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Numerical and experimental verifications on damping identification with model updating and vibration monitoring data

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Abstract. Identification of damping characteristics is of significant importance for dynamic response analysis and condition assessment of structural systems. Damping is associated with the behavior of the energy dissipation mechanism. Identification of damping ratios based on the sensitivity of dynamic responses and the model updating technique is investigated with numerical and experimental investigations. The effectiveness and performance of using the sensitivity-based model updating method and vibration monitoring data for damping ratios identification are investigated. Numerical studies on a three-dimensional truss bridge model are conducted to verify the effectiveness of the proposed approach. Measurement noise effect and the initial finite element modelling errors are considered. The results demonstrate that the damping ratio identification with the proposed approach is not sensitive to the noise effect but could be affected significantly by the modelling errors. Experimental studies on a steel planar frame structure are conducted. The robustness and performance of the proposed damping identification approach are investigated with real measured vibration data. The results demonstrate that the proposed approach has a decent and reliable performance to identify the damping ratios.

Keywords: damping identification; experimental verification; model updating; vibration data; sensitivity

1. Introduction

Damping is a significant factor when predicting and analyzing the dynamic behavior of a structure dominated by energy dissipation. Other system properties such as mass, stiffness that can be determined via system identification of structures (Li *et al.* 2015, Li and Hao 2015, Liu 2014, Chen and Maung 2014). The estimation of structural parameters is essential for the condition and reliability assessment of structures (Ye *et al*. 2015, Li *et al.* 2014, Ye *et al.* 2016a, Ye *et al.* 2016b). Compared with identifying the stiffness and mass parameters of structural systems, the process of accurately identifying damping for predicting and analyzing the structural vibration behavior is challenging, especially if the measured data is disturbed by model errors, noise pollution and other measurement errors (Huang 2007).

Accurate estimation of damping is important in predicting structural dynamic responses and energy dissipation behavior. The effective estimation method for damping ratios is required in a broad range of areas including the structural design, space technology, earthquake response analysis and damage prediction, and mechanical system fault diagnosis etc. Because of the complexity of large-scale engineering structures, a slight difference between the actual and estimated damping ratios may produce a significant difference in vibration response prediction. Vibration-based methods to accurately identify the damping ratios of structural systems under a wide range of conditions have been intensively studied. Barbieri *et al.* (2004) established a procedure to identify damping of transmission line cables. Xu *et al*. (2003) identified the damping ratio of a high rise building under strong typhoon. Wang *et al.* (2016) proposed a damping ratio identification method for rotor systems. Holland and Epureanu (2013) proposed a component damping identification method for mistuned blisks. Devriendt *et al*. (2013) identified the damping of an offshore wind turbine on a monopile foundation.

To identify the damping ratios, damping model needs to be defined first. The research on damping models have been dated for a long time and several damping models have been developed, for example, Rayleigh damping, modal damping and Caughey damping models. The first damping model was Rayleigh damping (Chopra 1995). Two coefficients associated with mass and stiffness matrices are determined by using only the first two vibration modes of structure. Caughey damping is also widely accepted as

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modal damping. Caughey and O'kelly (1965) proposed that the classical damping model can be applied to more than two modes of structures. Caughey damping can theoretically specify damping ratios for any number of modes of a structural system, however, with the large number of coefficients in the Caughey damping model, inappropriate damping coefficients may lead to a negative modal damping ratio which cannot exist in nature (Ding and Law 2011). Therefore, the Rayleigh damping model is still applied in most cases in engineering practice.

Damping identification methods can be classified into frequency domain method, time domain method, and time-frequency domain method. Methods in the frequency domain include half-power bandwidth method (Olmos and Roesset 2010, Papagiannopoulos and Hatzigeorgiou 2011, Wang 2011) and frequency domain decomposition (Brincker *et al*. 2011). Papagiannopoulos and Hatzigeorgiou (Papagiannopoulos and Hatzigeorgiou 2011) proposed the third order correction to improve the half-power bandwidth method, which provided conservative and more reliable results. Wang (2011) studied the error contribution from using either the classical or the third order half power approximations to calculate the damping effect. Results show that when the system damping is less than 0.1, the classical approximation itself introduced little error. A higher order correction may be used to reduce the truncation error for systems where the damping ratio is higher. Methods in the time domain include, such as logarithmic-decrement technique (Salzmann *et al*. 2003), eigensystem realization algorithm (Juang and Pappa 1985), STD method (Ibrahim 1986), etc. Time-frequency domain methods such as wavelet analysis method (Slavič, M. Boltežar 2011, Uhl and Klepka 2005, Zhang *et al*. 2014) and Hilbert–Huang Transform (HHT) method (Xu *et al*. 2003), have also been proposed. Uhl and Klepka (2005) proposed a recursive based wavelet method for modal parameters identification based on operational measurements. The results show that the natural frequencies identified by the HHT method are almost the same as those obtained by the FFT-based method. The first two modal damping ratios given by the HHT method are, however, lower than those by the FFT-based method, which may indicate that the FFT based method overestimates the modal damping ratios. It is noted that the above-mentioned are non-model based methods.

