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Structural damage detection including the temperature difference based on response sensitivity analysis

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Abstract. Damage detection based on a reference set of measured data usually has the problem of different environmental temperature in the two sets of measurements, and the effect of temperature difference is usually ignored in the subsequent model updating. This paper attempts to identify the structural damage including the temperature difference with artificial measurement noise. Both local damages and the temperature difference are identified in a gradient-based model updating method based on dynamic response sensitivity. The sensitivities of dynamic response with respect to the system parameters and temperature difference are calculated by direct integration method. The measured dynamic responses of the structure from two different states are used directly to identify the structural local damages and the temperature difference. A single degree-of-freedom mass-spring system and a planar truss structure are studied to illustrate the effectiveness of the proposed method.

Keywords: response sensitivity; damage detection; model updating; temperature difference

1. Introduction

Damage identification and health monitoring in mechanical system and civil engineering structures is a hot research topic and has received considerable attention in the past few decades. It is important to identify structural damage at its early stage of development. Non-destructive techniques have been developed for practical and accurate damage detection, and most of them are based on measured vibration responses. There are a lot of non-destructive methods for damage detection. Housner *et al*. (1997) presented an extensive summary on the state-of-the-art in control and health monitoring in civil engineering structures. Salawu (1997) discussed and reviewed the use of natural frequency as a diagnostic parameter in structural assessment procedures using vibration monitoring. Doebling *et al*. (1998) provided a comprehensive review of the damage detection methods by examining changes in the dynamic properties of a structure. Zou *et al*. (2000) summarized the methods on vibration-based damage detection and health monitoring for composite structures, especially in delamination modeling techniques and delamination detection.

Damage detection usually requires a mathematical model of the structure in conjunction with

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experimental modal parameters of the structure. The identification approaches are mainly based on the change in the natural frequencies (Cawley and Adams 1979, Wang and He 2007, Urgessa 2011, Majumdar *et al*. 2013), mode shapes (Pandey *et al*. 1991, Hadjileontiadis *et al*. 2005, Wang and Qiao 2008) or measured dynamic flexibility (Pandey and Biswas 1994, Doebling *et al*. 1996, Bijaya and Ren 2006, Wu and Law 2004, Yang 2011). The natural frequency is easy to measure and with a high level of accuracy, and it is the most common dynamic parameter for damage detection. However, problems may arise in some structures if only natural frequencies are used, since the structural symmetry would lead to non-uniqueness in the solution in the inverse analysis of damage detection. This problem can be overcome by incorporating the mode shape data in the analysis. Finite element model (FEM) updating method is the most popular tool for damage detection making use of these modal parameters.

A large number of gradient-based model updating methods have been discussed by Friswell and Mottershead (Friswell and Mottershead 1995). The major difficulty in using finite element model updating method lies in the differentiation between the local damages and modeling errors in the structure (Friswell and Mottershead 2001), and a two-stage method has been proposed to overcome this problem(Wu and Law 2004). The finite element model of the undamaged structure is firstly updated to remove most of the model errors to have a more accurate model. Then the differences in the modal parameters between the damaged and the intact structures are used to estimate the changes in the system parameters.

Damage detection methods using structural dynamic responses in time domain have also been explored. Cattarius and Inman (1997) used the time histories of vibration response of the structure to identify damage in smart structures. Majumder and Manohar (2003) proposed a time domain approach for damage detection in beam structures using vibration data. The vibration induced by a vehicle moving on the bridge was taken to be the excitation force. Koh *et al*. (2000) identified the structural stiffness parameters of a multi-storey framework in a system identification approach. In recent years, the dynamic response sensitivity based finite element model updating mehtod has been developed and it was used to identify structural damages and crack parameters using the measured dynamic responses (Lu and Law 2007, He and Lu 2010, Lu and Liu 2011, Lu *et al*. 2013). Although it only needs a few number of measurement points, it still can provide high accuracy for damage or crack identification taking advantage of the plentiful time histories data.

In practice, the environmental effect on damage detection is difficult to take into account in the damage detection algorithm. For example, the temperature difference between two measurement states of the structure leads to different member dimensions of the structure in the two states. This effect would be significant in the case of a structure with large dimensions, e.g. a long span cable-supported bridge structure. The temperature difference in the two subsequent measurements was often ignored by researchers.

This paper aims to identify the structural damages including the temperature difference in the structural components. Both local damages and the temperature difference are identified in a gradient-based model updating method based on dynamic response sensitivity. The sensitivities of dynamic response to the system parameters and temperature difference are calculated in the time domain. The measured dynamic responses of the structure from two different states are used directly to identify the location and extent of local damage, and the temperature difference as well. A single degree-of-freedom mass-spring system and a planar truss structure are studied to illustrate the effectiveness of the proposed damage detection method.

