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Studies on Damage Detection Using Frequency Change Correlation Approach for Health Assessment

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Abstract

Damage Location Assurance Criteria (DLAC) which is a correlation based approach between vectors of experimental natural frequency change ratios with vectors of analytical natural frequency change ratios, is adopted in this study for damage assessment. Here, the focus is on damage detection and correlation-based localization. For this study, numerical models of cantilever beam with three different damage locations have been modelled using finite element tool. Decreased mass is considered in this study to incorporate as damage. Natural frequencies for the first four modes are arrived for both undamaged and the damaged state of the structures. The damage incorporated is in the range of 10 percent of mass. From the correlation analysis carried out, the locations of the damage are matching with that of the damage considered. Further, to automate the correlation based algorithm, coding is developed using MATLab.

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Keywords: Natural Frequencies, Vibration, DLAC-damage identification, Beams, Structural Health.

1.0 Introduction to Health Monitoring

Structural health monitoring or condition monitoring by way of a structure's global dynamic behaviour is not a new concept. It has been suggested that some of the first clay potters would strike their clayware and listen to its tone as a way to determine the condition to the vessel [1]. The potters understood that any deviation from the expected norm in the tone indicated the presence of a defect in the work carried out. The oldest know collection of pottery has been dated to as early as 10500 BC [2], which is a quite an impressive discovery.The above mentioned concept is the basis of global vibration based structural health monitoring. There are really only two fundamental differences between the monitoring done by potters and such system today. Instead of human ear, innovative sensing devices are used to record data and the other is that the mathematics behind the monitoring process is better

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understood.The structural integrity world over is monitored by simple techniques such as visual inspection, concrete sounding and ultrasonic [3]. If the tests are performed on potential damaged areas, the above mentioned techniques can provide strong indication on the presence of damage. And, the prior knowledge of damage in the structure is a must, or this calls for scrupulously examination of the entire structure. The experience of the inspector comes in handy in diagnosing test results which may only reveal potential symptoms of damage.

Large amount of limitations concerning the use of the above procedures is highly prevalent. These methods are labour intensive and time consuming, perhaps requiring both a trained field technician to perform tests and a structural engineer to interpret results. Inspections are costly and this large expense is likely to affect the rate at which they are conducted. Fully constructed buildings may not be inspected until after a natural disaster occurs and damage is explicitly evident. Many methods mentioned above require visual inspection to locate potential damage sites in the testing [3]. Thus, these methods are most successful when all critical structural elements are exposed. The labour intensive manual inspection process coupled with hazardous working conditions can fatigue workers. This fatigue in turn could introduce judgment errors which may undermine safety of the structure despite the preventative measures being taken.

Due to the limitations associated with manual inspection methods and the need to keep structures functioning, more robust monitoring alternatives are being sought. Currently, analytical health monitoring methodologies based on the mathematics describing simple harmonic motion are being developed. These health monitoring schemes are generally classified by the extent of damage information they can extract from structural response behaviour. The last few decades saw the usage of these mathematical techniques. This technique is borrowed from the aerospace industry and applied to civil infrastructure with some success. The transition of this technique from one industry to another has been proven to be quite challenging. Rytter [1] is credited with the first to carry out such classification as given in Table 1.

Table 1: Rytter's classification of Damage Detection Methods

CATEGORY	CLASSIFICATION
Level 1	Detection- a qualitative indication that damage is present
Level 2	Localization-the probable location of damage
Level 3	Assessment-the size of damage
Level 4	Consequence-the safety of the structure given a certain damage state

2.0 Damage Detection Methodology

Despite new advancements in wireless radio transmitters, better radios themselves do not appear to be able to address the demands of a dense wireless sensor network as envisioned for health monitoring. That is to say that transmission power consumption, radio bandwidth, and latency attributed to data compression schemes will continue to stand in the way of the development and implementation of a full-scale Wireless Sensor Network (WSN) for centralized Structural Health Monitoring (SHM).