Sensitivity-based model updating method (Li *et al*. 2015) for damping identification with vibration measurements belongs to another category, which has gained significant attentions. Traditional non-modal based method is difficult to identify the damping of the high frequency modes because these modes are difficult to excite. Kang *et al*. (2005) used the Rayleigh damping and the two coefficients were identified from acceleration responses with optimization methods. Pradhan and Modak (2012) proposed a Frequency Response Function (FRF) based method for damping matrix identification through FE model updating. The method is formulated such that the damping matrix is identified iteratively so as to reduce the difference between the complex and the normal FRFs of a structure. Li and Law (2009) conducted the identification of damping ratios based on the sensitivity of acceleration response and model updating technique, and performed a numerical study on a five-bay frame structure to investigate the effectiveness and validity of the sensitivity-based model updating method. An iterative regularization based approach (Ding and Law 2011) was also proposed to identify time-invariant Rayleigh damping, time-variant Rayleigh damping and modal damping, respectively. A new constraint is imposed on the identified iterative increment as well as on the unknown structural parameters to ensure their physical meaning in the identification process is not lost. Regarding the sensor placement for the optimal system identification and modal estimation, Yi *et al*. (2016), Yi *et al*. (2016), proposed an original distributed wolf algorithm and an innovative swarm intelligent algorithm based on pigeon colony algorithm and have done the comprehensive study with detailed investigations. It is noted that the focus of this study is to investigate the performance of the sensitivity based model updating method for the damping identification.

This paper presents numerical and experimental investigations on civil engineering structures to identify the damping ratios with measured acceleration responses via dynamic response based model updating. Numerical studies on a three-dimensional truss bridge model are conducted to verify the effectiveness of the proposed approach. Measurement noise effect and the initial finite element modelling errors are considered. Experimental studies on a steel planar frame structure are conducted. The robustness and performance of the proposed damping identification approach are investigated with real measured vibration data.

2. Sensitivity-based model updating method

2.1 Sensitivity of acceleration response with respect to damping ratios

The general equation of motion of a damped structural system with n Degrees-of-Freedom (DOFs) can be written as

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=[D]\{f(t)\} \quad (1)$$

in which $[M]$, $[C]$ and $[K]$ are the $n\times n$ mass, damping and stiffness matrices of the structure respectively; $\{\ddot{x}(t)\}$, $\{\dot{x}(t)\}$ and $\{x(t)\}$ are respectively the acceleration, velocity and displacement response vectors of the structure; $\{f(t)\}$ is a vector of applied forces on the associated DOFs of the structure with the mapping matrix $[D]$ relating the excitation force location to the corresponding DOF. Rayleigh damping $[C]=a_1[M]+a_2[K]$ is assumed, where a_1 and a_2 are the Rayleigh damping coefficients, which can be calculated based on the first two natural frequencies and damping ratios. The dynamic responses of the structure can be obtained from Eq. (1) using the time integration algorithm.

The sensitivity of acceleration response with respect to damping ratios is expressed as $S=\partial\ddot{x}(t)/\partial\zeta$, where S and ζ denote the sensitivity matrix and damping ratio, respectively. With the Rayleigh damping considered in this study, only two damping ratios associated with the first two modes are considered. The sensitivity matrix is established as

$$S(t)=\begin{bmatrix} \frac{\partial\ddot{x}_k(t_1)}{\partial\zeta_1} & \frac{\partial\ddot{x}_k(t_1)}{\partial\zeta_2} \\ \frac{\partial\ddot{x}_k(t_2)}{\partial\zeta_1} & \frac{\partial\ddot{x}_k(t_2)}{\partial\zeta_2} \\ \cdots & \cdots \\ \frac{\partial\ddot{x}_k(t_{nt})}{\partial\zeta_1} & \frac{\partial\ddot{x}_k(t_{nt})}{\partial\zeta_2} \end{bmatrix} \tag{2}$$

where k is the measurement location on the structure. In the sensitivity matrix, the number of rows is the same as the total number of sampling points nt, and the number of column as the number of modes considered in the damping model. t is the time vector, $t=[t_1, t_2, \ldots, t_{nt}]^T$. In this study, numerical difference method is used to calculate this sensitivity matrix.

