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DAMAGE IDENTIFICATION IN STRUCTURES USING CORRELATION-BASED TECHNIQUE

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Abstract*:* The Finite Element (FE) model correlation and damage detection are important elements of Structural Health Monitoring (SHM). The feasibility of FE model correlation and modal identification as a tool for signal processing is explored here for locating structural anomaly. Anomalies can exist in a structure in the form of damage due to loss of stiffness in the structural and non-structural elements, and such anomalies alter a structure's dynamic properties. Experimental and operational modal analysis are successfully used by many researchers to estimate modal parameters, such as: modal frequencies, mode shapes and damping to measure structural damages in experimental and operational conditions employing vibration-based response of the structures. This paper emphasizes the process of identification and localization of structural damages based on a correlation coefficient, termed as Damage Location Assurance Criterion (DLAC). The work further demonstrates the effectiveness of the method by using an experimental case study on a five-storey scaled steel prototype. Further, a comparative study of damage detection by using the mode shape curvature technique and the DLAC has been carried out. It is shown that DLAC can effectively identify structural damage based on the changes in modal frequencies between the damaged and the intact/undamaged structure.

Keywords: Modal parameters; Vibration-based response; Damage Location Assurance Criterion (DLAC); Mode shape curvature; Damage detection

1 Introduction

Structural Health Monitoring (SHM) to detect and localize damage is one of the most active and effective fields of research that attracted a lot of interest in the recent years. From the last decade, researchers have employed Non-Destructive Testing (NDT) to find damages in structural and non-structural elements. The premise for these techniques is that damage causes a change in a structure's physical properties, mainly in stiffness at the damaged locations. The associated changes in the structure will result in changes in natural frequencies, mode shapes, damping ratios, modal strain energy, and other dynamic characteristics of the system. Therefore, monitoring one or more of these properties of the damaged structure, can be helpful in determining the location and severity of damage. Recently, optimization of Wireless Sensor Networks (WSN) have been employed to solve many civil engineering problems especially in case of damage detection. Vibration-based damage detection is performed by considering the changes in the vibration signature of a system. Vibration-based damage detection appears to be primitive, its actual application poses many significant technical challenges. The fundamental challenge is the fact that damage is typically a local phenomenon and in many cases, does not significantly influence the lower modes of global response of structures. It is proposed that the damage detection problem can be tackled based on the statistical patterns recognition techniques. In the present article, statistics-based correlation technique has been explored in detail to localize damage in an experimental structure [1].

In past years, pattern recognition technique has been implemented extensively for identification of structural parameters. Primarily, it was employed in theoretical research for assessing raw data of structural response. Recently, statistical parameter recognition has become an important part of finding anomalies in structural response data. Many different mathematical techniques are used for this purpose. The objective of statistical correlation-based approach is to analyze parameters for undamaged and damaged structure in experimental and numerical case studies. Experimental data is collected through wired or wireless sensors network modal correlation evaluate these observations. A further analysis is done by using information from these observations. These extracted features are then analyzed using statistical equations to find correlation between experimental data and the response of the numerical model in case of undamaged and damaged conditions. The process used for modal correlation recognition consists of many procedures that ensure efficient description of the different vibrating modes. Structural damage at single location is detected by the Damage Location Assurance Criterion (DLAC) using the correlation pattern changes in different modes [1] [2]. The DLAC for different location we computed using experimental and numerical data for different case studies. The following paper shows this method is more accurate as compared to traditional mode shape curvature algorithm [3], where damage located by estimating Curvature Damage Factor (CDF).

