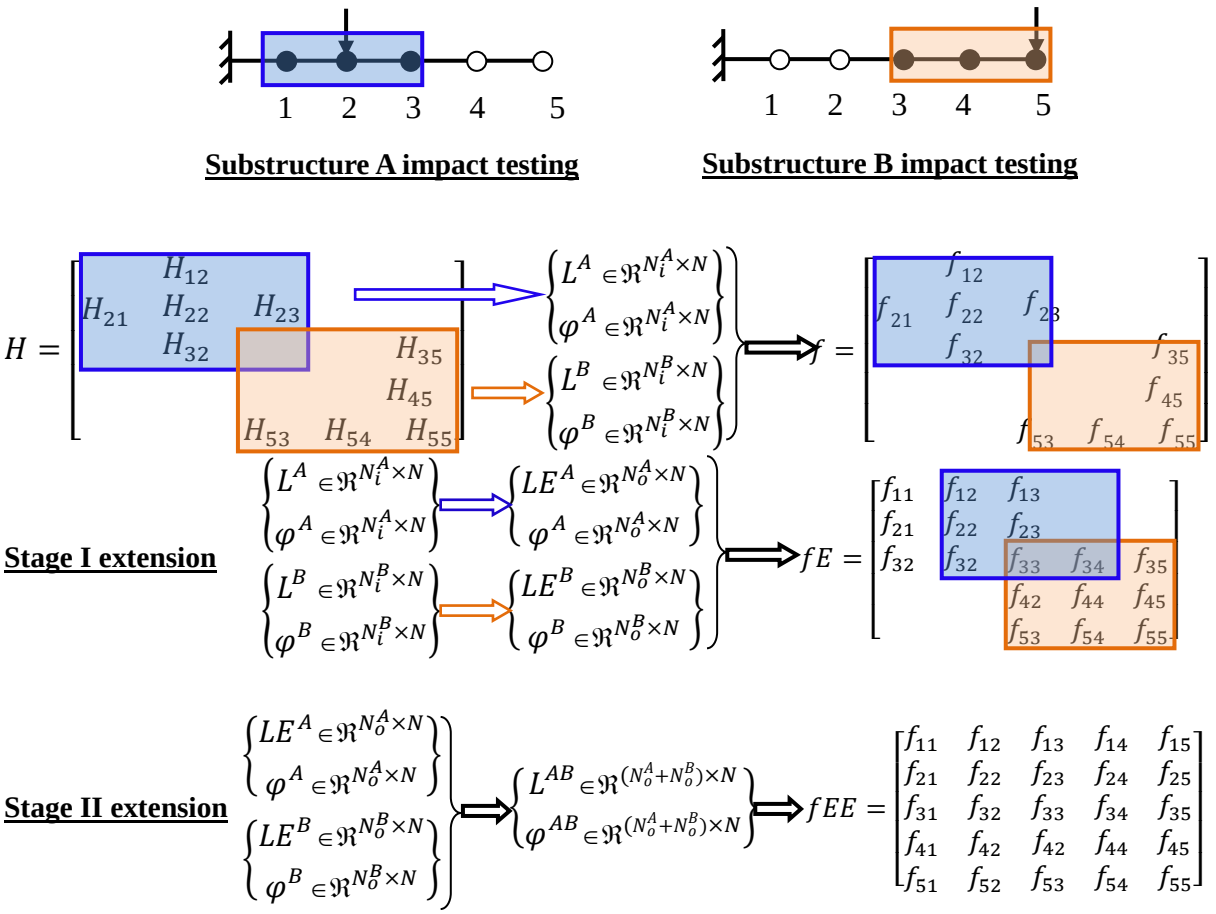

Figure 1. The idea of the proposed method

(a) Stage I extension

The dimensions of the modal vector and modal participation factor for the substructure A identified so far are $\varphi^A \in \Re^{N_0^A \times N_m}$ and $L^A \in \Re^{N_i^A \times N_m}$, respectively. It is known that φ and L has a relationship as follows:

$$Q_r^A = L_{ir}^A \varphi_{ir}^A \tag{6}$$

where Q_r^A is the scaling factor of the rth mode, i denotes the ith input location. From the sparse L^A and φ^A matrixes, the scaling factors are calculated from Equation (6). By using the identified scaling factors, the modal participate factor matrix is extended to

$$LE_r^A = Q_r^A \varphi_r^A \tag{7}$$

where $LE_r^A \in \Re^{N_0^A \times 1}$. By using this extended modal participate factor, the dimensions of the calculated residual and flexibility in Equation (4) are extended to $N_0^A \times N_0^A$. After making the similar extension for the identified flexibility matrix of the substructure B, the flexibility matrix of the whole structure is extended to be

$$fE = \begin{bmatrix} f_{11} & f_{12} & f_{13} & & \\ f_{21} & f_{22} & f_{23} & & \\ f_{32} & f_{32} & f_{33} & f_{34} & f_{35} \\ & & f_{42} & f_{44} & f_{45} \\ & & f_{53} & f_{54} & f_{55} \end{bmatrix} \tag{8}$$

(b) Stage II extension

The dimensions of the modal vector and modal participation factor identified so far are $\varphi^A \in \Re^{N_0^A \times N_m}$ and $LE^A \in \Re^{N_o^A \times N_m}$, respectively. It is seen from Equation (8) that when the impacting force is applied on a substructure, deflections of the nodes in another substructure still cannot be predicted. To overcome this problem, the identified flexibility matrix needs further extension. It is seen from Figure 1 that even though two substructures are tested independently, the outputs of the interface node 3 are measured during the impacting tests of both substructures, which provide a possibility to integrate impact test data of two substructures. For instance, the identified modal vectors of the rth mode are $\varphi_r^A = \{\varphi_{1r}^A \quad \varphi_{2r}^A \quad \varphi_{3r}^A\}^T$, and $\varphi_r^B = \{\varphi_{3r}^B \quad \varphi_{4r}^B \quad \varphi_{5r}^B\}^T$ respectively. Because the rth frequencies of two substructures are almost same, it makes senses to integrate the rth model vector of the whole structure from the identified substructure mode vectors in the following way:

$$\varphi_r^{AB} = \{\varphi_{1r}^A \quad \varphi_{2r}^A \quad \varphi_{3r}^A \quad \varphi_{3r}^A \varphi_{4r}^B / \varphi_{3r}^B \quad \varphi_{3r}^A \varphi_{5r}^B / \varphi_{3r}^B\}^T \tag{9}$$

Similarly, the rth modal participation factor can also be extended to:

$$L_r^{AB} = \{L_{1r}^A \quad L_{2r}^A \quad L_{3r}^A \quad L_{3r}^A L_{4r}^B / L_{3r}^B \quad L_{3r}^A L_{5r}^B / L_{3r}^B\} \tag{10}$$

By performing the above extension to all other modes, the modal vector matrix $\varphi^{AB} \in \Re^{N_0^{AB} \times N}$, and modal participation factor matrix, $L^{AB} \in \Re^{N_0^{AB} \times N}$, of the whole structure are produced. Therefore, the identified flexibility matrix from Equation (4) is a full matrix as follows:

$$fEE = \begin{bmatrix} f_{11} & f_{12} & f_{13} & f_{14} & f_{15} \\ f_{21} & f_{22} & f_{23} & f_{24} & f_{25} \\ f_{31} & f_{32} & f_{33} & f_{34} & f_{35} \\ f_{41} & f_{42} & f_{42} & f_{44} & f_{45} \\ f_{51} & f_{52} & f_{53} & f_{54} & f_{55} \end{bmatrix}$$

The above procedure to identify the full flexibility matrix of the whole structure from the sparse FRF matrixes of substructures is summarized in Figure 1. It is seen that the proposed method requires less instruments during the impacting test, and it is still able to identify the full flexibility by employing a two-stage signal processing procedure.