2.2 Sensitivity-based model updating method

Damping ratios identification by the sensitivity-based model updating method is performed through an iterative process to match the analytical response with the measured response (Li and Law 2009). The basic formula is derived from Taylor's series

$$f(x)=\sum_{n=0}^{\infty}\frac{f^{(n)}(a)}{n!}(x-a)^n \tag{3}$$

The higher order terms are ignored when expanding Eq. (3). For simplicity, only the first two terms are considered, the approximated Taylor's series expansion is obtained as

$$f(x)=\frac{f(a)}{0!}+\frac{f'(a)}{1!}(x-a) \tag{4}$$

Substituting $f(x)$, $f(a)$ and $f'(a)$ with $\ddot{x}_k^m(t)$, $\ddot{x}_k^a(t)$, and $S(t)$ respectively, the expression of damping ratios identification equation is derived as

$$S(t)\cdot\Delta\zeta=\Delta\ddot{x}(t)=\ddot{x}_k^m(t)-\ddot{x}_k^a(t) \tag{5}$$

where $\Delta\zeta$ denotes the change in the damping ratios. $\ddot{x}_k^m(t)$ is the measured acceleration from experimental test on the k-th Degree-of-Freedom (DOF). $\ddot{x}_k^a(t)$ is the analytical response from the finite element analysis, which can be calculated by time-step integration method, i.e., Newmark-beta method (Newmark 1959). Tikhonov regularization (Tikhonov 1963) is used to stabilize the solution of Eq. (5) by defining a modified objective function which controls the errors between the accuracy and stability of the solution. The Tikhonov regularized solution is obtained by minimizing the following objective function

$$J=\left\|S(t)\Delta\varsigma-\Delta\ddot{x}(t)\right\|^2+\lambda\left\|\Delta\varsigma\right\|^2 \tag{6}$$

where λ is the optimal regularization parameter which balances the weight of the norm of the solution and the minimization of the identification equation. The L-curve method (Hansen 1992) is employed to obtain this optimal regularization parameter λ . The solution of can be expressed as

$$\Delta\alpha=\left(S^TS+\lambda I\right)^{-1}S^T\Delta\ddot{x}(t) \tag{7}$$

where I is an identity matrix.

An iterative procedure is followed to obtain $\Delta\zeta$ in each iteration from Eq. (5) to minimize the difference between measured and updated analytical responses. The damping ratio is updated with $\zeta^{i+1}=\zeta^i+\Delta\zeta$ after each iteration. The procedure of using model updating for damping ratios identification is presented as the following three steps:

1) Based on the initial finite element model, calculate the analytical response with the Newmark-beta method and the sensitivity matrix with the numerical difference method, and then form the identification equation in terms of Eq. (5).

2) Solve the above equation with Tikhonov regularization method to obtain the increment of the damping ratios.

3) The damping ratio vector ζ is updated as $\zeta^{i+1}=\zeta^i+\Delta\zeta$. With the new damping ratios, the finite element model is updated, and the analytical responses are re-calculated.

4) The iterative process will stop until the following two convergence criteria are satisfied

$$\frac{\left\|\ddot{x}_k^{i+1}-\ddot{x}_k^i\right\|}{\left\|\ddot{x}_k^i\right\|}\leq 10^{-7}; \qquad \frac{\zeta^{c+1}-\zeta^c}{\zeta^{c+1}}\leq 10^{-7} \tag{8}$$

The flowchart of the proposed approach is shown in Fig. 1.

3. Numerical studies

3.1 Finite element model of a steel truss

Numerical studies on a three-dimensional steel truss bridge model are conducted to verify the effectiveness and performance of the proposed approach for damping identification. The dimensions and mesh of the finite element model are shown in Fig. 2. Finite element model of the truss bridge model is built in Matlab by using the two nodes space truss elements based on the material and system properties as listed in Table 1.

Each node consists of six DOFs which include the translational and rotational displacements. The finite element model includes totally 104 elements and 72 nodes. Simply supported boundary conditions are assumed with supports at nodes 1, 9, 19 and 27. The system mass and stiffness matrices can be established based on the geometry and material properties of the model. The first two natural frequencies of the truss bridge model are 50 Hz and 213 Hz, respectively.

