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Wavelet-Based Method for Damage Detection of Nonlinear Structures

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ORIGINAL ARTICLE

ABSTRACT: In the recent decades, damage detection and system identification methods that are based on wavelet analysis and signal processing for structural health monitoring of engineering structures have been developed. Analyses that are based on time-frequency domain provide more information about non-stationary signals. In this paper, an effective method is presented for damage detection of nonlinear structure based on restoring force by using wavelet transform. Two nonlinear frame models are used for simulation of the real condition of structures and restoring force response is calculated by Runge-Kutta method. The results for damage detection by the proposed method in the structures show the reliability of the method.

Keywords: Damage Detection, Nonlinear Structure, Restoring Force, Wavelet Transform.

INTRODUCTION

More attention should be paid to infrastructures, buildings, and long life facilities. Even though these structures are usually designed to be used for 50-100 years, some factors such as overloads, excessive usage, and exposure to extreme corrosion may cause more rapid deterioration. Having a successful structural health monitoring system needs to have sensing technology and the associated signal analysis. Recent seismic disasters such as Bam, 2003 earthquake have shown that lifeline and infrastructures near urban areas are very important for emergency access. Structural health monitoring systems can provide an invaluable tools in future urban management by giving quick assessments of the damage level of a structure shortly after a disaster. By data collection during an earthquake it will be possible to access the damaged areas of structures without wasting time (Hera et al., 2004). New technologies can help human to overcome the effects of disaster. Nowadays by using different types of sensors such as fiber optic, wireless not only online monitoring of structures is possible, but also having full intelligent infrastructures is in access.

Over the past decade wavelet analysis has become an important tool for signal processing (Kim et al., 2004) and it has been applied in system identification and damage detection (Bayissa et al., 2008). In addition, it has been widely implemented for various purposes, such as characterization of non-stationary dynamic responses and identification of nonlinear structural dynamic systems (Brenner, 2003; Kitada, 1998). The application of wavelet analysis in damage detection has reported by Kim et al.(2003). They used wavelet analysis to identify structural damage in a concrete beam subjected to fatigue damage. In that research, wavelet analysis and its applications for damage detection on two different structural responses has been investigated. The merits of wavelet analysis in comparison with Fourier transform lie in its ability to examine local data with zoom ability and having an adjustable focus. This help to have multiple levels of details and approximations of the original signal by zooming and windowing. A General overview of damage detection by wavelet analysis has done by Kim et al.(2004) and a review on some of the wavelet application such as time-frequency analysis of signals, the fault feature extraction, the de-noising and extraction of the weak signals has been done by Peng et al. (2004). Furthermore, the possibility of applying various wavelets for crack detection of beams has been studied by Sun et al. (2004), Han et al. (2005) and Poudel et al. (2007). Damage detection of frame structures via wavelet transform has analysed by Ovanesova et al. (2004) and Hou et al. (2000).

In this study, damage in structures with nonlinear materials subjected to a real earthquake ground motion is detected, which is related to the numbers of spikes in wavelet results. The proposed methodology is applied to examples subjected to a real earthquake. The building is modelled simply with springs and dampers in three and five degree of freedoms. The efficiency of the presented method is shown based on the obtained results for damage detection.

2. A brief background of wavelet analysis

This section presents a brief background on wavelet analysis that has been used in this paper. The major strength of wavelet analysis over other time-frequency transforms, such as short time Fourier transform is that it enables one to conduct a multi-resolution analysing by

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windowing and zooming in a special domain that we have a different signal. By selecting wavelet mother ψ, the continuous wavelet transform of a signal *f(t)* is defined as (Daubechies, 1992) :

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

where, *a* and *b* are scale and shifting parameters, respectively and ψ^* is the complex conjugate of ψ.

The shifting parameter indicates the location of the moving wavelet window in the time axis. Shifting the wavelet window along the time axis implies examining the signal in the neighbourhood of the current window location. By scaled windows the same portion of data can be examined with different resolutions. The scaling parameter indicates the width of the wavelet window and a smaller value of the scaling parameter implies a higher-resolution filter. Both are real numbers and a must be positive.