2. Sensitivity in time domain

2.1 Dynamic response of the system

For a general finite element model of a linear elastic time-invariant system with *n* element, the equation of motion is given by

$$[M]\{\ddot{d}\}+[C]\{\dot{d}\}+[K]\{d\}=[B]\{F\} \tag{1}$$

where [M], [C] and [K] are the system mass, damping and stiffness matrices respectively. Rayleigh damping model is adopted, which is of the form $[C]=a_1[M]+a_2[K]$, where a_1 and a_2 are constants to be determined from two given damping ratios corresponding to two modal frequencies. $\{\ddot{d}\}$, $\{\dot{d}\}$ and $\{d\}$ are the acceleration, velocity and displacement response vectors of the system, $\{F\}$ is a vector of applied forces with matrix $[B]$ mapping these forces to the associated degrees-of-freedom of the system. The dynamic responses of the system can be obtained by direct numerical integration using Newmark method.

2.2 Sensitivity of response with respect to system parameters

The mass matrix can be formulated from either the consistent mass matrix or the lump mass matrix. In this paper, the consistent mass matrix is adopted. Differentiating both sides of Equation (1) with respect to the *i*th mass parameter the system will give

$$[M]\{\frac{\partial\ddot{d}}{\partial\alpha_m^i}\}+[C]\{\frac{\partial\dot{d}}{\partial\alpha_m^i}\}+[K]\{\frac{\partial d}{\partial\alpha_m^i}\}=-a_1\frac{\partial[M]}{\partial\alpha_m^i}\{\dot{d}\}-\frac{\partial[M]}{\partial\alpha_m^i}\{\ddot{d}\} \qquad (i=1,2,\ldots n) \tag{2}$$

where *n* is the total number of the finite element for the structure, $\{\frac{\partial d}{\partial\alpha_m^i}\}$, $\{\frac{\partial\dot{d}}{\partial\alpha_m^i}\}$, $\{\frac{\partial\ddot{d}}{\partial\alpha_m^i}\}$ are the displacement, velocity and acceleration sensitivities with respect to the mass parameter of the *i*th element, the subscript *m* denotes the mass parameter. Note that Eq. (2) is of the same form as Eq. (1). Since the dynamic responses have been obtained from Eq. (1), the right-hand-side of Eq. (2) serves as the equivalent force input, and the sensitivities can then be obtained numerically by direct integration. The sensitivities of response with respect to each stiffness parameter, i.e., $\{\frac{\partial d}{\partial\alpha_k^i}\}$, $\{\frac{\partial\dot{d}}{\partial\alpha_k^i}\}$, $\{\frac{\partial\ddot{d}}{\partial\alpha_k^i}\}$ can be obtained in a similar way

$$[M]\{\frac{\partial\ddot{d}}{\partial\alpha_k^i}\}+[C]\{\frac{\partial\dot{d}}{\partial\alpha_k^i}\}+[K]\{\frac{\partial d}{\partial\alpha_k^i}\}=-a_2\frac{\partial[K]}{\partial\alpha_k^i}\{\dot{d}\}-\frac{\partial[K]}{\partial\alpha_k^i}\{d\} \quad (i=1,2,\ldots n) \tag{3}$$

where subscript *k* denotes the stiffness parameter.

This response sensitivity approach, theoretically, could be used to update all the system parameters of the structure from measured dynamic measurements of sufficient length. The same approach could be used further to identify the structural damage and the temperature difference from measurements obtained from two different states of the structure.

(a) (b)

Fig. 1 (a) A cantilever bar, (b) The equivalent single DOF system

2.3 Sensitivity of response with respect to temperature difference

Differentiating both sides of Eq. (1) with respect to the temperature difference of the *i*th element the system, we have

$$[M]\{\frac{\partial\ddot{d}}{\partial\Delta T^i}\}+[C]\{\frac{\partial\dot{d}}{\partial\Delta T^i}\}+[K]\{\frac{\partial d}{\partial\Delta T^i}\}=-a_2\frac{\partial[K]}{\partial\Delta T^i}\{\dot{d}\}-a_1\frac{\partial[M]}{\partial\Delta T^i}\{\dot{d}\}-\frac{\partial[K]}{\partial\Delta T^i}\{d\}-\frac{\partial[M]}{\partial\Delta T^i}\{\ddot{d}\}$$
$$(\,i=1,2,\ldots n\,) \tag{4}$$

It is assumed that the temperature difference ΔT only affect the parameters of the stiffness matrix and does not affect the parameters of the mass matrix, that is to say, the mass matrix is not the function of ΔT. Thus the second and fourth terms on the right hand side of Eq. (4) vanish. Eq. (4) is rewritten as

$$[M]\{\frac{\partial\ddot{d}}{\partial\Delta T^i}\}+[C]\{\frac{\partial\dot{d}}{\partial\Delta T^i}\}+[K]\{\frac{\partial d}{\partial\Delta T^i}\}=-a_2\frac{\partial[K]}{\partial\Delta T^i}\{\dot{d}\}-\frac{\partial[K]}{\partial\Delta T^i}\{d\}\quad(\,i=1,2,\ldots n\,) \tag{4a}$$

Again, the sensitivity of response with respect to the temperature difference can be obtained from Eq. (4a) by direct integration method.