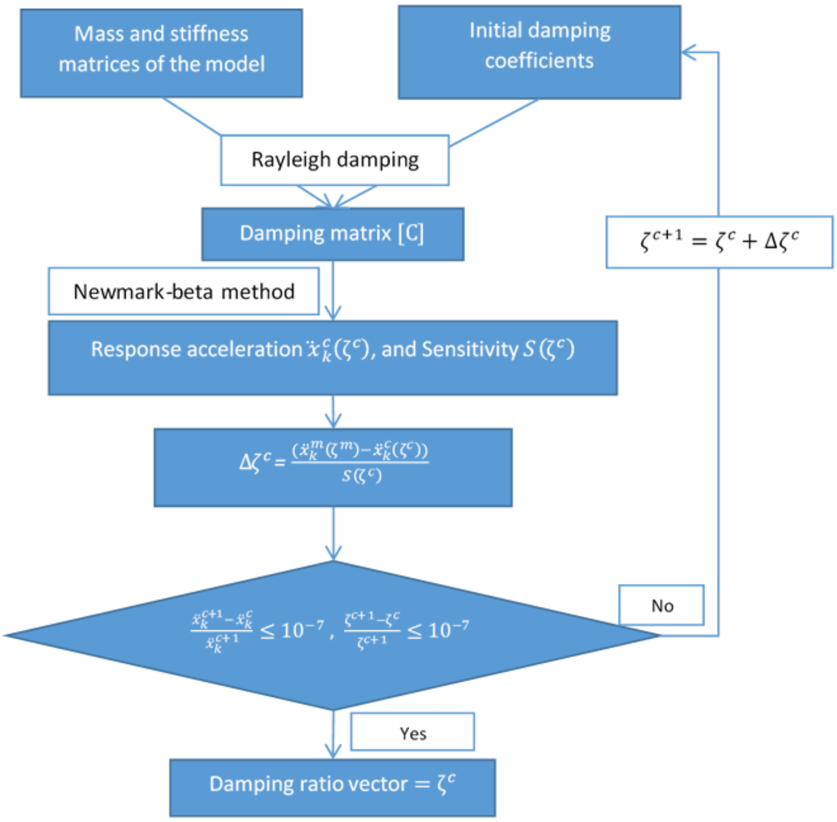

Fig. 1 The flowchart of the proposed approach

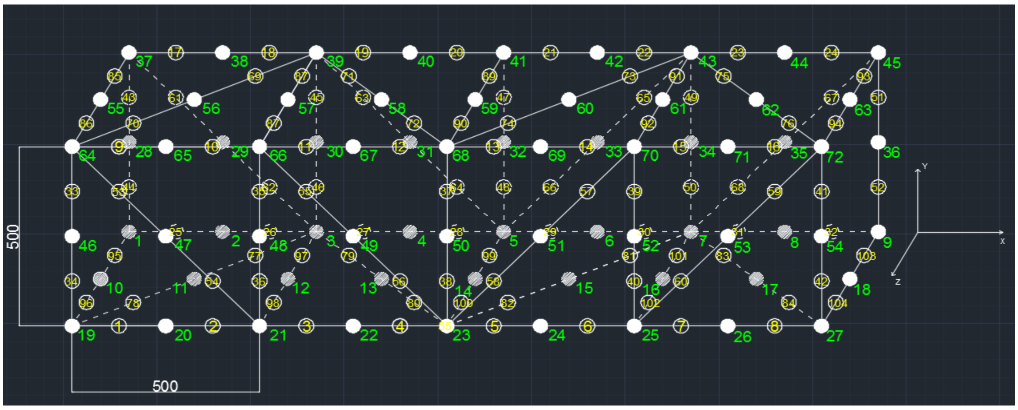

Fig. 2 Geometry and dimensions of the numerical truss bridge model (unit: mm)

Considering a steel bridge usually has a low damping effect, the damping ratio coefficients associated with the first and second modes are assumed as 1% and 2%, respectively. The truss model is subjected to an impact force at node 67 in Y direction, and the acceleration response at node 66 in Y direction is obtained for identification.

The sampling rate is set as 2000 Hz and the first 0.25s data are used in the damping identification. Since the truss bridge has a low damping effect, the energy after 0.25s dissipates very quickly.

3.2 Identification under ideal conditions

No measurement noise, finite element modelling errors and other errors are considered in this case. The response from the ideal conditions are used for the damping ratio identification by following the procedure presented in Fig. 1. The damping ratio identification results are presented in Table 2. When the identified damping ratios are used for calculating the dynamic responses, it can be observed from Fig. 3 that the analytical response after updating can match the simulated measured response very well, indicating the good accuracy in identifying the damping effect.

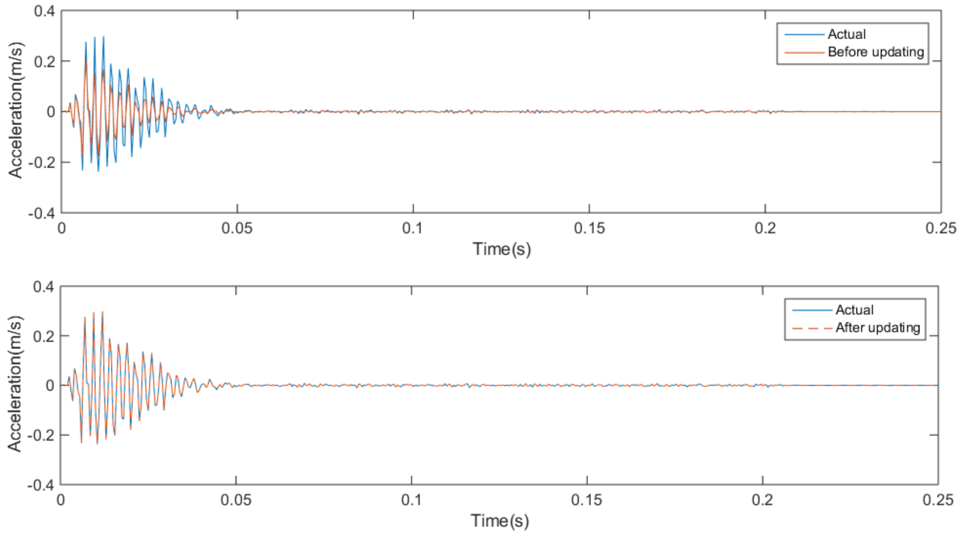

Fig. 3 Comparison between the simulated measured and analytical responses after updating