Two different type of wavelet analysis are: continuous and discrete wavelet transform. The properties and benefit of them has studied by researchers (Kim et al., 2004). In continuous wavelet transform, the time resolution becomes arbitrary good at high frequencies, while the frequency resolution becomes arbitrary good at low frequencies. This property helps to overcome the limitation of short fast Fourier transforms in which the time-frequency resolution is fixed (Kim et al., 2004; Rioul, 1991). While the continuous wavelet transform requires much calculation effort to find the coefficients at every single value of the scale parameter, the discrete wavelet transform adopts dynamic scales and translations in order to reduce the amount of computation, which results in better efficiency of calculation (Kim et al 2004).

3. Damage detection method

Damage detection in a structure that subjected to seismic excitation, usually use a simple shear frame model. In this model assumed that the masses are lumped in each floor and the floor just move laterally. The dynamics equation of the frame can be represent as:

$$m\ddot{x}(t) + c\dot{x}(t) + f(x,t) = -m\ddot{x}_g(t) \qquad (2)$$

where *m*, *c* and *f(x,t)* are mass, damping coefficient, and restoring shear force of the structure, respectively; $\ddot{x}$, $\dot{x}$ and $\ddot{x}_g$ are acceleration, velocity and seismic excitation, respectively.

In this study, the Bouce-Wen nonlinear model(Wen, 1976) used to simulate elastic-perfectly plastic polynomial-like nonlinearity. Therefore, the restoring shear force can be express as:

$$f(x,t) = \alpha kx + (1-\alpha) k d_y z \qquad (3)$$

where *k* and α are pre-yielding stiffness and ratio of post-yielding to pre-yielding stiffness, respectively; and *z* is defined as follows:

$$\dot{z} = \frac{1}{d_y} [A\dot{x} - \beta |\dot{x}| |z|^{p-1} z - \gamma \dot{x} |z|^p] \qquad (4)$$

where *p*, d_y, γ, β and *A* control the shape of the hysteresis loop.

To solve Eqs. (2) to (4) simultaneously, different solutions were proposed. In this paper, the equations were wrote in the state space and then solved by Rounge-Kutta method and then the responses of structure in each floor were calculated.

The restoring shear force can be represented by approximations and details by discrete wavelet transform. The detail at level *j* is defined as:

$$D_j(t) = \sum_{k \in Z} cD_{j,k}(k) \psi_{j,k}(t) \qquad (5)$$

where *Z* is the set of positive integers, and $cD_{j,k}$ is wavelet coefficients at level *j* which is defined as:

$$cD_j(k) = \int_{-\infty}^{\infty} f(x,t) \psi_{j,k}(t) dt \qquad (6)$$

The approximation at level *j* is defined as:

$$A_j(t) = \sum_{k=-\infty}^{\infty} cA_j(k) \varphi_{j,k}(t) \qquad (7)$$

where φ is the scaling function and $cA_{j,k}$ is scaling coefficients at level *j* which is defined as:

$$cA_j(k) = \int_{-\infty}^{\infty} f(x,t) \phi_{j,k}(t) dt \qquad (8)$$

Finally, the peak values of the details can be expressed the damage locations in the model.

4. Numerical studies

In these sections, three and five-story shear frames are modelled as case studies for showing the feasibility of this method.

4.1. Three-story shear frame

This numerical example is a three-story shear frame with the following physical properties:

$M_1 = M_2 = M_3 = 10\,KN.\sec^2/m$

$K_1 = 16.22\,KN/m,\ K_2 = 10.09\,KN/m,\ K_3 = 5.92\,KN/m$

$c_1 = 0.381\,KN.\sec/m,\ c_2 = 0.32\,KN.\sec/m,\ c_3 = 0.2\,KN.\sec/m$

$\alpha = 0.045$

Also, the parameters of the hysteresis loop are:

$d_{y1} = 2.10,\ d_{y2} = 2.44,\ d_{y3} = 2.85$

$A = 1.0,\ \beta = 0.5,\ \gamma = 0.5,\ p = 107$

To illustrate the potential application of the proposed method two earthquake ground motions were considered for numerical simulations that were El-Centro (1940) and Zarand (2005).These two earthquake were used as base excitations to simulate the responses of a three-story shear frame.