3. Identification of damage and temperature difference

The difference of responses at time t_i between two different measurements of the damaged and the intact structures ΔR_{t_i}, under the same excitation can be expressed as a first order differential equation with respect to the system parameter of the system. The differential of response with respect to the temperature difference can also be calculated for each finite element. When writing in the form of Taylor first order approximation

$$\Delta R_{t_i}=\sum_{j=1}^{n}\frac{\partial R_{t_i}}{\partial\alpha_m^j}\Delta\alpha_m^j+\sum_{j=1}^{n}\frac{\partial R_{t_i}}{\partial\alpha_k^j}\Delta\alpha_k^j+\sum_{j=1}^{n}\frac{\partial R_{t_i}}{\partial\Delta T^j}\Delta(\Delta T^j) \tag{5}$$

The temperature differences in all members may be assumed equal for simplicity, i.e., $\Delta T^1=\Delta T^2=\ldots=\Delta T^n$. In fact, the pattern of temperature distribution in a structure can be obtained from temperature sensors or from theoretical model on the temperature distribution. If there is $N_t(N_t>3\times n)$ time steps in a single measured response, Eq. (5) is over-determined, and it can be written in a matrix form

$$\begin{bmatrix} \frac{\partial R_{t_1}}{\partial \alpha_m^1} & \cdots & \frac{\partial R_{t_1}}{\partial \alpha_m^n} & \frac{\partial R_{t_1}}{\partial \alpha_k^1} & \cdots & \frac{\partial R_{t_1}}{\partial \alpha_k^n} & \frac{\partial R_{t_1}}{\partial \Delta T^1} & \cdots & \frac{\partial R_{t_1}}{\partial \Delta T^n} \\ \frac{\partial R_{t_2}}{\partial \alpha_m^1} & \cdots & \frac{\partial R_{t_2}}{\partial \alpha_m^n} & \frac{\partial R_{t_2}}{\partial \alpha_k^1} & \cdots & \frac{\partial R_{t_2}}{\partial \alpha_k^n} & \frac{\partial R_{t_2}}{\partial \Delta T^1} & \cdots & \frac{\partial R_{t_2}}{\partial \Delta T^n} \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial R_{t_i}}{\partial \alpha_m^1} & \cdots & \frac{\partial R_{t_i}}{\partial \alpha_m^n} & \frac{\partial R_{t_i}}{\partial \alpha_k^1} & \cdots & \frac{\partial R_{t_i}}{\partial \alpha_k^n} & \frac{\partial R_{t_i}}{\partial \Delta T^1} & \cdots & \frac{\partial R_{t_i}}{\partial \Delta T^n} \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial R_{t_{Nt}}}{\partial \alpha_m^1} & \cdots & \frac{\partial R_{t_{Nt}}}{\partial \alpha_m^n} & \frac{\partial R_{t_{Nt}}}{\partial \alpha_k^1} & \cdots & \frac{\partial R_{t_{Nt}}}{\partial \alpha_k^n} & \frac{\partial R_{t_{Nt}}}{\partial \Delta T^1} & \cdots & \frac{\partial R_{t_{Nt}}}{\partial \Delta T^n} \end{bmatrix} \begin{Bmatrix} \Delta\alpha_m^1 \\ \vdots \\ \Delta\alpha_m^n \\ \Delta\alpha_k^1 \\ \vdots \\ \Delta\alpha_k^n \\ \Delta(\Delta T^1) \\ \vdots \\ \Delta(\Delta T^n) \end{Bmatrix} = \begin{Bmatrix} \Delta R_{t_1} \\ \Delta R_{t_2} \\ \vdots \\ \Delta R_{t_i} \\ \vdots \\ \Delta R_{t_{Nt}} \end{Bmatrix} \tag{6}$$

or in short

$$S\Delta P = \Delta R \tag{7}$$

where S is the response sensitivity matrix, ΔP is the vector of unknown incremental parameters and the temperature difference, ΔR is the vector of incremental measured responses. Eq. (7) can be solved by the simple least-squares method

$$\Delta P = [S^T S]^{-1} S^T \Delta R \tag{8}$$

or

$$P_{j+1} = P_j + [S_j^T S_j]^{-1} S_j^T \Delta R \tag{8a}$$

where the subscript j indicates the iteration number at which the sensitivity matrix is computed.