Table 1 Physical properties of the numerical truss bridge model

Members	Chords	Diagonal and vertical elements
Material	Steel	Steel
Young's modulus	210GPa	210GPa
Cross section area *A*	475 mm^2	250 mm^2
Density,	7800 kg/m^3	7800 kg/m^3
Moment of area I_y	1.125 x 10^5 mm^4	5.21 x 10^2 mm^4
Moment of area I_z	1.125 x 10^5 mm^4	5.21 x 10^4 mm^4
Torsional constant J	2.0604 x 10^3 mm^4	3.9583 x 10^3 mm^4
Poisson ratio	0.3	0.3

Table 2 Damping identification under ideal conditions

Damping ratio	Before updating	After updating	True value
ζ_1	5%	1%	1%
ζ_2	5.5%	1.5%	1.5%

3.3 Uncertainty effects

The robustness of the proposed approach for identifying the damping ratios is investigated when the uncertainty effects, i.e., the measurement noises in responses and the finite element modelling errors are considered.

3.3.1 Measurement noise

White Gaussian noise is added to the actual acceleration to simulate the polluted response. The identifications of damping ratios with acceleration contaminated by 2%, 5% and 10% noise effects are conducted. The results listed in Table 3 demonstrates that the proposed approach is not sensitive to the noise effect and the accuracy is generally good.

3.3.2 Initial finite element modelling errors

The initial finite element modelling errors inevitably exist in the modelling process due to the possible structural damage, inaccurate estimation of boundary conditions and inhomogeneous material properties etc. Random uncertainties are considered in the stiffness of the truss model. 2% and 5% random levels of normal modelling errors are considered and the identification results are presented in Table 4. It should be noted that in this case, the damping ratios for the first and second modes are defined as 2% and 2.5%, respectively. It can be observed from Table 4 that the identification of damping ratios are significantly affected by the initial random finite element modelling errors.

Table 3 Damping ratios identification under measurement noise effect

Mode	True	2% noise	5% noise	10% noise
1	1%	1.02%	1.02%	0.87%
2	1.5%	1.51%	1.5%	1.47%

Table 4 Damping ratios identification under initial random modelling errors

Mode	True	2% modelling errors	5% modelling errors
1	2%	2.28%	6.42%
2	2.5%	2.53%	3.63%

4. Experimental investigations

4.1 Experimental model

Experimental studies on a seven-storey planar frame structure are conducted to investigate the effectiveness of the proposed approach. The steel frame structure in the laboratory is shown in Fig. 4. The total height of the frame is 2.1 m where each storey has a height of 0.3 m. The parallel beams at seven stories have a length of 0.5 m. Beams and columns are connected by a continuous weld at two ends of beam section. The cross-sections of the column and beam elements are measured as 49.98 mm × 4.85 mm and 49.89 mm × 8.92 mm, respectively. The measured mass densities of the column and beam elements are 7850 kg/m^3 and 7734.2 kg/m^3, respectively. Two pairs of mass blocks are bolted at 1/4 and 3/4 length along the beam members to represent the mass on the floor in practical structure. Each pair of mass blocks is approximately 4 kg containing two steel blocks fixed on top and bottom of beam with washers between steel block and beam member. The two bottom ends of frame are welded to a thick and flat steel plate connecting with the floor. Therefore, the connections of both ends are considered as fixed supports. All the measurement equipment and cables are connected to the ground to reduce the disturbances of AC power effect on the measured response. The first seven frequencies of the structures are 2.54, 7.66, 12.86, 18.03, 18.03, 26.99 and 29.91 Hz, respectively.

The acceleration responses of the structure were measured from Model B&K 3023 and KD 1010 accelerometers. The measuring sampling rate is set as 2000 Hz. A low-pass filter with a cutoff frequency of 1000 Hz is defined. The SINOCERA LC-04A hammer with a rubber tip is used to generate the excitation.

Fig. 4 The laboratorysteel frame model

The signals were recorded with National Instruments (NI) data acquisition system and DEWESoft data acquisition software was employed to communicate with the NI system and record the vibration testing responses.

4.2 Finite element modelling

The finite element model of the frame structure is built in a two-dimensional Cartesian coordinate system. Each beam and column in every storey is equally defined as four and three elements respectively with two-node planar beam elements. In this two-dimensional frame finite element model, every node consists of three DOFs which are the translational displacements in X and Y directions and the rotational displacement in XY plane.