Structural damage is simulated by nonlinearity in the shear frame and when the drift of story exceed from 80% of maximum drift it was considered as damage in that floor.

the used responses of structures were based on restoring force, that better shown the properties of structure in compare to other responses, as it is directly relate to the properties of material that are used in structures such as stiffness and damping. In this way, using wavelet analysis can provide a good procedure to detect abrupt changes in the response by decomposing, windowing and zooming. In this research, all of the restoring forces decomposed in 2 levels with wavelet mother *db4*.

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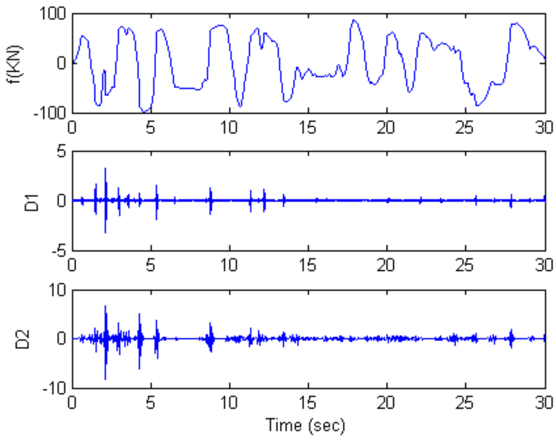

Figure 1. The obtained results of the restoring force and damage detection at the first story of the three-storey shear frame for the El-Centro (1940) earthquake.

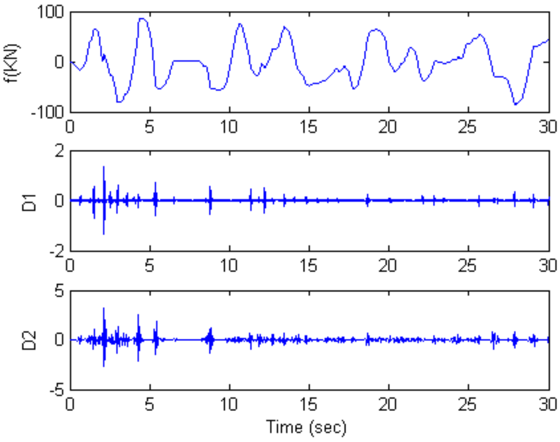

Figure 2. The obtained results of the restoring force and damage detection at the second story of the three-storey shear frame for the El-Centro (1940) earthquake.

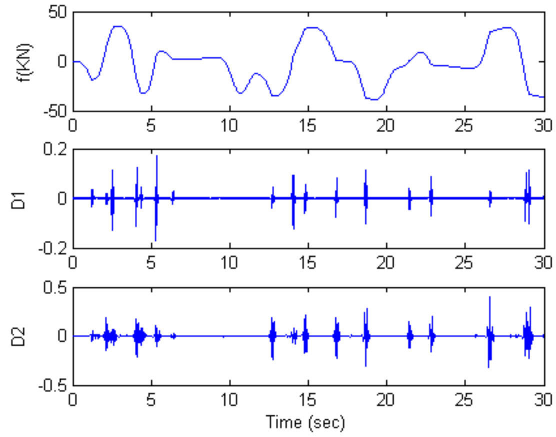

Figure 3. The obtained results of the restoring force and damage detection at the third story of the three-storey shear frame for the El-Centro (1940) earthquake.

Figures 1-3 show the obtained results of the restoring force and damage detection at the stories of the frame under El-Centro (1940) earthquake. For Zarand (2005) earthquake, the obtained results for the frame in the floors under this seismic excitation are shown in Figs. 4 to 6. Spikes in details are corresponding to abrupt changes in the response that associated with structural damage. Therefore, damage of a building with nonlinear restoring force that subjected to a real earthquake ground motion is related to the number of spikes in the wavelet results.