Clearly, the idea of using a dense WSN that can exchange reduced sets of data to increase the global sensitivity of an SHM method would be advantageous. As such, distributed SHM algorithms which extract meaningful features from response data without multiple channels of data need to be embedded on wireless system. The potential of vibration- based SHM coupled with smart wireless sensors has not yet been fully appreciated. To date, WSNs have been configured in civil engineering applications to operate in a fashion consistent to that of a centralized data acquisition system. While complex routing and compression algorithms have been to send all data to one centralized collection center for post processing.In response to this limitation placed on data transmission a decentralized smart wireless sensor paradigm for vibration-based SHM is proposed here. Comprehensive literature reviews of vibration-based SHM implementing smart wireless sensors are available in Lynch et al. and Spencer et al. [4, 5]. Feature correlation-based monitoring techniques essentially function by comparing the characteristics of a numerical model to those of the actual structure. In general, these methods are implemented according to the following concept. Mathematical features are extracted from measured structural response behavior and compared to a database of features extracted from response behaviour generated by a numerical model of the structure. The numerical model is studied with various damage scenarios by simulating in various ways to simulate all, or nearly all, of the likely damage scenarios. A strong correlation between a set of observed structural features and those features generated by way of numerical model can indicate the actual structure's condition similar to that of model's, i.e. one can assert whether the actual structure is damaged in the same way the model is damaged.

The numerical model of healthier structure is used to generate and subsequently simulate all of the possible damage scenarios. The damage models are then used to generate mathematical features which are correlated to those extracted from the real structure. If a strong correlation exists between a particular damage model and the real structure, damage is identified and located on the actual structure according to the damage case simulated in that model.

The success of a correlation- based method hinges on both the correlation technique and the feature one selects for monitoring. For example, it has been suggested that Ritz vectors are a feature which is highly sensitive to even low levels of damage [6]. As such, selecting this feature to monitor may help to more precisely distinguish damage cases apart from one another and enhance the performance of the correlation technique used. However there is often a cost associated with extracting such sensitive features. Stacked mode shapes have been shown to be an extremely good indicator for damage detection and localization. However, multiple channels of data are required to be processed simultaneously to accurately obtain mode shapes. As previously discussed, acquiring and transmitting multiple channels of data with SWS is considered to be a permanent hurdle.Cawely and Adams [7] presented one of first types of correlation techniques to be used for damage localization. This rather crude technique compared ratios of consecutive natural frequencies obtained experimentally with those obtained using a numerical model. Since then more sophisticated methods have been introduced which aim to reduce both the database size and the computational intensity, yet heighten localization accuracy.

3.0 Damage Location Assurance Criterion

In this study the Damage location Assurance Criterion (DLAC) correlation method developed by Messina et al [8] is utilized. The proposed method was developed from the Modal Assurance Criterion (MAC). MAC value measures the extent of linear correlation between an experimental and analytical mode shape and is typically used for validating the fidelity of an analytical model, and as such the metric is very similar the inner product vector operation. In their work, Messina et al. show that the MAC concept can be extended damage localization by comparing natural frequency characteristics of a model with the actual structure. The DLAC metric is a measure of correlation between vectors of experimental natural frequency change ratios with a vector of analytical natural frequency change ratios as given below.

$$\text{DLAC}(j) = \frac{|\{\Delta f\}^T.\{\delta f_j\}|^2}{(\{\Delta f\}^T.\{\Delta f\}\{\delta f\}^T.\{\delta f_j\})} \quad (1)$$

Where, the observed frequency change vector is defined as

$$\{\Delta F\} = \{\Delta F_1, \Delta F_2, \Delta F_3, \ldots \Delta Fn\} \quad (2)$$

And the hypothesis frequency change vector is defined for the jth location as

$$\{\delta fj\} = \{\delta f_{1j}, \delta f_{2j}, \delta f_{3j} \ldots \delta fnj\} \quad (3)$$