Like many other inverse problems, Eq. (11) is ill-conditioned. In order to provide bounds to the solution, the damped least-squares method (DLS) (Tikhonov 1963) is used and singular-value decomposition is employed in the pseudo-inverse calculation. Eq. (8) can be written in the following form in the DLS method

$$\Delta P = (S^T S + \lambda I)^{-1} S^T \Delta R \tag{9}$$

where λ is the non-negative damping coefficient governing the participation of the least-squares error in the solution. The solution of Eq. (9) is equivalent to minimizing the function

$$J(\{\Delta P\}, \lambda) = \left\| S\Delta P - \Delta R \right\|^2 + \lambda \left\| \Delta P \right\|^2 \tag{10}$$

with the second term providing bounds to the solution. When the parameter λ approaches zero, the estimated vector $\{\Delta P\}$ approaches the solution obtained from the simple least-squares method. L-curve method (Hansen 1992) is used in this paper to obtain the optimal regularization parameter λ.

4. Numerical example

4.1 Example 1: Single degree-of-freedom system

Fig. 1 shows a cantilever bar and its equivalent model of a single degree-of-freedom system. The mass and damping of the system is m and c respectively, and the spring coefficient equals to $k=EA/L$. The parameters of the original system are: m=10 Kg, c=1.9 N·s/m, EA=1000 N and L=1 m. The equation of motion of the system is

$$m\ddot{d} + c\dot{d} + \frac{EA(1-\alpha\Delta T)}{L} d = F(t) \tag{11}$$

Performing differentiation on both sides of Eq. (11) with respect to the mass, damping, axial stiffness of the system and ΔT, we have

$$m\frac{\partial \ddot{d}}{\partial m} + c\frac{\partial \dot{d}}{\partial m} + \frac{EA(1-\alpha\Delta T)}{L}\frac{\partial d}{\partial m} = -\ddot{d} \tag{12}$$

$$m\frac{\partial \ddot{d}}{\partial c} + c\frac{\partial \dot{d}}{\partial c} + \frac{EA(1-\alpha\Delta T)}{L}\frac{\partial d}{\partial c} = -\dot{d} \tag{13}$$

$$m\frac{\partial \ddot{d}}{\partial \Delta T} + c\frac{\partial \dot{d}}{\partial \Delta T} + \frac{EA(1-\alpha\Delta T)}{L}\frac{\partial d}{\partial \Delta T} = \frac{\alpha EA}{L} d \tag{14}$$

$$m\frac{\partial \ddot{d}}{\partial EA} + c\frac{\partial \dot{d}}{\partial EA} + \frac{EA(1-\alpha\Delta T)}{L}\frac{\partial d}{\partial EA} = -\frac{(1-\alpha\Delta T)}{L} d \tag{15}$$

Responses from different measurement states are used for the identification. The bar is subject to an axial excitation of F=400sin16πt N along the local x-axis. Sampling rate is taken equal to 200 Hz and measured acceleration data along the x-axis are used for the identification. The measurement time duration is two seconds.

Study case 1: System parameters identification including temperature difference

The set of damaged system parameter is taken to be m=10 Kg, c=2.0 N·s/m, EA=950 N, and assuming that there is a temperature difference of ΔT=+20℃ between the two sets of measurements. The initial values for model updating are taken as the parameters of the original system, i.e., m=10 Kg, c=1.9 N·s/m, EA=1000 N, and the initial value for temperature difference is ΔT=0. Table 1 gives identified results of the system parameters m, c, and k and the temperature difference ΔT. The number of iteration required for convergence is 18, and the optimal regular parameters is 3.66×10^{-3}. Table 1 shows that the system parameters and the temperature difference have been identified accurately.

Study case 2: Effect of additional mass of measurement sensor

The set of damaged system parameters is the same as the case 1. A sensor mass of 0.01 Kg is added to the system and assume that there is a temperature difference of ΔT=+20℃ between the two sets of measurements. Table 2 gives the identified results with (Case A) and without (Case B)

Table 1 System identification including temperature difference

	m	c	k	ΔT
True	10	2.0	950	+20
Identified	10/(0.0)	2.0/(0.0)	950/(0.0)	+20/(0.0)

Note: (•) percentage error in identification

Table 2 Effect of additional mass

	Updated mass	Updated damping	Updated axial stiffness	Updated temperature difference
Case *A*	10.01/(0.0)	2.0/(0.0)	950/(0.0)	+20/(0.0)
Case *B*	10.0/(0.1)	2.013/(0.6)	948.97/(0.1)	+19.8/(1.0)

