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Damage detection in structures using finite element model updating based on changes in wavelet transform coefficients of a correlation function

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ABSTRACT: In this paper, an innovative finite element updating method is presented based on the sensitivity of wavelet transform coefficients of correlations function structural parameters is proposed to identify the damage. The Quasi-linear sensitivity of the wavelet coefficients of the WTCF concerning the structural parameters is evaluated based on incomplete measured structural responses. This WTCF sensitivity is more sensitive to local structural changes than the wavelet transform function response sensitivity. The model is updated by the wavelet transform coefficients achieved in the frequency range in the vicinity of the resonances, in which damping and incomplete measurements have no significant effect on the results of the parameter estimation. The proposed algorithm is used to estimate the structural parameters of the frame model. By the solution of the sensitivity equation through the Least-squares method, the finite element model of the structure is updated for estimation of the location and severity of structural damages, simultaneously. The proposed method was successfully applied to a 2D frame model using simulated data contaminated by measurement and modeling errors. The robustness of the method against modeling and mass measurement errors is investigated by adding random errors to the mass parameters of the frame model.

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1- Introduction

Large structures such as marine platforms, ships, bridges, and so on are designed to be used for long periods of time. The lack of proper functioning of these structures or their failure may lead to irreparable economic and life losses. Thus, to prevent these, researchers are always looking for methods to identify the damages created in the structure and the remaining life of the structure despite the damage [1]. The main methods for damage identification of the structures are: visual inspection methods, non-destructive tests using piezoelectric and ultrasonic equipment, as well as the use of identification algorithms based on data collection from the structure to identify damages [2]. Therefore, an ideal method for damage detection should be able to detect the occurrence of the damage in the initial stages without having previous data, and also identify the location and severity of the damage within the scope of the sensors' performance [3]. Therefore, in this research, a new sensitivity equation has been extracted using the wavelet transform coefficients of the correlation function to update the finite element model. This index is more sensitive to changes in structural parameters than other modal indices and frequency response function. The sensitivity equation provides a quasi-linear relationship for changes in wavelet coefficients according to changes in structural parameters.

2- Theoretical relationships

For the arbitrary function $f(t)$, the continuous wavelet transform is presented as follows:

$$W_{(a,b)}^{f} = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\Psi^{*}(\frac{t-b}{a})dt \qquad (1)$$

Where $\Psi^{*}(t)$ is the complex conjugate of the mother wavelet function, a and b are the time scale and time transfer of function $\Psi(t)$, respectively. In order to speed up calculations, the binary discrete wavelet transform is proposed. Discrete wavelet transform is shown as Equation 2:

$$DWT_{(j,k)}^{f} = 2^{-\frac{j}{2}} \int_{-\infty}^{\infty} f(t)\psi^{*}(2^{-j}t-k)dt \qquad (2)$$

The relationship between the wavelet transform function of the response and the wavelet transform of the correlation function of the multi-degree-freedom structural response is presented as Equation 3 [4]:

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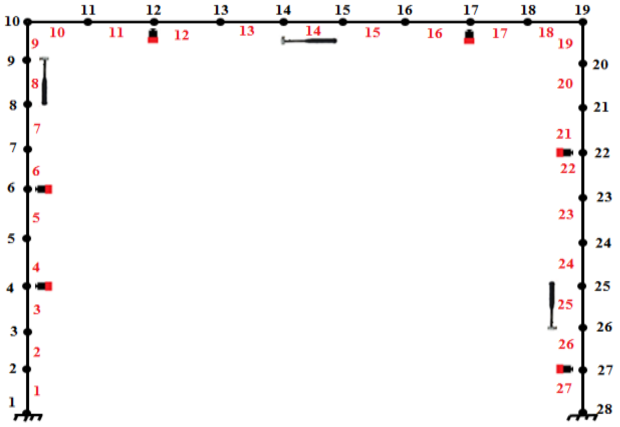

Fig. 1. The geometry model of the frame

$$S^{xx}_{\psi(j,k)} = H_{\psi(j,k)} S^{ff}_{\psi(j,k)} H^{*}_{\psi(j,k)} \tag{3}$$

Where, $H_{\psi(j,k)}$ is the wavelet transform function of the structural response; $H^{*}_{\psi(j,k)}$ shows the complex conjugate transpose (Hermit matrix) of the WTF of the structural response; $S^{fxx}_{\psi(j,k)}$ and $S^{ff}_{\psi(j,k)}$ are the wavelet transform of the response correlation function and the wavelet transform of the input correlation function to the system, respectively. The final sensitivity equation of the wavelet transform of the correlation function for all degrees of freedom is as follows(equation(4)):

$$\begin{aligned}\Delta S^{xx}_{\psi(j,k)} &= H^{*D}_{\psi(j,k)} S^{ff}_{\psi(j,k)} (\Delta Z_{\psi(j,k)}) H_{\psi(j,k)} \\ &- H^{*D}_{\psi(j,k)} (\Delta Z^{*}_{\psi(j,k)}) H^{*}_{\psi(j,k)} S^{ff}_{\psi(j,k)} H_{\psi(j,k)}\end{aligned} \tag{4}$$

3- Numerical validation

This algorithm is used to identify the damage to a frame structure presented in Figure 1. The length of the sides of the frame is 0.9 meters, and the number of degrees of freedom is 78 (each node has two translational degrees along the X and Y axes and one rotational degree around the Z axis).