2 LITERATURE REVIEW

Modal correlation algorithm is based on the theory that a structure’s vibration properties will alter with the onset of damage. Different correlation-based methods have been developed by researchers to determine the location of damage in structure. Nobahari et al. [4] introduced the algorithm to find required frequency by using Finite Element Analysis (FEA) and used an efficient correlation-based index to optimize the algorithm. In the study Hackmann et al. [5] developed the damage localization system using decentralized computer algorithm for DLAC. The developed algorithm proved the accuracy of its damage localization capability. In practice, the model frequency is not sensitive to the local damage scenarios. Numerical model is used to simulate damage at discrete locations along the structure, providing an estimate of what the natural frequencies would be if the structure was damaged at each of these locations. From the works done by Hackmann et al. [5], the frequency change vector in case of numerical model can we expressed as:

$$\delta\omega_j = \frac{\omega'_{\text{healthy}} - \omega_j}{\omega'_{\text{healthy}}} \tag{1}$$

Where vector ω_j predicts the structure’s natural frequencies when damage is simulated at location j using structure’s numerical model, and ω'_{healthy} is natural frequency vector of the structure computed using purely numerical techniques.

On the other hand, the experimental frequency change vector can be expressed as [5]:

$$\Delta\omega = \frac{\omega_{\text{healthy}} - \omega_{\text{damage}}}{\omega_{\text{healthy}}} \tag{2}$$

Where ω_{healthy} is estimated from the experimental studies in the healthy condition of the structure, and ω_{damage} is estimated from the experimental studies in damaged conditions.

Messina et al. [2] proposed an assurance criterion, DLAC that detect the single damage location that could be extended to the multiple damage location conditions. DLAC for singular damage condition can be expressed as [2]:

$$\mathrm{DLAC}(\mathrm{j}) = \frac{\left|\{\Delta\omega\}^{\mathbf{T}} \cdot \{\delta\omega_j\}\right|^{2}}{\left(\{\Delta\omega\}^{\mathbf{T}} \cdot \{\Delta\omega\}\right) \cdot \left(\{\delta\omega_j\}^{\mathbf{T}} \cdot \{\delta\omega_j\}\right)} \tag{3}$$

DLAC for location j can be defined using Equation (3), which is similar to the Modal Assurance Criterion (MAC) used for comparing frequency vectors.

DLAC value lies in the range of 0 to 1, with 0 indicating no correlation and 1 indicating an exact match between the patterns of frequency changes [1]. The location j giving the highest DLAC value gives the best match to the measured frequency change pattern and is therefore taken as the predicted damage site.

3 Methodology

In the present work, the response of a five-storey steel frame structure is obtained in the lab using WSN of accelerometers placed at different floor levels. Then, the data is analyzed using Fast Fourier Transform (FFT) to obtain the different modal frequencies using SigVIEW signal processing software [6]. A sample response of the structure is shown in Figure 1.

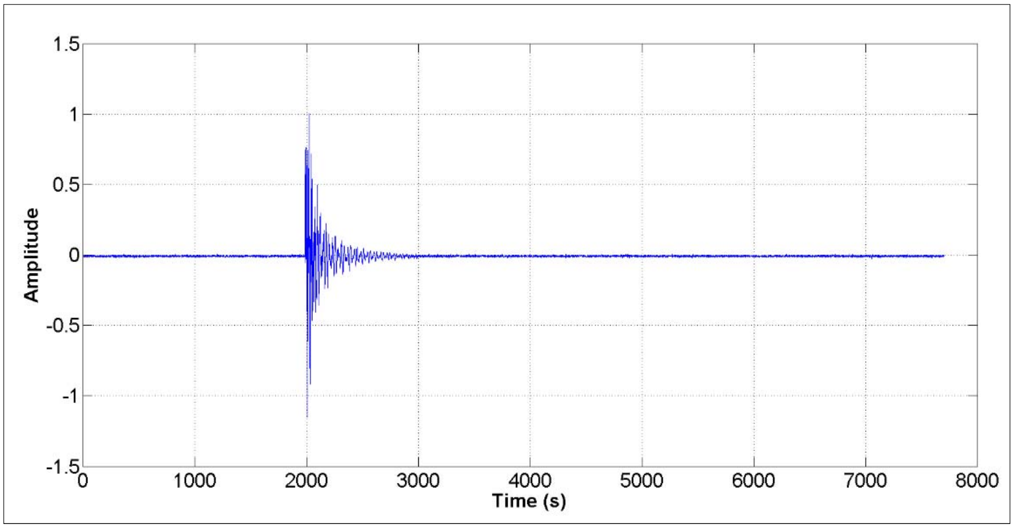


Figure 1: Raw data from the undamaged response of the structure

The FFT of the signal is shown in Figure 2.