3. NUMERICAL EXAMPLE

To illustrate how to use the proposed method for structural flexibility identification, the 5-DOF structure as shown in Figure 1 is investigated in this section. The mass lumped to each node is selected as m=[8 7 6 5 4] kg, while the stiffness of each element is k=[10 9 8 7 6] KN/m. The time interval is 0.005 second. The Rayleigh damping is adopted. It should be noted that the equations presented in last section were derived based on the single reference impact test (SRIT) of each substructure, in which only a single impact was performed on each structure. They are easily extended to the multiple-reference impact testing (MRIT) case. In this example, impacting forces were applied to nodes 1 and 2, respectively, on the substructure A, while the impacting locations were nodes 4 and 5 for the substructure B, to illustrate that the proposed method also works in the MRIT case. Structural responses were simulated through the Newmark β method, in which the used impacting forces were hammer hitting forces recorded in a real bridge field test. Ten percent standard white noise was added into both impacting forces and structural responses as observation noise, where ten percent means the standard deviation of the noise is 10% of that of the simulated data.

After the impact test data of two substructures were simulated, a data pre-processing procedure was first implemented for uncertainty reduction. Force and acceleration records were first filtered by using a digital Butterworth band pass filter with certain cut-off frequencies to remove the low and high frequency components. Following that, the exponential window was used to artificially force the response data to decay to zero at the end of measurement thus minimizing leakage. While the exponential window was applied to structural responses, the rectangular window was used to impact forces to set the whole force time series to be zero except the short time window when the impact device hits the structure. After the windowing, the impact force and accelerations were used to generate cross power spectra, from which frequency response functions (FRFs) were estimated by using the H1, H2 or Hv method [10].

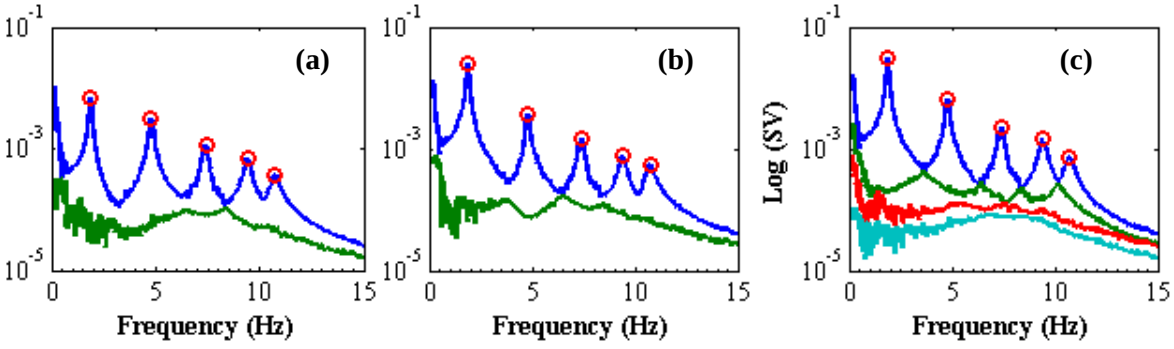

Figure 2. CMIF Plots, (a) The substructure A, (b) The substructure B, and (c) The whole structure

The FRF matrixes estimated from the impact test data of two substructures are sparse matrixes, $H^A \in \Re^{N_o^A \times N_i^A}$, and $H^B \in \Re^{N_o^B \times N_i^B}$, where $N_o^A = N_o^b = 3$, and $N_i^A = N_i^b = 2$. By performing SVD of the FRF matrixes as presented in Equations (2-3), the CMIF plots of the substructure A and B were made as shown in Figure 2 (a) and (b). For comparison, the tradition impact test was also performed