Hence, $\{\Delta F\}$ and $\{\delta fj\}$ are two vectors of dimension n, Note that both $\{\Delta F\}$ and $\{\delta fj\}$ vectors which are normalized with respect to the structure's health frequencies,

$$\Delta Fi = (Fi,_{observe} - fi,_{health}) / (fi,_{health}) \quad (4)$$

Only single damage scenarios are considered in this study to prevent the technique from becoming too computationally intensive for operation. It is important to note that equation 1 can only be used to detect single damage occurrences, more complex methodologies must be employed to localize damage in structures suffering from multiple damages. Contursi et al [9] developed the Multiple Damage Location Assurance Criterion (MDLAC) based on the DLAC metric, which would be used in the future work for detecting multiple damages.

Often numerical identification models are dynamically tuned in order to facilitate accurate damage recognition and localization. For some correlation-based algorithms tuning, or updating, the numerical model so that it will more accurately depict the response of the structure may also reduce the number of calculations required for convergence. While it is common for numerical models of aerospace and mechanical structures to be dynamically tuned with experimental modal analysis results [9], this is not common practice for civil structures models. As such, in the models used for the DLAC correlation metric will not be updated.A notable benefit of the DLAC metric is that the magnitude of damage simulated in the suite of hypotheses vectors does not significantly affect the results of damage localization.

4.0 Numerical Investigations

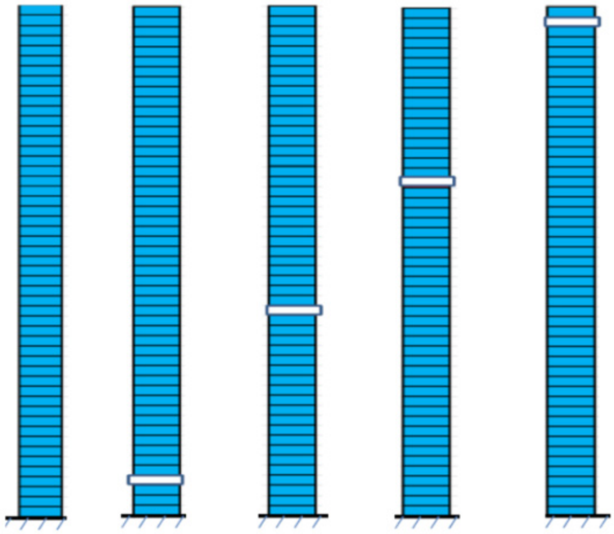
To implement DLAC and integrate into WSN, the numerical modelling of cantilever beam is carried out. The cantilever beam having a clear span of 1000 mm with a solid rectangular cross section of 75×35 mm, and oriented so that bending occur about its weak axis is used. Four damage scenarios (D1, D2, and D3) are chosen from the study. Damage is incorporated in two different ways in the model first being the reduction and other being the addition of the cross section area. In the reduction process, the size of the cross section is changed to be 50×35 mm from 75×35 mm. The physical and mechanical properties of steel are assumed initially an young's modulus = 2.1×10^5N/mm^2, Poisson's ratio=0.3.

Model of the cantilever beam of the dimension mentioned above is modelled in finite element numerical tool. The element chosen is the Euler Bernoulli beam element. One end of the beam is fixed giving a restrain for translation in X, Y direction and rotation in Z direction. The total length of the beam was split into 50 numbers of elements each having a length of 20mm. As the focus of the study is single damage, three different arbitrary element locations were identified as damage, namely 4, 20 and 49 which were 80, 400 and 980 mm away from the fixed end support. The different models considered in the study are shown in Figure 1.
The modal analysis is initially carried out for undamaged cantilever beam. Here the first four modes are considered and the corresponding natural frequencies for the first four modes are arrived. Then subsequently modal analysis is carried out for decreased cross section. The Natural frequencies of undamaged cantilever beam model and for decreased cross sections of the beam element are given in Table 2.