Note: (•) percentage error in identification

Table 3 Effect of measurement noise

Noise Level	Updated mass	Updated damping	Updated axial stiffness	Updated temperature difference
1%	9.997/(0.03)	1.97/(1.5)	950.7/(0.07)	+19.8/(1.0)
5%	9.987/(0.13)	2.097/(4.85)	948.34/(0.17)	+19.5/(2.5)
10%	9.97/(1.5)	2.2/(10)	946.7/(0.39)	+18.2/(9.0)

Note: (•) percentage error in identification

considering the additional mass. The required number of iteration for convergence is 21 for both cases, and the optimal regularization parameters are 0.011 and 0.08, respectively. Results from Table 2 show that the omission of 0.01 Kg in the system mass leads to a spread of errors in the identified parameters of 0.1%, 0.6%, 0.1% and 1.0% in the system mass, damping, axial stiffness and temperature difference, respectively.

Study case 3: Effect of measurement noise

In practice, measurement noise exists in the measured responses. The effect of 1%, 5% and 10% noise level on the identified results is investigated. A normally distributed random error with zero mean and unit standard deviation is added to the measured acceleration as

$$\hat{\ddot{d}} = \ddot{d}_{cal} + Ep \times N_{oise} \times \mathrm{var}(\ddot{d}_{cal}) \tag{16}$$

where $\hat{\ddot{d}}$ is the vector of polluted acceleration, E_p is the noise level, N_{oise} is a standard normal distribution vector with zero mean and unit standard deviation, var(•) is the variance of the time history, $\ddot{d}_{cal}$ is the vector of calculated acceleration. 2000 measurement data from 10 seconds measured responses are used in the study. Table 3 shows the identified results. The number of iteration for convergence is 34, 36 and 37 respectively for the three noise levels, and the corresponding optimal regularization parameters are 0.94, 1.02 and 1.15. Results in Table 3 show that the identified results are satisfactory with noise level below 10% with a maximum error of 10% in damping.

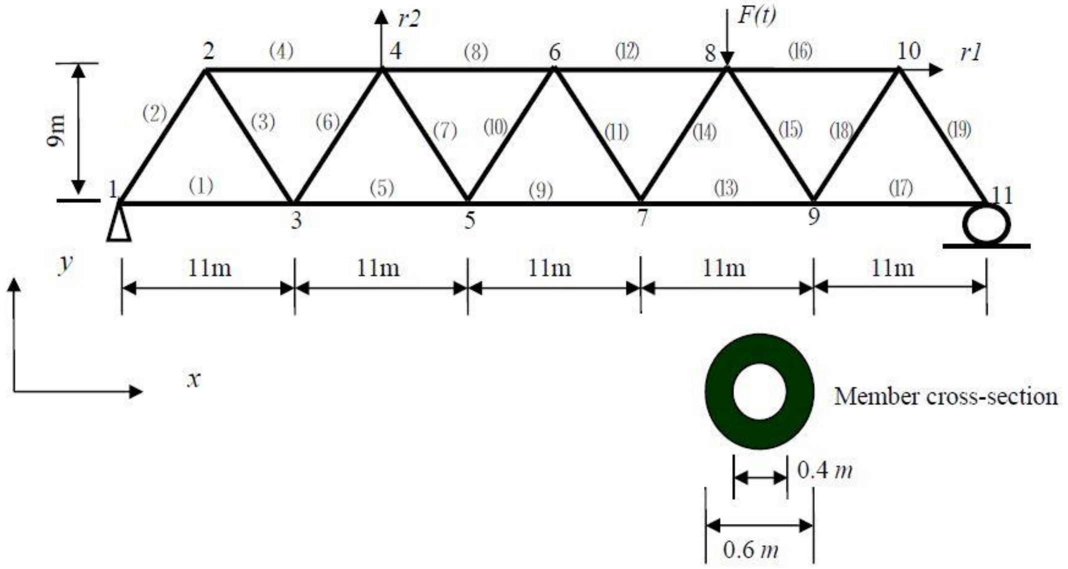

Fig. 2 The planar truss structure

Table 4 Damage scenarios on the planar truss

Damage Scenario	Damage Location	Reduction in *EA*	ΔT (℃)	Noise level
1	Element 5	10%	+40	Nil
2	Element 12	5%	Nil	5%, 10%
3	Elements 2, 5 and 19	5% each	+40	10%