for the whole structure, in which impacting forces were applied to nodes 1, 2, 4, 5, respectively, and structural responses of all noses were simulated. The similar data pre- and post- processing procedure was also implemented to process the traditional impact test data, and its CMIF plot is shown in Figure 2c. Structural frequencies were identified from the CMIF peaks as denoted by red circles in Figure 2. It is seen from Table 1 that the identified frequencies for the substructure A, the substructure B, and the whole structure are very close. After model vector and modal participation factor matrixes of two substructures, $\varphi^A \in \Re^{N_0^A \times N}$, $\varphi^B \in \Re^{N_0^B \times N}$, $L^A \in \Re^{N_i^A \times N}$ and $L^B \in \Re^{N_i^B \times N}$, were identified from the CMIF method, they were extended to full matrixes by using Equation (7) then they were integrated to generate the mode vector and modal participation factor of the whole structure, $\varphi^{AB} \in \Re^{N_0^{AB} \times N}$, and $L^{AB} \in \Re^{N_o^{AB} \times N}$ by using Equations (8-9). MAC values of the modal vectors identified from the proposed method and those from the traditional impact test method were calculated as shown in Figure 3. The minimum MAC value is 0.998, which illustrates that the identified mode vectors from two methods are comparable. After the modal vector and the modal participation factor were integrated, structural flexibility matrix of the whole structure was identified through Equation (4). Due to the identified structural flexibility matrix is a full matrix, structural deflections under any load can be predicted. For instance, structural deflections under the static load, F=[1 1 1 1 1] kN were predicted as shown in Figure 4 (labeled as "Method I"). The predicted deflections from the traditional impact test method are also plotted (labeled as "Method II") for comparison. The agreement between them illustrates that the proposed method produced the very close results as those from the traditional impact test method.

4. EXPERIMENTAL EXAMPLES

4.1 Grid experiment description

To further verify the effectiveness of the proposed method, multi-reference impact test data of a grid structure (Figure 5) was investigated. This grid structure was designed and constructed to have dynamic similitude with common medium-span bridges. It has an overall length of 6.09 m and a width of 2.74 m. The continuous three longitudinal members and the fourteen transverse members were manufactured from A36 grade steel, and had an HSS 3x2x3/16 cross section. The individual tube sections in the grid were bolted together using a combination of top and bottom gusset plates and vertical clip angles. The ends of each longitudinal grid member were founded on pin supports mounted on steel pedestal. A VXI data acquisition system together with the Matlab-based X-Acquisition software was used to acquire the impact test data.

4.2 Mobile testing case I

To perform the proposed mobile testing, the grid structure could be subdivided into two substructures as shown in Figure (6). First, the hammer impact test was performed for the substructure A, in which 12 accelerometers were deployed on the nodes as shown in Figure (6) and the impacting forces were applied to nodes 2, 11, and 18, respectively. Second, the substructure B was tested by selecting the

impact locations at nodes 11, 18, and 20, respectively. To check the effectiveness of the proposed method, the traditional impact test was also performed for the whole structure by putting 21 sensors on all nodes and impacting the structure on nodes 2, 11, 18 and 20, respectively.

The typical impacting force, structural acceleration and structural frequency response function are shown in Figure 7. The pre-processing procedure similar to that presented in the numerical example in last section was first performed to reduce the uncertainty. The FRF matrixes for the substructures A and B are $H^A \in \Re^{N_o^A \times N_i^A}$, and $H^B \in \Re^{N_o^B \times N_i^B}$, where $N_o^A = N_o^B = 12$, and $N_i^A = N_i^B = 3$. The CMIF

Table 1. Identified frequencies and damping ratios

Mode number	Substructure A		Substructure B		The whole structure	
	Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)
1	1.87	2.12	1.86	2.07	1.86	2.08
2	4.78	1.47	4.79	1.41	4.79	1.44
3	7.40	1.65	7.40	1.67	7.40	1.65
4	9.40	1.62	9.41	1.72	9.41	1.62
5	10.73	2.08	10.74	2.10	10.71	1.98