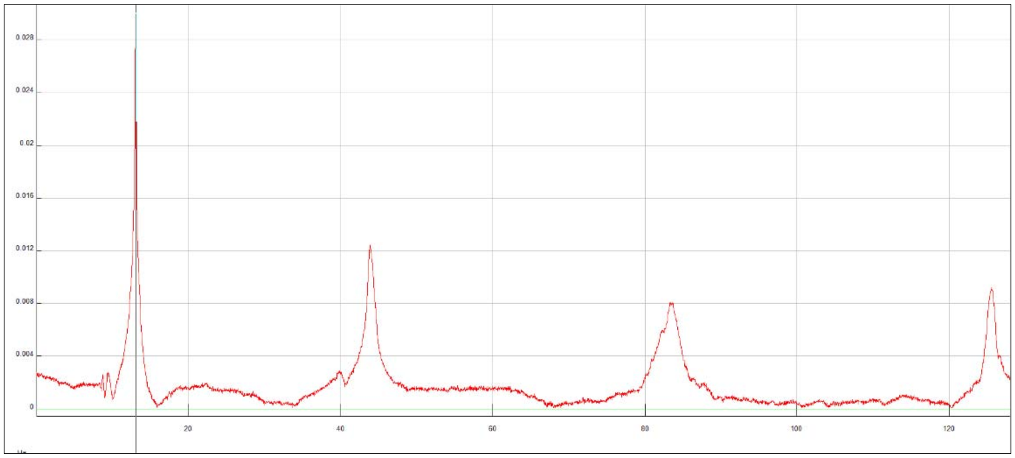
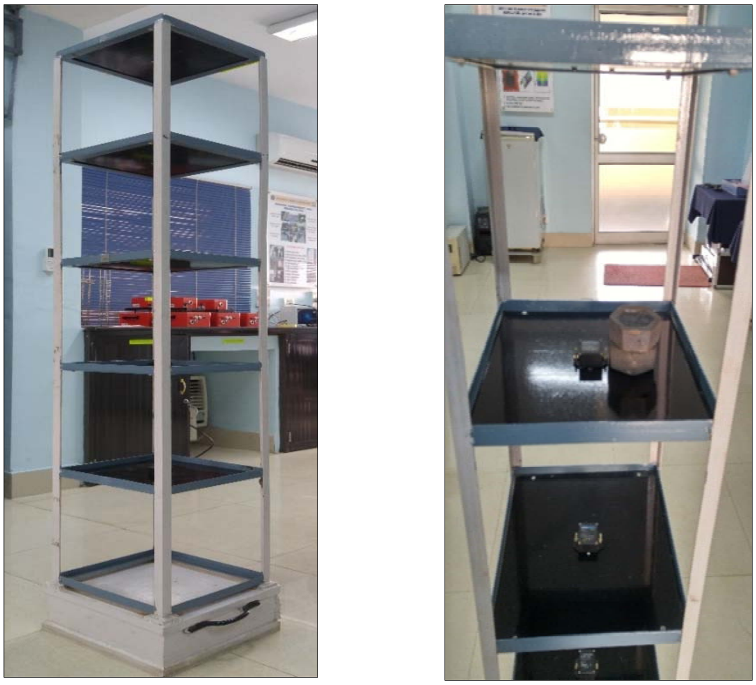


Figure 2: FFT of the raw data using SigVIEW (X axis – Frequency in Hz, Y axis – Amplitude)

The modal frequencies obtained from FFT are used for correlating the numerical model, which is developed using Finite Element (FE) software SAP2000 [7]. Undamaged and damaged frequency vectors are estimated from healthy and damaged cases in case of experimental and numerical studies, respectively. In numerical modeling of the structure, different damage cases have been simulated by predicting damage at different locations along the structure. After that DLAC is calculated from the Equation (3) by employing equation (1) and (2). The mathematical estimation of DLAC has been performed in MATLAB software [8]. The final values of DLAC are plotted and damage is localized from the maximum values of DLAC for different signals.