The weights of mass blocks are added to the corresponding nodes of the finite element model as lumped masses. The finite element model of the frame includes totally 70 planar elements and 65 nodes. With 3 DOFs at each node, the model has 195 DOFs in total. Two fixed supports are at node 1 and 65. The accelerometers are attached to the columns, and the impact load is applied by an impact modal hammer. The locations of sensors and impact load are shown in Table 5. The finite element model of the frame structure is shown in Fig. 5.

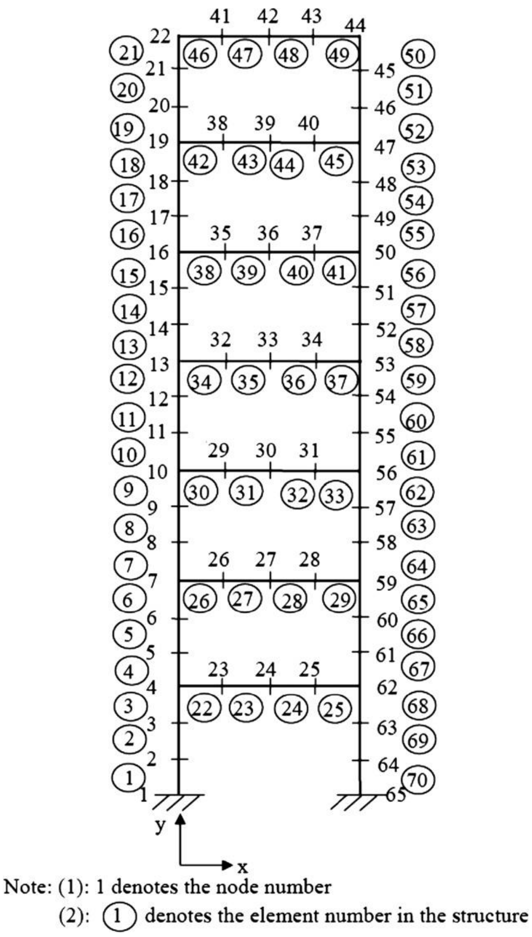

Fig. 5 Finite element model of the frame structure

Table 5 Location of sensors and impact load

Sensor number	Sensor Location (Node)	Sensor Location (DOF)
1	19(x)	55
2	16(x)	46
3	13(x)	37
4	10(x)	28
5	7(x)	19
Impact load location	44(x)	130

4.3 Updating structural stiffness and boundary conditions

The accuracy of sensitivity-based model updating method is significantly influenced by the finite element modeling errors. The mass matrix is constructed accurately because in this experiment test the mass and dimensions of used steel members can be easily measured. While the stiffness of the finite element model is difficult to accurately establish with the initial estimation due to the stiffness of connections and the inhomogeneous material properties. To reduce the discrepancy between the analytical model and the experimental model, the initial stiffness matrix and boundary conditions are updated before the damping ratios identification. Detailed updating procedure and results can be found in the literature (Li *et al.* 2012, Li and Hao 2014).

The accuracy of updating the structural stiffness and boundary conditions is demonstrated with the minimized errors in the frequencies and Modal Assurance Criteria (MAC) values before and after updating, indicating that the analytical finite element model matches well the actual experimental model.

4.4 Identification of damping ratios by sensitivity-based model updating method

The damping ratios are identified by using the proposed approach with different lengths of time responses to investigate the robustness of the approach. The response duration varies from 1s, 2s, 3s, 4s to 5s. Measured responses from five accelerometers at sensor numbers 1, 2, 3, 4 and 5, as shown in Table 5, are used simultaneously to obtain more information from the testing model such that the identification results are more reliable. The initial damping ratios for 1^{st} and 2^{nd} modes are set as ζ_1=1% and ζ_2 =0.5% respectively.

As the actual damping ratios of the frame structure are unknown, the errors of the true damping ratios and identified ones cannot be directly presented in the experimental study. Therefore, the relative error is calculated by comparing the measured responses and analytical responses with the updated damping ratios.

Table 6 shows the identified damping ratios for the 1st and 2nd modes. It is observed that the relative errors between the measured and analytical responses increase with the extension of used response time duration. This is because when a longer period is used, higher modes are involved since the response decays very quickly for this planar steel frame with very low damping coefficients. When higher modes are engaged, the Rayleigh damping model has the limited capacity to simulate the energy dissipation. Figs. 6-8 show the measured responses from tests and analytical responses calculated with the updated damping ratios identified by using 1s, 2s and 5s measurement data respectively. It can be seen that a good agreement between measured and analytical responses is achieved using identified damping ratios as shown in Figs. 6 and 7. The identification of damping ratios for the 1st and 2nd modes by the sensitivity-based method is more accurate with short term responses. As shown in Figs. 6 and 7, the analytical acceleration response is very close to the measured response for the first second and first two seconds data, respectively. It indicates that the damping ratios of the 1st and 2nd modes obtained from the first 1 or 2 seconds acceleration responses are more reliable due to the small discrepancy in responses. A satisfactory result is observed between those two responses as shown in Fig. 8. The differences in the identified damping ratios with 3s, 4s and 5s data, respectively as shown in Table 6, are not prominent. Therefore the damping ratios identification results are still acceptable to reconstruct the dynamic acceleration responses.