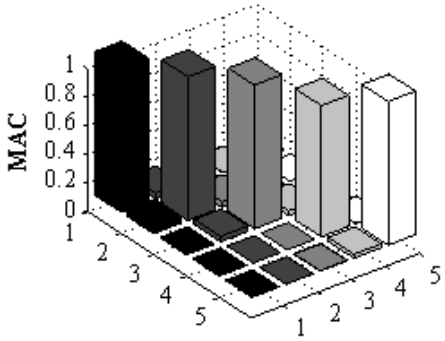

Figure 3. MAC value calculation

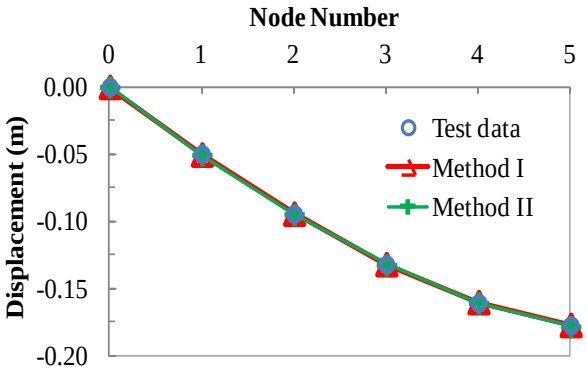

Figure 4. Deflection prediction

Figure 5. The investigated grid structure

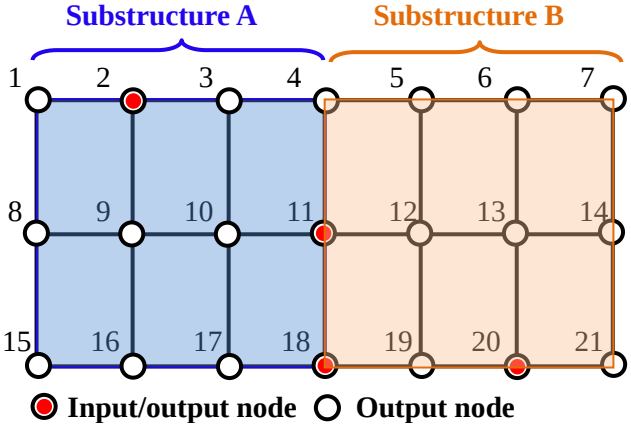

Figure 6. Mobile impacting testing case I

method was used to process the data for structural modal identification. Structural frequencies were determined by selecting the peaks at the CMIF plots as shown in Figure 8, which illustrate that identified frequencies of the substructures A, B and the whole structure are very close. The identified model vector and modal participation factor matrixes of two substructures from the CMIF method have the following dimension: $\varphi^A \in \Re^{N_0^A \times N}$, $\varphi^B \in \Re^{N_0^B \times N}$, $L^A \in \Re^{N_i^A \times N}$ and $L^B \in \Re^{N_i^B \times N}$. After performing the two-stage extension defined by Equations (7-9), the modal vector and modal participation factor of the whole structures were identified: $\varphi^{AB} \in \Re^{N_0^{AB} \times N}$, $L^{AB} \in \Re^{N_o^{AB} \times N}$, where $N_o^{AB} = 21$, and N=8. The identified modal vectors in the first eight modes from the proposed method and the traditional method are plotted in Figure 9 for comparison, in which f(I/II) means the identified frequency from the proposed method/the traditional method. MAC values between them plotted in Figure 10 further demonstrate that the model vectors identified from two methods are comparable. Finally, the full structural flexibility matrix was identified by substituting the identified φ^{AB} and L^{AB} into Equation (4). Structural deflections predicted from the proposed method, the traditional impact test method and the static test results data when a 4.448kN force was applied at node 11 are plotted in Figure 11a. Similarly Figure 11b plot structural deflections when a 4.448kN force was applied at node 17. Agreement between them illustrates that the proposed method produced accurate flexibility identification results, which are almost same as those from the traditional impact test method.