Table 2: Natural Frequency of the Cantilever Beam for decreased Damage

Mode	Frequencies (Hz)			
	D_o	D_1	D_2	D_4
1	0.61	0.63	0.62	0.61
2	3.82	3.86	3.83	3.78
3	10.58	10.63	10.60	10.49
4	12.66	12.72	12.67	12.58

Based on the frequency data, the DLAC was arrived for decreased cross sections. The natural frequencies for the first four modes were arrived, by reducing the cross section of each element every single time. Damages were analyzed separately since the study was focused on single damage. The damage location i.e., the damaged element and their location are given in Figure 1. The mode shapes of the typical damaged beam are given in Figure 2.



Damage	D_0	D_1	D_2	D_3	D_4
Element	0	4	20	33	49
Distance	0 mm	80 mm	400 mm	660 mm	980 mm

* Location of the single damage element is indicated in white.

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Fig.1: Undamaged and damaged Cantilever Models

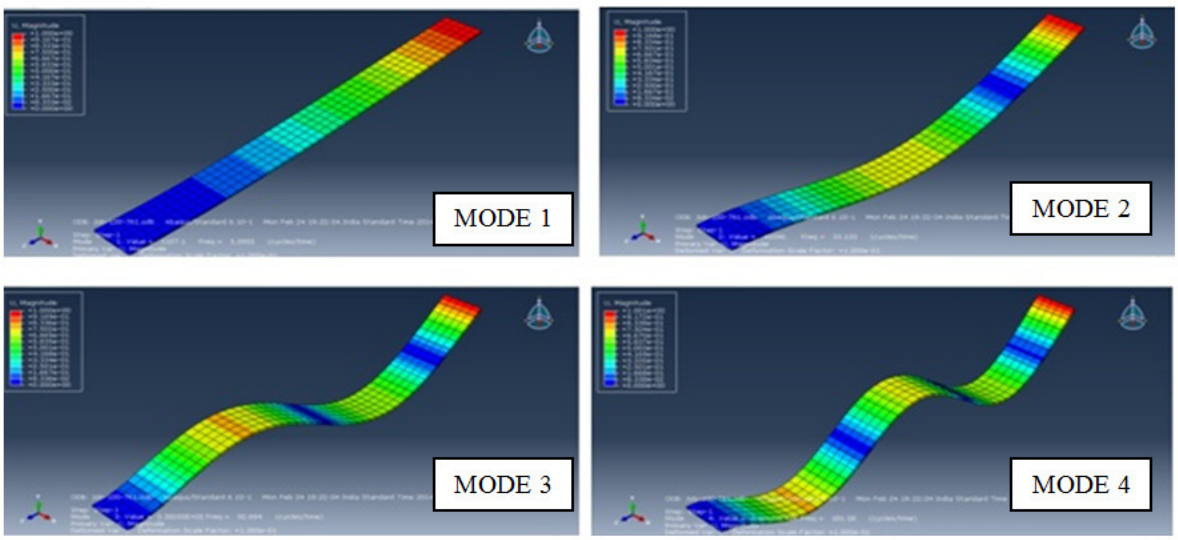

Fig.2: Typical damaged Cantilever Beam

The natural frequencies of all the four modes by introducing damage for each 50 elements are arrived.

5.0 Damage Detection Using DLAC

The numerical model of the cantilever beam is carried out using the Finite Element tool. Each cantilever with different damage scenarios were analysed for damage localization. As mentioned earlier, the damage localization is carried out using DLAC method. For arriving at DLAC value the variation in experimental frequency change vector and the hypothesis frequency change vector for different location are mandatory. And in this study only the first four mode shape are used. Experimental frequency change vector for different modes has to be arrived based on the difference with the natural frequency of undamaged and damage structure for their corresponding modes. And for arriving at hypothesis frequency change, numerical frequency difference for undamaged and damage structure is carried out at each location. It has to be noted that the frequency change arrived in the experimental and numerical should be for the same number of modes. By using the experimental frequency change and hypothesis frequency change vector the damage was detected using DLAC value. Since, DLAC method is based on correlation approach,