Table 6 Identified damping ratios with sensitivity-based model updating method

Time duration(s)	ζ_1	ζ_2	Relative error between analytical and measured responses
1	1.10%	0.38%	7.64%
2	0.79%	0.27%	11.26%
3	0.70%	0.24%	15.67%
4	0.67%	0.23%	20.11%
5	0.66%	0.22%	24.34%

Table 7 The relative errors in the measured and analytical responses with identified damping ratios by half-power bandwidth method and the proposed approach

Response duration (s)	With damping ratios by half-power band width method	With damping ratios by the proposed approach
1	9.02%	7.64%
2	12.39%	11.26%
3	17.66%	15.67%
4	22.87%	20.11%
5	43.34%	24.34%

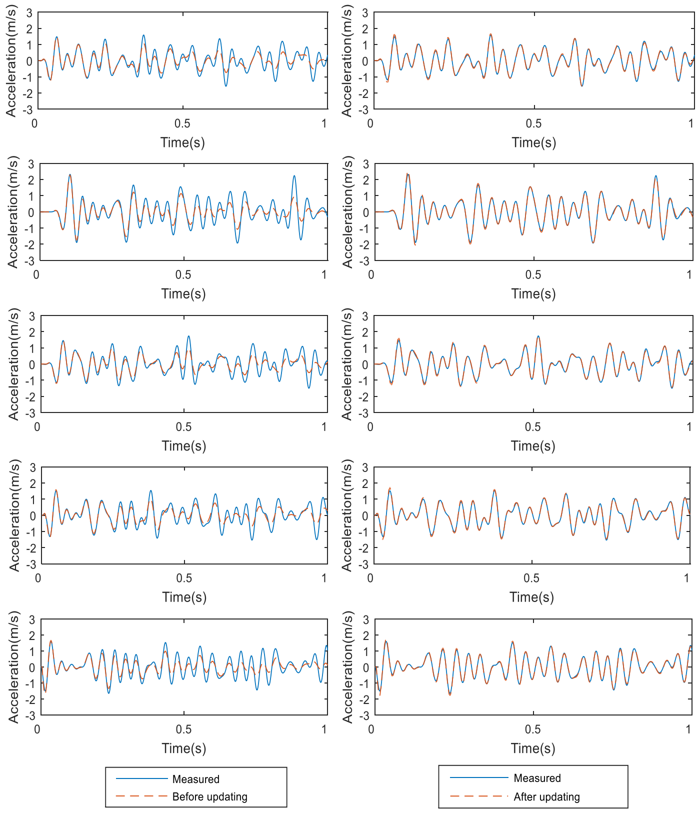

Fig. 6 Measured responses and calculated responses before and after updating with 1s data

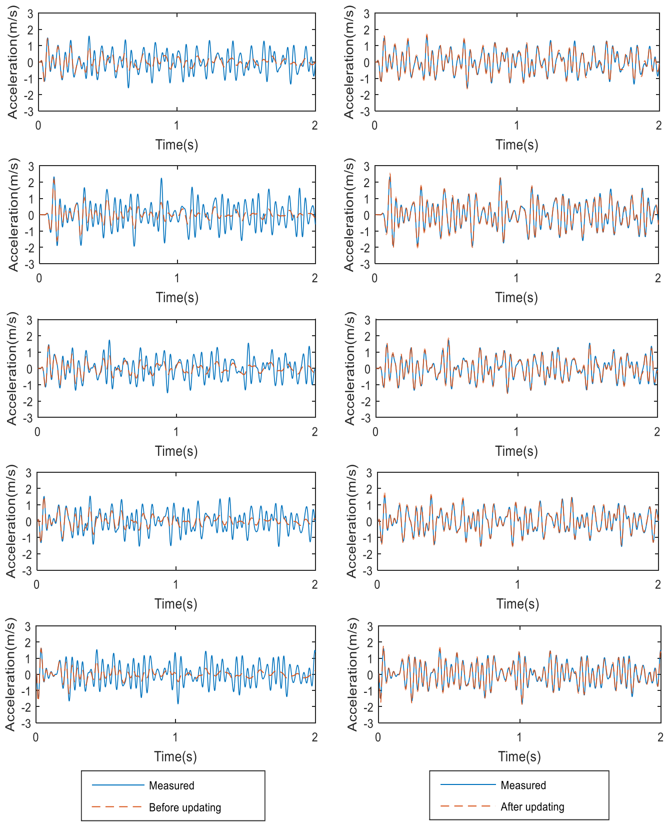

Fig. 7 Measured responses and calculated responses before and after updating with 2s data