4.2 Example 2: a planar truss structure

The study is extended to a five-bay plane truss structure as shown in Fig. 2, and the effect of measurement noise on the identified results is studied. It is assumed that there is no change in the mass and the damping with the occurrence of damage in the structure. The material parameters are: mass density ρ=7860 Kg/m^3 and Young's modulus E=200 GPa. The finite element model of the structure consists of nineteen two-dimensional truss elements with eleven nodes and twenty-two DOFs. The geometrical data of the structure in the initial finite element model are also shown in Fig. 2. The external and internal diameter of the circular hollow member sections are 0.6 m and 0.4 m, respectively. An excitation force of $F=-10000\sin 20\pi t$ N is acting at the 8th node in the negative direction of the global y-axis. Two accelerometers are used to collect the acceleration responses at the 4th node along the global y-axis, and at the 10th node along the global x-axis. The measurement time duration is 3 seconds. Three damage scenarios as shown in Table 4 are studied. Measurements from the first sensor are for the study of the first two damage scenarios. Measurements from both sensors are used for the study of damage scenario 3. Sampling frequency is 1000 Hz, and all the 3000 time steps data are used for the identification. The initial values for the temperature difference in the identification are all set to be zero.

Damage scenario 1 is for the study of identification of the local damage and the temperature difference. It is assumed that there is a uniform temperature difference of +40℃ in all truss

Table 5 Natural frequency changes due to local damage and temperature difference

	Natural Frequencies (Hz)		
Mode order	Original	Scenario 1	Scenario 2
1	*6.957*	*6.916*/(0.58)	*6.914*/(0.61)
2	*14.406*	*14.328*/(0.54)	*14.325*/(0.57)
3	*23.367*	*23.222*/(0.62)	*23.216*/(0.64)
4	*41.475*	*41.328*/(0.35)	*41.318*/(0.38)
5	*45.123*	*44.931*/(0.43)	*44.919*/(0.45)
6	*64.213*	*63.770*/(0.69)	*63.754*/(0.71)
7	*72.028*	*71.723*/(0.42)	*71.705*/(0.45)
8	*74.486*	*74.284*/(0.27)	*74.2654*/(0.30)

Note : (•) frequency change percentage with respect to the intact structure.