4 Experimental set up

For the following work, a scaled five-storey steel frame prototype made of mild steel is used for experiments. The one-tenth scale frame is made of ISA 25x25x3 sections. The plan width and depth of the structure is 350 mm x 350 mm, and the inter-storey height is 350 mm. The joints of the frame are welded to provide stiffness in the structure. Each-storey is instrumented with wireless G-Link micro-strain sensor and all the sensors are connected to a wireless data acquisition system. Damage has been simulated in the structure by addition of masses. In this work, a damage case or alteration to the structure is created by addition of 1 kg weight on third floor of the structure. The experimental set up is shown in Figure 3.



(a) (b)

Figure 3: Experimental set up; (a) undamaged case, and (b) damaged case

The numerical modeling has been done following experimental works to correlate or tune the model according to the experimental response.

5 Finite Element Model

The FE model is developed and tuned as per analysis results obtained from the experimental work. In the present case, the first modal frequency has been used for the tuning modal parameters. The model is shown in Figure 4 and the properties of the model is shown in Table 1.

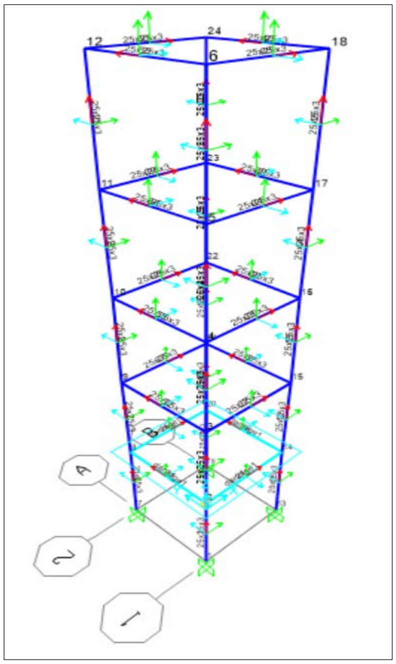


Figure 4: FE model of the frame structure

Table 1: Properties of the FE model

Weight per unit volume	7.697E-08 KN/mm^3
Modulus of Elasticity, E	199.948 KN/mm^2
Poisson Ratio	0.3
Shear Modulus	76.9031 KN/mm^2
Section Size	ISA 25x25x3

For the damaged cases considered here, the measurements are taken at twenty different points with arbitrary amount of masses placed at different points in the numerical model, from which it is possible to correlate frequency change pattern to estimate DLAC.

6 Results and Discussions

I. Results

Different frequencies are obtained from experimental study using FFT for five undamaged and damaged sensor data, as shown in Table 2.

Table 2: Frequencies for undamaged (U) and damaged (D) sensor data from experiment (in Hz)

Sensor Location (Floor)	**1st Mode**		**2nd Mode**		**3rd Mode**		**4th Mode**	
	U	**D**	**U**	**D**	**U**	**D**	**U**	**D**
5	13.438	13.125	44.25	43.825	83.813	83.344	124.72	125.56
4	13.438	13.125	44.156	43.84	83.781	82.125	124.63	125.6
3	13.438	13.125	44.281	43.906	83.625	83.156	124.78	125.53
2	13.469	13.125	44.313	43.906	83.688	82.969	124.81	125.56
1	13.5	13.125	44.344	43.875	83.813	83.594	124.5	125.59

A. Curvature of Mode Shapes and CDF

Curvature of Mode Shapes and CDF is calculated from the undamaged and the damaged response of the structure, as proposed by Pandey et al. (1991) [3] and Foti (2013), shown in Equation 4 [9].

$$CDF = \frac{1}{N}\sum_{i=1}^{N}|v_{oi} - v_{di}| \qquad (4)$$

Where, N is the total no of modes considered, v_{oi} is the curvature mode shape of intact structure and v_{di} is that of the damaged structure.

The estimated CDF plot is shown in Figure 5. The figure shows that the modal curvature is the highest in the 4th storey, while the damage or mass change is the 3rd storey. This indicates that while the general area of the change in the structure can be identified by this method, its accuracy requires further improvement.