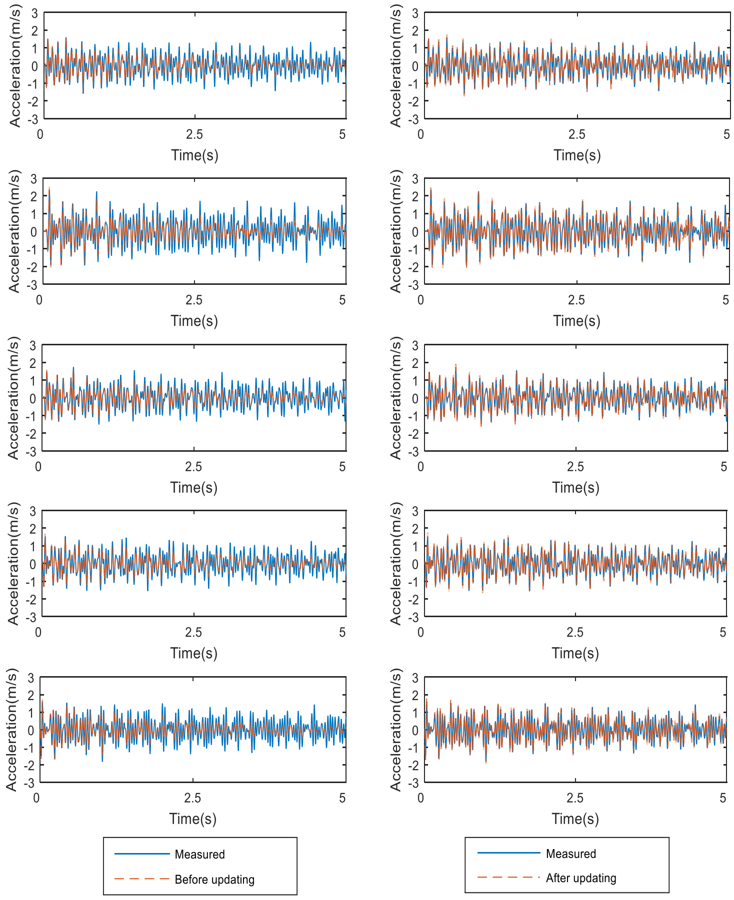

Fig. 8 Measured responses and calculated responses before and after updating with 5s data

4.5 Comparing the response prediction error with the identified damping ratios by half-power bandwidth method

Half-power bandwidth method is a simple and popular method, which is employed to calculate the damping ratios. To investigate the accuracy of using the damping ratios obtained by the half-power bandwidth method and the proposed approach to respectively predict the structural vibration responses, those damping ratios will be used to calculate the analytical responses with the finite element analysis and compare with the measured response.

The relative errors between the analytical and measured responses with identified damping ratios by half-power bandwidth method and the proposed approach are listed in Table 7. The damping ratios calculated with 90 seconds response with the half-power bandwidth method are 0.2% and 0.19% for the first and second modes respectively. They are different as the damping ratios identified with the proposed model updating method. However, it can be observed from Table 7 that using the identified damping ratios with the proposed approach to calculate the analytical response gives a smaller relative error in the dynamic response prediction compared with the experimental measured response.

The relative error by using the damping ratios from sensitivity-based model updating method is generally lower than that using the two pairs of the damping ratios from half-power bandwidth in all the time durations from 1s to 5s, as shown in Table 7. This demonstrates that the proposed approach may provide a more accurate response prediction for dynamic analysis with the estimated damping ratios.

5. Conclusions

Compared with other damping identification methods, sensitivity-based model updating method has a very good performance to predict the structural vibration responses with the identified damping ratios. Rayleigh damping model is assumed and the response sensitivity based model updated is performed to identify the damping ratios by minimizing the measured responses and analytical responses from finite element analysis. Numerical and experimental studies on a truss bridge model and a steel frame structure are conducted respectively to investigate the effectiveness and performance of the proposed approach. Identification results in numerical studies demonstrate that the damping ratio identification with the proposed approach is not sensitive to the noise effect but could be affected significantly by the modelling errors. It can be observed from the results in experimental investigations that the proposed approach can identify the damping ratios of the 1st and 2nd modes simultaneously with the Rayleigh damping model. When a longer time domain response period is involved, higher modes responses may be observed. If the damping ratios for more than two modes need to be determined, the modal damping model may be used, and the similar approach and procedure can be followed. The steel frame structure is of very small damping ratios, which may be difficult for the sensitivity-based model updating method to give an accurate identification result. With the identified damping ratios, the analytical responses from the finite element analysis can match well with the experimentally measured responses, indicating that a good estimation of damping ratios can be helpful for accurately analysing the structural vibration behavior and performing the response analysis.

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