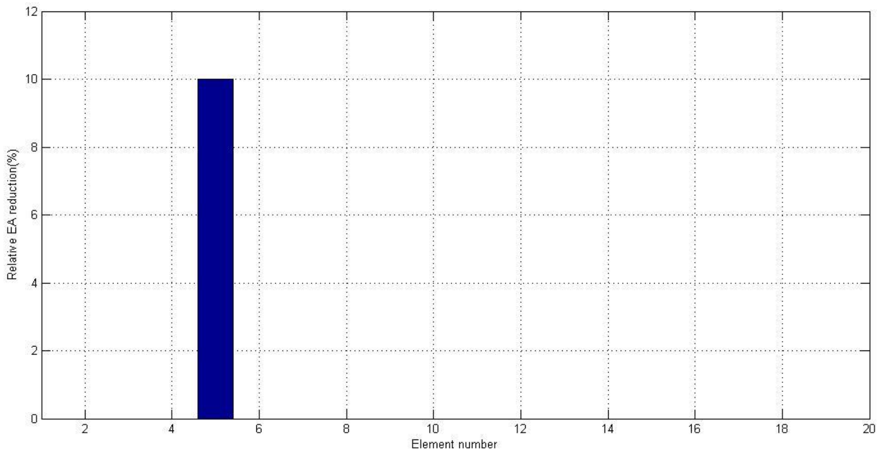

Fig. 3 Identification of single local damage in element 5

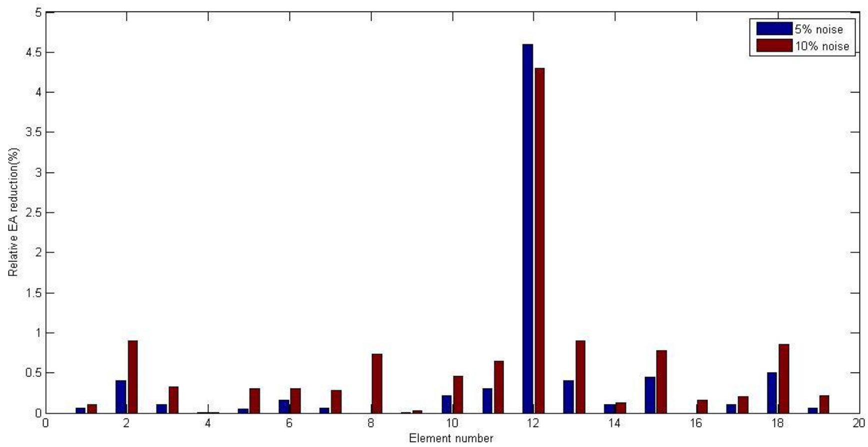

Fig. 4 Damage detection under different noise levels

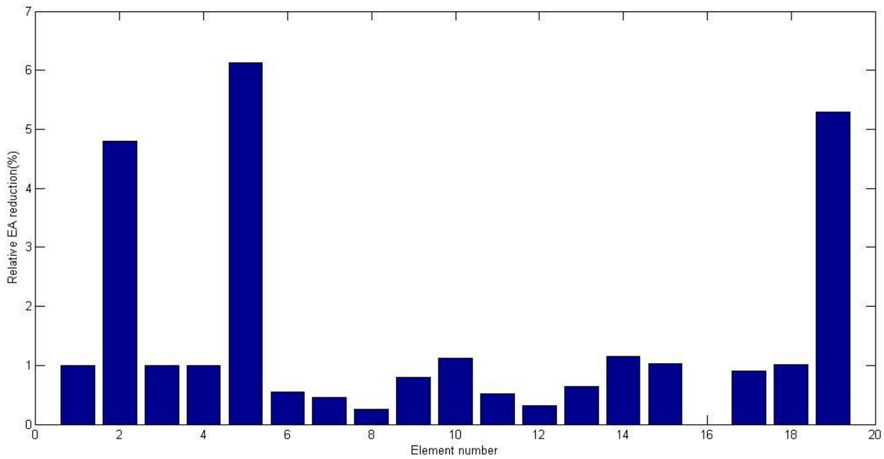

Fig. 5 Multiple damage detection with 10% noise level

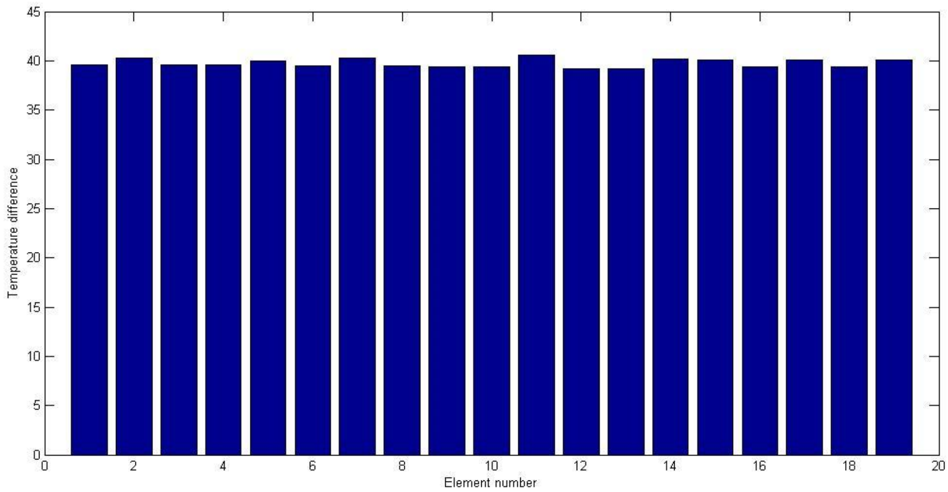

Fig. 6 Identification of temperature difference in each member

members between the two measurement states. The identified relative reduction in the axial stiffness for each of the elements is shown in Fig. 3. It is noted that the local damage in element 5 can be identified very accurately. The temperature difference in each truss member converges to the true value +40℃.

Damage scenario 2 is for the study of noise effect on the damage identification, and the identified relative reduction in the axial stiffness is shown in Fig. 4. The results show that the local damage at element 12 can be accurately identified even under 10% measurement noise level, and an increase in the noise level from 5% to 10% lead to an error of approximately +1% in the magnitude of the identified local damage. The maximum percentage error for temperature difference is 2.5% in the 10^{th} element.

Damage scenario 3 is for the study of a combination of local damages in element 2, 5 and 19, temperature difference and 10% noise level. The use of 3000 data from a single sensor has been checked to give accurate results on the local damage for this combination. The identified relative reduction in the axial stiffness and the temperature difference of each truss member are shown in Figs. 5 and 6, respectively. Number of iteration required for convergence is 38 and the regularization parameter is 2.9×10^{-10}. The maximum percentage error for damage detection and temperature difference is 1.3% in the 5^{th} element and 3.2% in the 10^{th} element. This study case indicates that the proposed method has the potential for identifying both the structural local damages and the temperature difference in structural member.

5. Conclusions

A damage detection method is proposed making use of the dynamic response sensitivity with respect to the different parameters of a structure system and the temperature difference. The measured response can be obtained from as few as a single sensor. All the system parameters including the system mass, damping, stiffness and the temperature difference can be updated successfully using noisy measurements. Results of the numerical simulation indicate that the proposed method has the potential for real application of identification of both the structural local damages and the temperature difference in structural member.