Each and every element hypothesis frequency arrived is correlated with that of experimental frequency change vector. Wherever there is correlation i.e., wherever there is damage, the DLAC values gives 1 as output and remaining location, the DLAC value gives less than 1. Making DLAC as a basis of damage detection, algorithm for damage detection has been developed using MATLAB. Due to the absence of the experimental frequency change vector, the numerical frequencies valueare used in this study to arrive at the DLAC value. The results of the different damage scenarios are discussed below:

CASE 1: Damage D1

In this case, the damage (D1) is assumed to be happened at location 80 mm from the fixed support i.e., element no. 4. The DLAC values for all the elements are calculated and are given in figure 3. The DLAC values varied from 1 to 0.05. The DLAC value along with element no. 4, element no. 3 also shows value of 1, which means there is a presence of damage. The element number 3 showing a DLAC value of 1 along with element no 4 is due to the presence of damage near to the end support.

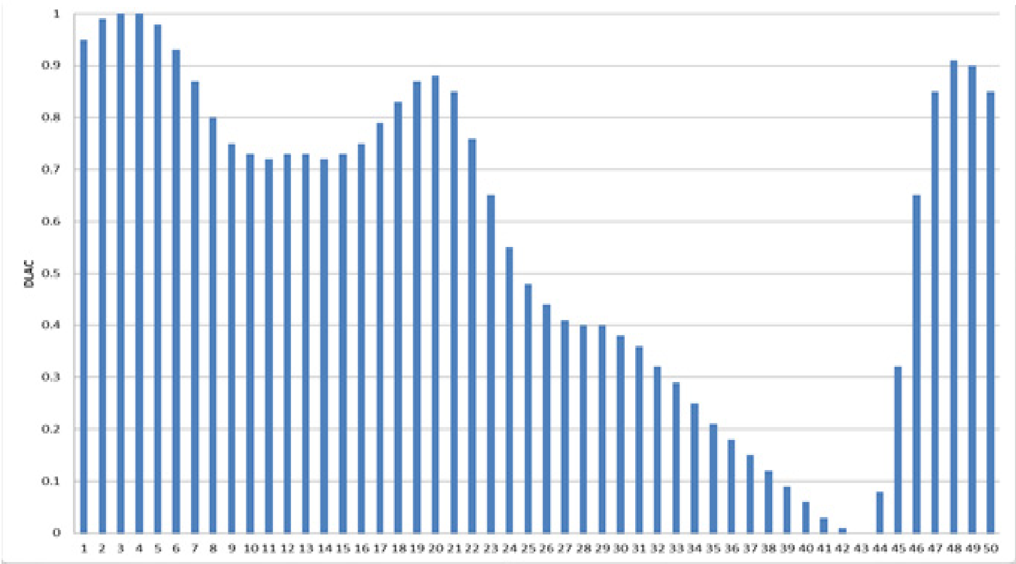

Fig.3: DLAC Value for Damage at position S1- Element no. 4

CASE 2: Damage D2

In this case the Damage D2 is assumed to be happened at element no 20, 400 mm from the face of the fixed support. In this case the damage was clearly identified as shown in figure 4, as the DLAC value for element no. 20 gives a value of 1. It is also seen that there is no influence of the support in locating the damage.