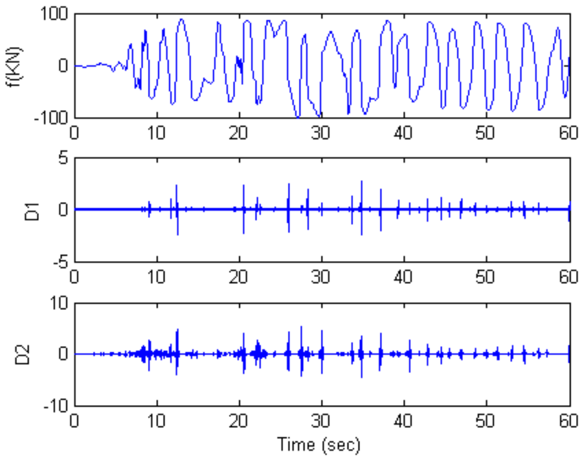

Figure 4. The obtained results of the restoring force and damage detection at the first story of the three-storey shear frame for the Zarand (2005) earthquake.

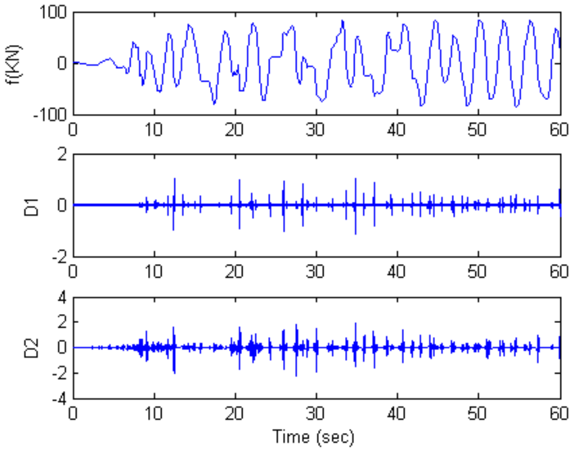

Figure 5. The obtained results of the restoring force and damage detection at the second story of the three-storey shear frame for the Zarand (2005) earthquake.

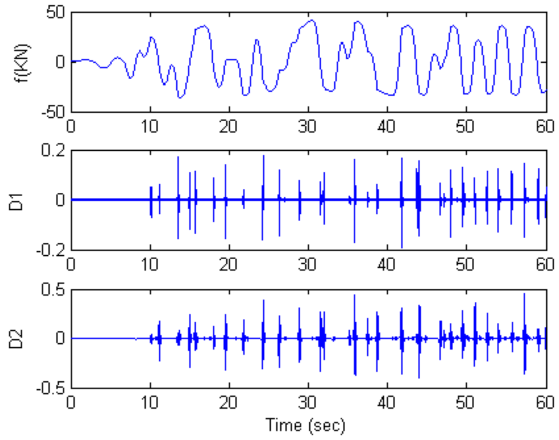

Figure 6. The obtained results of the restoring force and damage detection at the third story of the three-storey shear frame for the Zarand (2005) earthquake.

4.2. Five-story shear frame

The second numerical model was a five-story shear frame with the following physical properties:

$M_1 = ... = M_5 = 15\,KN.\sec^2 / m$

$K_1 = K_2 = K_3 = 10.09\,KN / m,\ K_4 = K_5 = 5.92\,KN / m$

$c_1 = 0.381\,KN.\sec/ m,\ c_2 = 0.32\,KN.\sec/ m,\ c_3 = c_4 = c_5 = 0.2\,KN.\sec/ m$

$\alpha = 0.045$

In addition, the parameters of the hysteresis loop are: $d_{y1} = d_{y2} = d_{y3} = 2.44,\ d_{y4} = d_{y5} = 2.85$