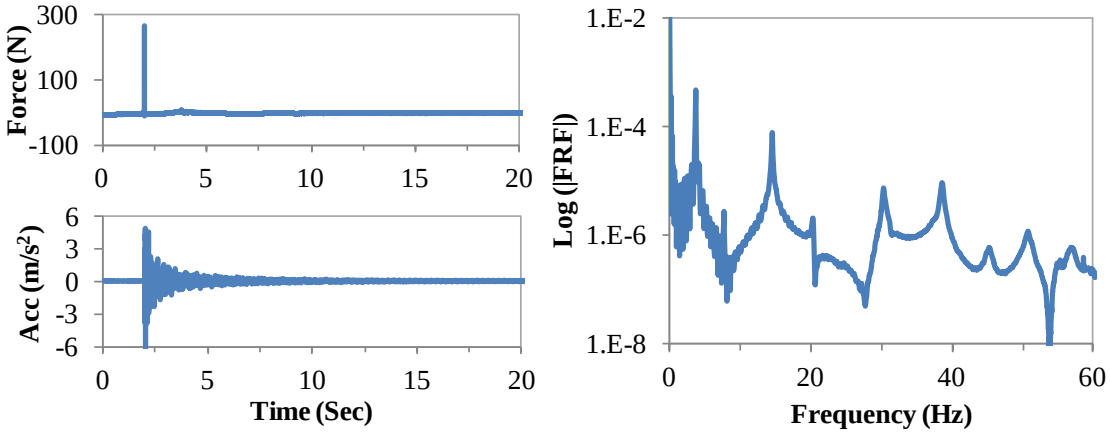

Figure 7. Typical impacting force, acceleration, and FRF

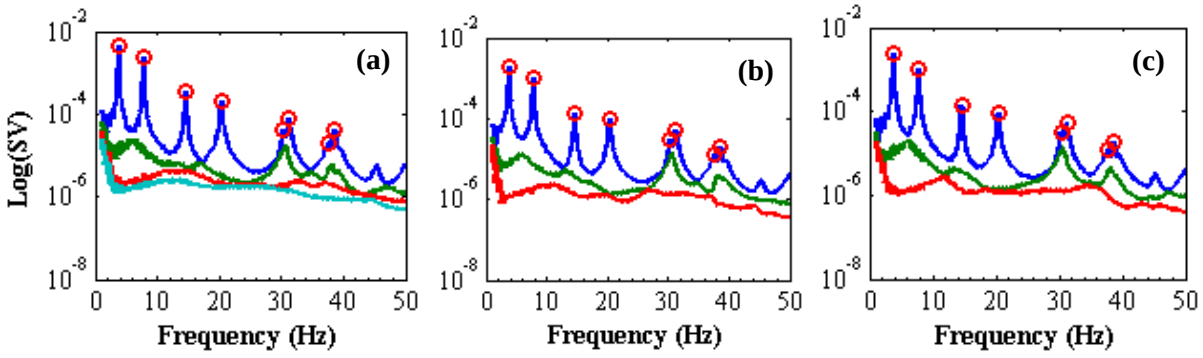

Figure 8. Case I CMIF Plots, (a) The substructure A, (b) The substructure B, and (c) The whole structure