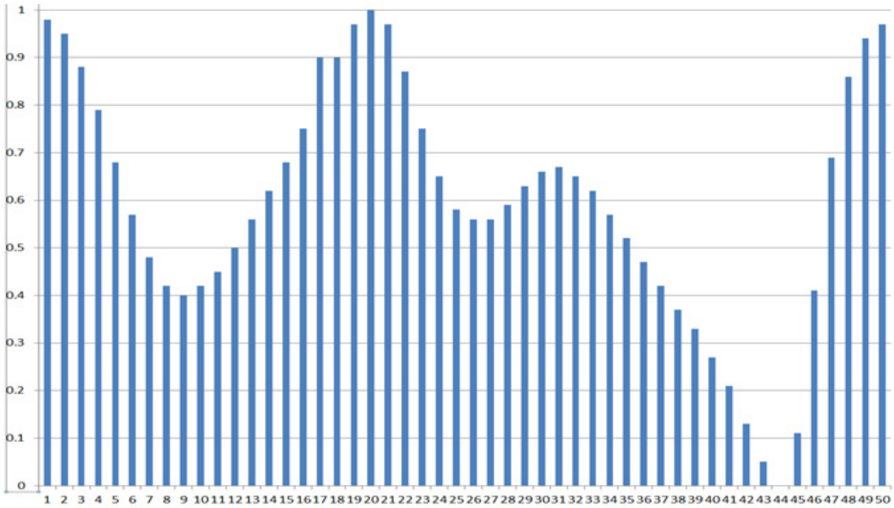

Fig.4: DLAC Value for Damage at position S2- Element no. 20

CASE 3: Damage D3

In this case the Damage D3 is assumed to be happened at element no 49, 980 mm from the face of the fixed support. In this case the damage was clearly identified by as shown in figure 5, as the DLAC value for element no. 49 gives a value of 1. Damage at the end of the beam has no influence as compared to the case 1.

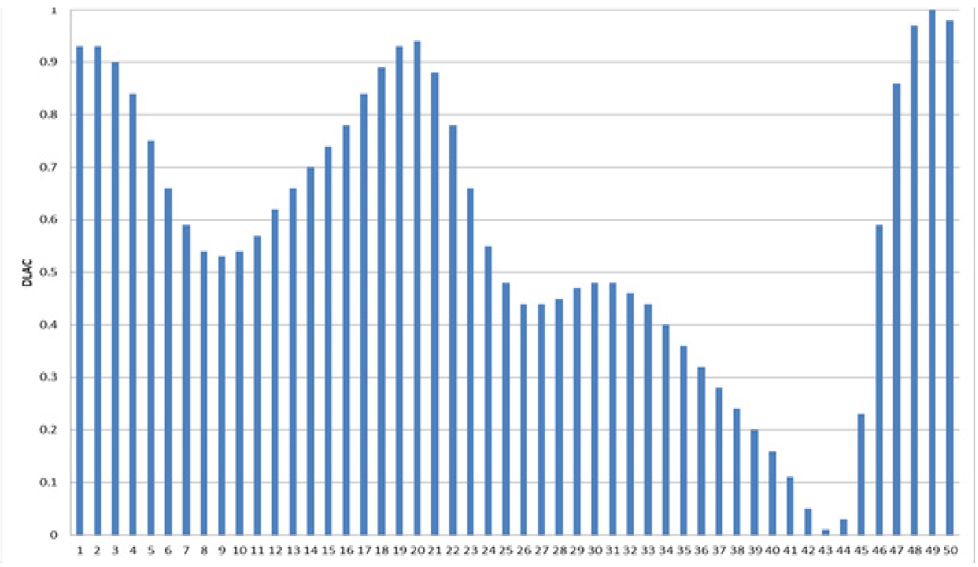

Fig.5: DLAC Value for Damage at position S3- Element no. 49

The DLAC correlation procedure proved to perform robustly in majority of the cases when applied to a continuous system. It is seen that when the damage is closer to the support there is an influence of support in the damage location assurance value.

6.0 Summary

Here a 2-D cantilever beam was developed as a numerical model to study the DLAC method of damage detection. The first four modes and the corresponding natural frequencies were arrived for both damage and undamaged beam. Four damage scenarios chosen for damage location study were exactly matched using the DLAC method.

The DLAC correlation procedure proved to perform robustly when applied to a continuous system. It is seen that when the damage is closer to the support there is an influence of support in the damage location assurance criterion value. An advantage of this approach is its capacity of localizing damage with data collected by numerical models.The DLAC health monitoring technique has been developed for implementation as a part of distributed smart wireless sensor network.

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