The frame is made of steel, the Young's modulus of the members is 200 GPa, the mass per unit length of each element is 2.813 kg/m, the moment of inertia is 0.264 cm^4, the cross-sectional area of each member is 3.61 cm^2, and the length of each member of the structure is 10 cm. The unknown structural parameters of the beam-column element are EI flexural stiffness and AE axial stiffness, where A, I and E are cross-sectional area, the moment of inertia and Young's modulus, respectively. Structural responses are decomposed into Daubechies4 (Db4) wavelet levels.

Table 1. The selected range of $a_{(j,k)}$ coefficients for updating

	Damage Case
$a_{(j,k)}$ range *10(e+3)	(-0.6)~(-0.9)
	(-2.1)~(-2.8)
	(-2.3)~(-3.4)
	(-12.2)~(-13.7)

4- Results and Discussion

The selection of $a_{(j,k)}$ wavelet coefficients is very effective based on the structural parameters for the success of the estimation. In order to increase the accuracy of approximated $H^{*D}_{\psi(j,k)}$ and as a result of increasing the sensitivity equation, $a_{(j,k)}$ coefficients have been chosen close to the natural frequencies of the damaged and intact structure. The selected range of these coefficients is presented to be placed in the proposed sensitivity equation in Table 1 in different time and shift scales.

The result of updating the model presented in Figure 2a shows that the proposed sensitivity equation is capable of accurately identifying the location and the severity of structural damage. The stability of the results obtained from the proposed sensitivity equation by evaluating the coefficient of variation of COV parameters is shown in Figure 2b. The low coefficient of variation shows the good accuracy of the method and the low dispersion of the predicted results.

In order to quantitatively study the predicted results and compare them, the closeness index can be used, which indicates the relative distance between the predicted and actual damage vectors. Therefore, it can be written [5] :

$$CI = 1 - \frac{\left\| \delta \bar{P}_t - \delta \bar{P}_p \right\|}{\left\| \delta \bar{P}_t \right\|} \tag{5}$$

Where, $\delta \bar{P}_t$ and $\delta \bar{P}_p$ are actual and predicted values of damage vector. The CI values of the considered damage scenarios are presented in Table 2:

5- Conclusion

This article has developed a method of updating the structural model in the domain of time-scale using the wavelet transform of the correlation function and it has been used to identify the damage to the studied structure. The structure model is updated by using the wavelet transform coefficients obtained in the range of natural frequencies, in the vicinity of resonance frequencies, where damping and incomplete measurements do not have a major impact on the results obtained from the parameters. The proposed sensitivity equations to reach the changes in structural parameters have

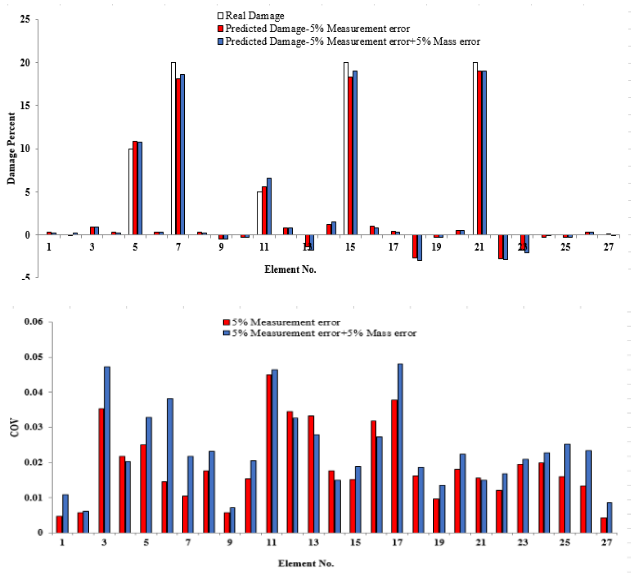

Fig. 2. (a) First case damage predicted parameter at considering 5% measurement error and 5% modeling error, b) COV of the predicted parameters.

been solved using the least squares method. In order to reduce the negative effects of incomplete measurements in structures, the approximation method and the data related to the damaged and intact structures have been used. The proposed method was successfully applied to a two-dimensional frame model using simulated data containing measurement and modeling errors.

Table 2. Closeness index of frame model considering measurement and modeling error.

Damage Cases	CI	
	With measurement error	with measurement and modeling error
1	0.84	0.83

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