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References

Cattarius, J. and Inman, D.J. (1997), "Time domain analysis for damage detection in smart structures", *Mech. Syst. Signal Pr.*, **11**, 409-423.

Cawley, P. and Adams, R.D. (1979), "The location of defects in structures from measurements of natural frequencies", *J. Strain Anal.*, **14**, 49-57.

Deobling, S.W., Farrar, C.R., Prime, M.B. and Shevitz, D.W. (1998), "A review of damage identification methods that examine changes in dynamic properties", *Shock Vib. Dig.*, **30**, 91-105.

Doebling, S.W., Peterson, L.D. and Alvin, K.F. (1996), "Estimation of reciprocal residual flexibility from experimental modal data", *Am. Inst. Aeronaut. Astronaut. J.*, **34**, 1678-1685.

Friswell, M.I. and Mottershead, J.E. (1995), *Finite element model updating in structural dynamics*, Kluwer Academic Publishers.

Friswell, M.I. and Mottershead, J.E. (2001), "Inverse methods in structural health monitoring", *DAMAS 2001: 4th International Conference on Damage Assessment of Structures*, Cardiff, 201-210.

Hadjileontiadis, L.J., Douka, E. and Trochidis, A. (2005), "Fractal dimension analysis for crack

identification in beam structures", *Mech. Syst. Signal Pr.*, **19**, 659-674.
Hansen, P.C. (1992), "Analysis of discrete ill-posed problems by means of the L-curve", *SIAM Rev*., **34**, 561-580.
He, Z.Y. and Lu, Z.R. (2010), "Time domain identification of multiple cracks in a beam", *Struct. Eng. Mech.*, **42**, 13-24.
Housner, G.W. *et al*. (1997), "Structural control: Past, present, and future", *J. Eng. Mech*., ASCE, **123**(9), 897-971.
Jaishi, B. and Ren, W.X. (2006), "Damage detection by finite element model updating using modal flexibility residual", *J. Sound Vib*., **290**, 369-387.
Koh, C.G., Hong, B. and Liaw, C.Y. (2000), "Parameter identification of large structural systems in time domain", *J. Struct. Eng.*, ASCE, **126**, 957-963.
Lu, Z.R. and Law, S.S. (2007), "Features of dynamic response sensitivity and its application in damage detection", *J. Sound Vib*., **303**, 305-329.
Lu, Z.R. and Liu, J.K. (2011), "Identification of both damages and parameters of vehicles for bridge-vehicle system from measured dynamic responses", *Comput. Struct*., **89**, 1397-1405.
Lu, X.B., Liu, J.K. and Lu, Z.R. (2013), "A two-step approach for crack identification in beam", *J. Sound Vib*., **332**(2), 282-293.
Majumdar, A. *et al*. (2013), "Damage assessment of beams from changes in natural frequencies using ant colony optimization", *Struct. Eng. Mech.*, **45**, 391-410.
Majumder, L. and Manohar, C.S. (2003), "A time domain approach for damage detection in beam structures using vibration data with a moving oscillator as an excitation source", *J. Sound Vib*., **268**, 699-716.
Pandey, A.K. and Biswas, M. (1994), "Damage detection in structures using change in flexibility" *J. Sound Vib*., **169**, 3-17.
Pandey, A.K., Biswas, M. and Samman, M.M. (1991), "Damage detection from change in curvature mode shapes", *J. Sound Vib*., **145**, 321-332.
Salawu, O.S. (1997), "Detection of structural damage through changes in frequency: A review", *Eng. Struct*., **19**(9), 718-723.
Urgessa, G.S. (2011), "Vibration properties of beams using frequency-domain system identification methods", *J. Vib. Control*, **17**(9), 1287-1294.
Wang, B.S. and He, Z.C. (2007), "Crack detection of arch dam using statistical neural network based on the reductions of natural frequencies", *J. Sound Vib*., **302**, 1037-1047.
Wang, H. and Qiao, P. (2008), "On irregularity-based damage detection method for cracked beams", *Int. J. Solid. Struct*., **45**, 688-704.
Wu, D. and Law, S.S. (2004), "Model error correction from truncated modal flexibility sensitivity and generic parameters. I: Simulation", *Mech. Syst. Signal Pr.*, **18**, 1381-1399.
Tikhonov, A.M. (1963), "On the solution of ill-posed problems and the method of regularization", *Soviet Math*., **4**, 1035-1038.
Yang, Q.W. (2011), "A new damage identification method based on structural flexibility disassembly". *J. Vib. Control*, **17**(7), 1000-1008.
Zou, T., Tong, L. and Steve, G.P. (2000), "Vibration based model-dependent damage (delamination) identification and health monitoring for composite structures- a review", *J. Sound Vib*., **230**(2), 357-378.

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