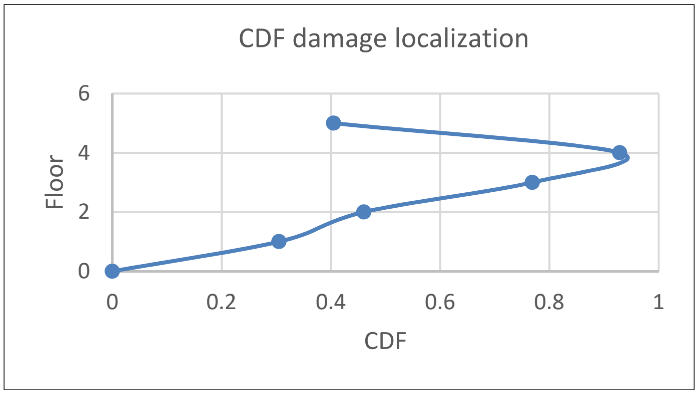


Figure 5: CDF-based damage detection

B. Correlation algorithm

Based on the correlation algorithm, the estimated DLAC values are plotted against the element numbers and from the plot it is shows that the CDF value is highest at element 12, the location where damage is simulated in experiment (third storey) (Figure 6). The maximum value of DLAC is 0.68, which is less than maximum and represents maximum damage at location 12 of the numerical model.

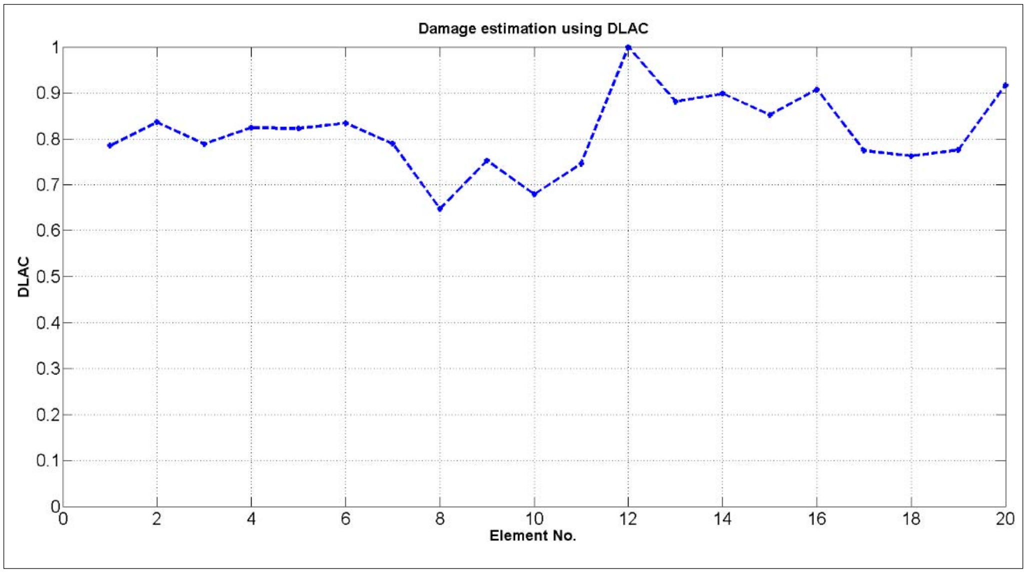


Figure 6: Correlation-based damage detection

DLAC values for all first four modes are plotted against the element number from the numerical model, to represent the damage scenario, as shown in Figure 7.