$A = 1.0,\ \beta = 0.5,\ \gamma = 0.5,\ p = 107$

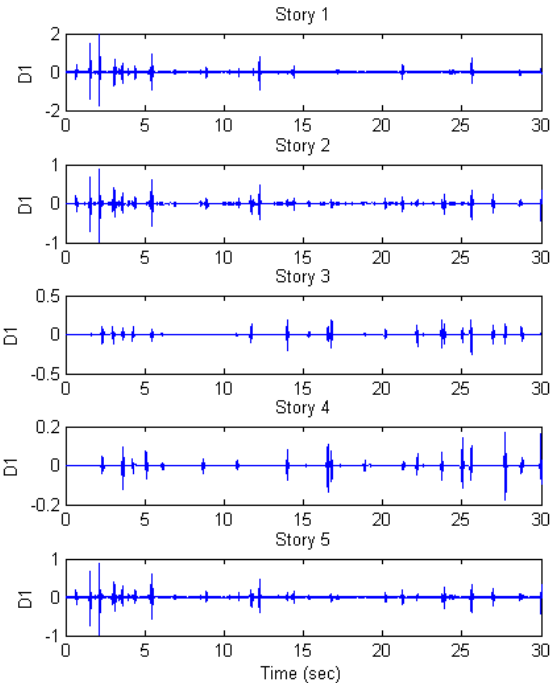

Fig. 7. The obtained results of damage detection at the stories of the five-storey shear frame for the El-Centro (1940) earthquake.

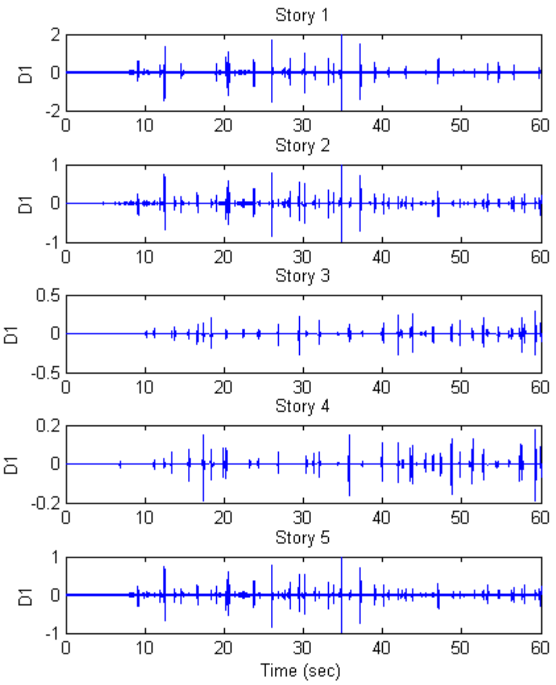

Fig. 8. The obtained results of damage detection at the stories of the five-storey shear frame for the Zarand (2005) earthquake.

In this numerical model, results of damage detection based on the level 1 (D1) at floors of the frame under the El-Centro (1940) earthquake were shown in Fig. 7 and the one under Zarand (2005) earthquake were shown in Fig. 8. In all of the obtained results, damage detection based on the restoring force shows the damages clearly. In Zarand (2005) Earthquake, based on the excitation earthquake, damages occur after the 10th second. But in the El-Centro (1940) earthquake there is another rhythm of damages. Finally, it can be concluded that the proposed method is much more sensitive to location of damage in the structures. This is due to the use of wavelet analysis based on the restoring force for decomposition in the presented method for damage identification.

5. CONCLUSION

According to results it can be concluded that damage detection of structure based on the restoring force was a accurate method. Furthermore, changes in restoring force signals are directly related to changes in the properties of structures such as stiffness, damping and mass. Each variation in these signal demonstrate the changes in restoring force and abrupt change of these signal in wavelet analysis shown the damage of structure. Using signal processing, provide a tool to detect the damage under excitations and results were related to the nature of earthquake waves and the magnitude of excitation. This method will help us for online monitoring in infrastructures and detect the damages that occur in structures. Using the wavelet analysis is less dependent to model and it dependent to measured data. Using different level of decomposition and different wavelet mother showed that wavelet mother ***db4*** is the best choose for damage detection in case 1 and *db1* for case 2.

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