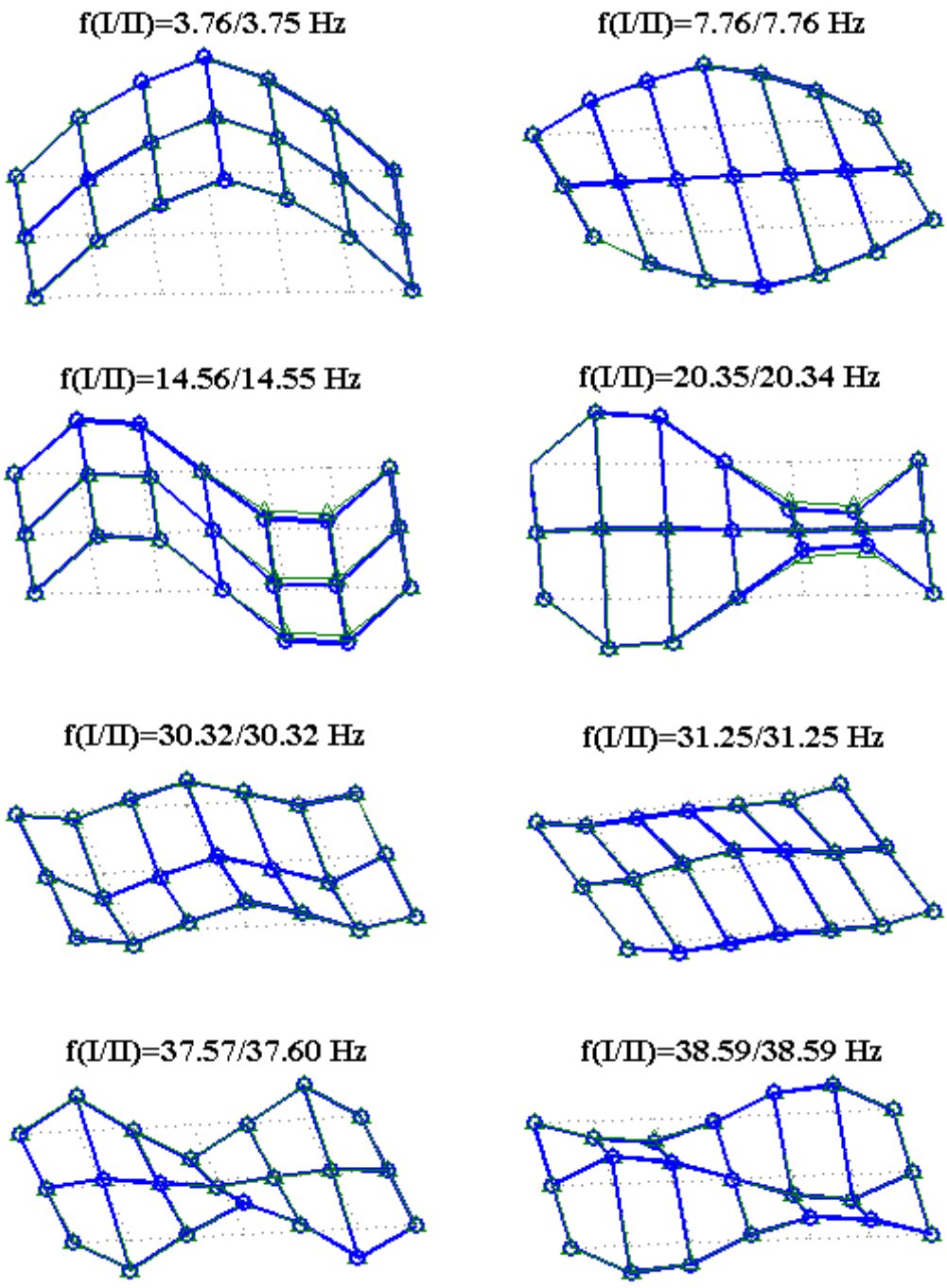

Figure 9. Identified frequencies and mode shapes (the thick blue line with circles: the proposed method (I); the thin green line with triangles: the traditional method (II))

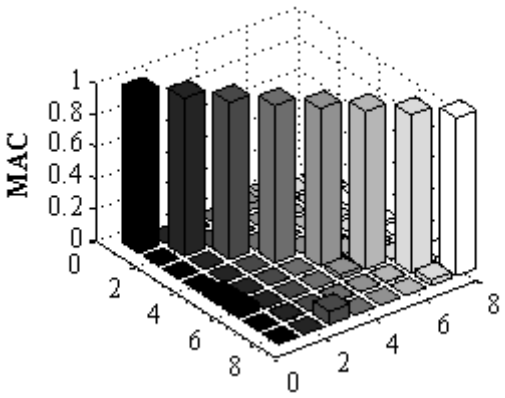

Figure 10. MAC values (grid structure, case I)