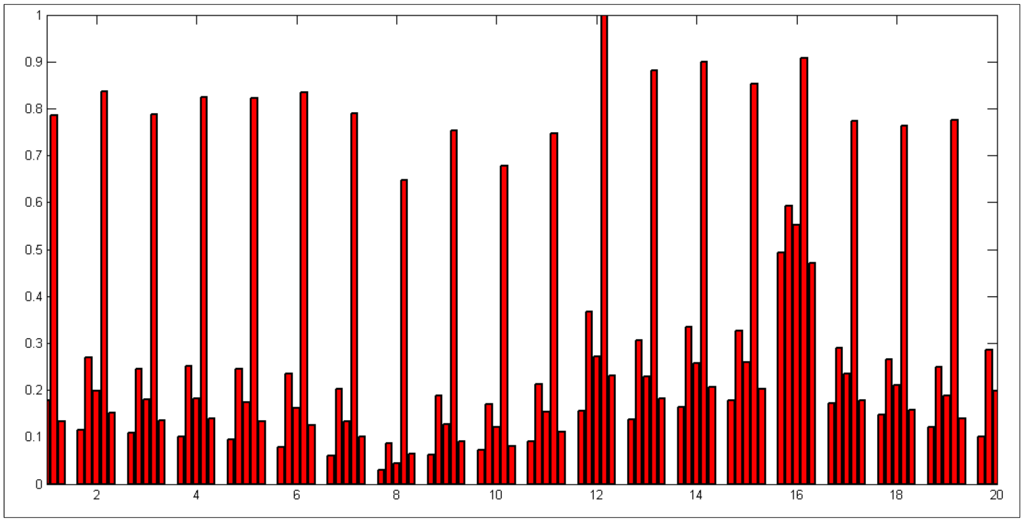


Figure 7: Bar Chart for correlation-based damage detection (X axis – Member no, Y axis – DLAC)

From Figure 7 it is noticed that damage is located using correlation of the modal frequencies, where correlation 1 indicates exact damage location, where each of the red line indicates correlation value from each sensor in the experimental and numerical case study.

II. Discussions

From the case study it is observed that the DLAC-based correlation method successfully locates the damage. But the CDF technique detects damage location incorrectly, although it shows the vicinity of the damage. By increasing number of elements in the numerical model, the damage is located more accurately by employing correlation method. Numerical results for different singular damage cases demonstrate that the DLAC is a more robust tool to find location and severity of structural damage.

7 Conclusions

It is concluded from the work that the DLAC is more accurate to detect damage sensitive features from signal compared to CDF. The accuracy of DLAC depends on number of modal frequencies employed for its calculation, and number of elements used in FE model to simulate different arbitrary damage cases. DLAC depends on correlation of frequencies between the experimental and numerical structural response for singular damage cases. But in multiple damage scenarios, Multiple Damage Location Assurance Criterion (MDLAC) should be used to obtain the frequency vectors. Here the results show that DLAC is effective, although large damage with nonlinear effects are not accounted for. Further study is required to determine the effectiveness of this method in case of multiple damage locations and also in case of different degrees of damage.

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References

1. Roy; T.B., Banerji; S., Panigrahi; S.K., Chourasia; A., Tirca; L., Bagchi; A., 2017. Modal identification and damage detection in structures using non-linear and nonstationary vibration response. Journal of Structural Engineering, 44(3), pp. 220-227.
2. Messina, A., Williams, E.J. and Contursi, T., 1998. Structural damage detection by a sensitivity and statistical-based method. *Journal of sound and vibration*, *216*(5), pp.791-808.
3. Pandey, A.K., Biswas, M. and Samman, M.M., 1991. Damage detection from changes in curvature mode shapes. Journal of sound and vibration, 145(2), pp.321-332.
4. Nobahari, M. and Seyedpoor, S.M., 2011. Structural damage detection using an efficient correlation-based index and a modified genetic algorithm. Mathematical and Computer modelling, 53(9-10), pp.1798-1809.
5. Hackmann, G., Sun, F., Castaneda, N., Lu, C. and Dyke, S., 2008, November. A holistic approach to decentralized structural damage localization using wireless sensor networks. In *Real-Time Systems Symposium, 2008* (pp. 35-46). IEEE.
6. SigVIEW32, 2012. Goran Obradovic and SignalLab, 2.5.1
7. SAP2000, (2014): SAP2000 Advanced User Manuals, Release 10.0.5, CSI Computers & Structures, Inc.
8. MATLAB (2013): MATLAB User Manual, Release 7.2, The MathWorks, USA
9. Foti, D. (2013). “Dynamic identification techniques to numerically detect the structural damage”, The Open Construction and Building Technology Journal, 7(1), pp. 43-50.