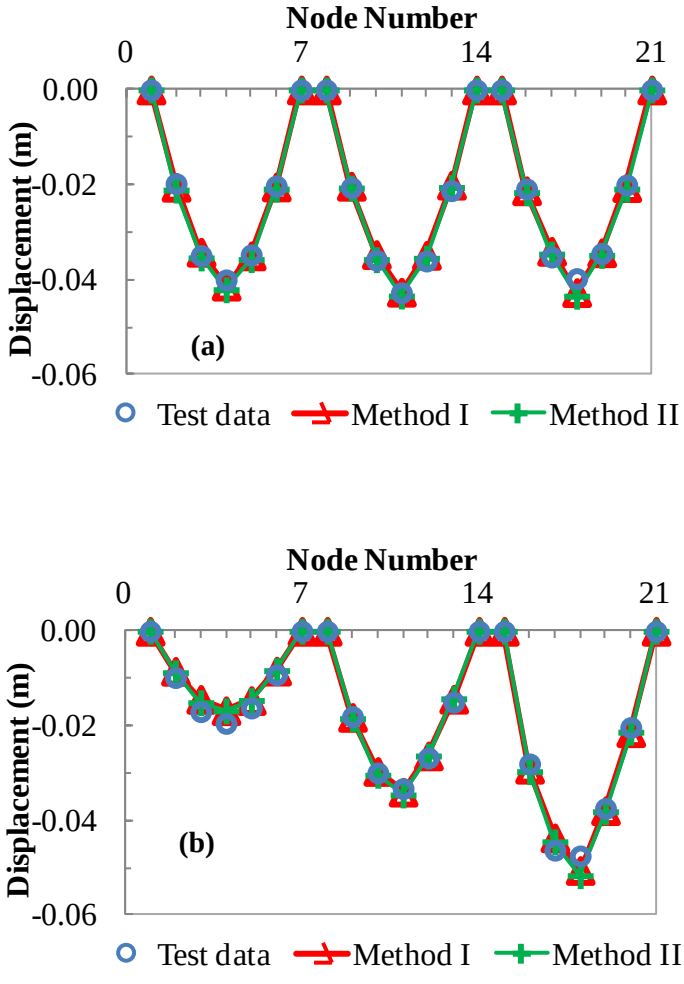

Figure 11. Case I deflection prediction,
(a) static load at node 11, (b) static load at node 17

4.3 Mobile testing case II

In the proposed method, the way to subdivide the structure into substructures is very flexible. The substructure can be any shape thus the proposed method can work even when the bridge deck has a non-regular shape which is frequently happened for real bridges. For the same gird structure as presented above, another case to subdivide the whole structure into two irregular substructures is investigated here. As shown in Figure 12, impact test of the substructure A was performed by impacting nodes 2, 11, 16 and 18, respectively. For the substructure B, the impacting locations are node 11, 13, 18 and 20 respectively. By performing the similar pre-processing and post-processing as described above, the CMIF plots are plotted in Figure 13, and structural frequencies, mode vectors and modal participation factors were identified. Subsequently, the identified modal parameters were integrated to produce the modal parameters and the full flexibility of the whole structure through Equations (7-10). Figure 14a and 14b plot structural deflections predicted from the proposed method, traditional method and static test results when a 4.448KN force was applied to node 11 and node 17, respectively. It is seen that the proposed method also worked well when subdividing the structure into substructures with irregular shapes.

5. CONCLUSIONS

A new impact test method has been proposed for flexibility identification and deflection prediction of short/middle span bridges. It includes (a) subdividing the whole structure into small substructures, (b) performing impact testing for each substructure independently, and (c) integrating impact test data of all substructures for flexibility identification of the whole structure.

The proposed experiment method has the merits that requiring less instrumentation and reducing the experiment time, thus it is potential to make rapid and automatic bridge safety monitoring. While the proposed method has the above merits, substructure impacting tests produce sparse FRF matrixes, which leads that the identified flexibility matrix is also sparse. A two-stage signal processing procedure has been proposed to identify the full mode vector and modal participation factor matrixes from the sparse FRF matrixes, then to generate a full flexibility matrix of the whole structure, which is able to predict structural deflections under any static load.

Numerical and experimental examples have been investigated to illustrate the effectiveness of the proposed method. The results show that the proposed method produced very close flexibility identification results with those from the tradition impact test method. Investigation of the experiment example also illustrated that the substructure used in the proposed method could be any shape (regular or irregular), therefore the engineers can subdivide the whole structure into any kinds of substructures based on their requirement when they use the proposed method for rapid bridge impacting testing and flexibility identification.

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