DAMAGE ASSESSMENT OF BRIDGES USING COMPOUND SHM– SIGNAL PROCESSING AND COMMUNICATION CHALLENGES

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ABSTRACT

A novel compound Structural Health Monitoring (SHM) method as well as some signal processing and communication challenges for a robust methodology are presented in this paper. The performance of the two-step SHM method is compared to some other established damage detection techniques. The proposed method was found to identify the location of local damage more accurately than the other methods. Significant signal processing and communication aspects still need to be addressed in order to enhance the robustness of the method.

***Index Terms*—** Structural Health Monitoring, Long Span Bridges, Wireless Sensor Network, Signal Processing and Communication Challenges

1. INTRODUCTION

Bridges play a vital part in the economy of the country, as they facilitate the movement of goods and people around. These structures are subject to deterioration over time due to the continuous use and exposure to de-icing salts, humidity, temperature variations, etc. The closure of a bridge due to extensive damage or failure may affect millions of people monetarily, or even cause loss of life in some cases. Hence it is important to evaluate the condition of the structure in order to avoid any failure and plan maintenance actions without disrupting its operations. Traditionally, the evaluation of the condition of civil infrastructure has been carried out through visual inspection mainly due to its low cost and simplicity. However, visual inspection is prone to human errors, as it depends on the perception and the experience of the inspector. Furthermore, visual inspection can be carried out periodically and therefore cannot provide information of the condition of the system in between two inspections. The realisation of these shortcomings along with the increasing dependence of the society on the civil engineering infrastructure has made the Structural Health Monitoring (SHM) systems an imperative. The process of damage can be broadly classified into 4 levels, namely detection of the presence of damage (level 1), identification of damage location (level 2), determining the extent of damage (level 3), and estimating the remaining life of the structure (level 4) [1].

The SHM systems should be able to perform continuous monitoring, be low cost for setting up and maintenance and able to raise an alarm in case the system performance undergoes a sudden change. The study of vibration characteristics like the natural frequencies and mode shapes is an inexpensive way for continuous monitoring. Doebling et al. [2] give an extensive overview of the vibration based detection methods. Many different parameters for the damage detection have been suggested in literature [3-5]. These methods are able to detect the presence and locate the damage, but are unable to diagnose the extent of damage. Thus, a robust method which can be able to diagnose the extent of damage is still needed. Furthermore, the presence of measurement noise together with noise amplification due to improper data processing can affect significantly the performance of these methods. Therefore, the use of proper signal processing and efficient communication techniques can help overcome these problems, thus allowing the development of a more robust methodology.

The present paper proposes a new compound, two-step method making use of modal macro strains using long gauge strain sensors and natural frequencies for level 3 damage detection of the structure. The first step uses long gauge strain sensors for damage isolation and then a sensitivity-based model updating technique is implemented for determining the extent of damage. The two-step methodology ensures that the shortcomings of using methods on their own are overcome, thus yielding a more robust method. The methodology is applied to a finite element (FE) model of the Great Belt East Bridge and its performance is compared with some widely used methods namely the Enhanced Co-ordinate Modal Assurance Criterion (ECOMAC) [6], the Mode Shape Curvature Method [3], and the Modal Flexibility Index Method [4]. In addition, the paper outlines some signal processing and communication challenges for specific SHM applications.

2. NUMERICAL MODELLING OF BRIDGE

The Great Belt East Bridge used in this study is a suspension bridge with a central span of 1624 m and two side spans of 535 m each as shown in Fig. 1. The entire length of the girder is suspended from two massive pylons which have a height of 254 m. The bridge uses a continuous bridge girder without supports at the pylons. The main suspension cables carry the dead weight of the girder and also the service loads. The bridge was modeled in commercial software ABAQUS [7]. The fish bone model was employed for its simplicity. The bridge mass was distributed in three locations: two equal masses were placed where the hangers are attached to the girder and one mass was placed below the neutral axis to preserve the location of

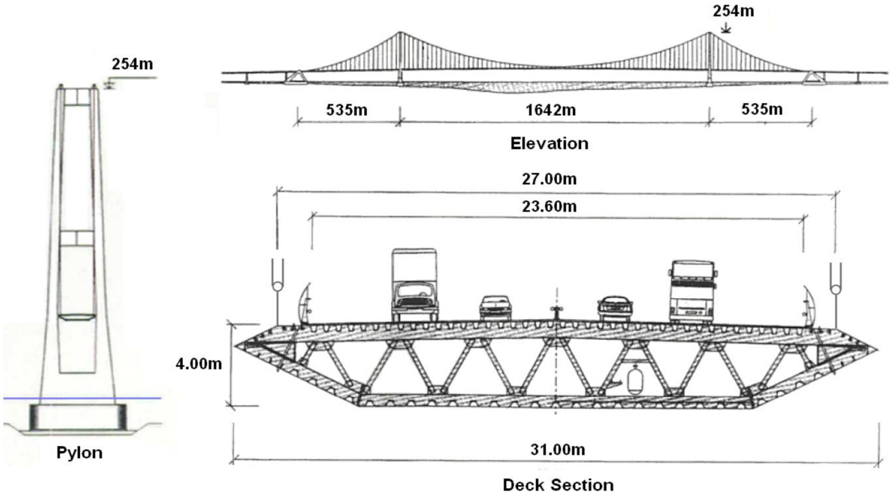

Fig. 1: Main Dimensions of the Great Belt East Bridge [7]

the neutral axis and the center of gravity. The main cables and the hangers were modeled as beam elements with very low stiffness in compression and bending. The pylons were modeled using 30 beam elements for each tower. Fig. 2 shows the FE model of the bridge.

The FE model of the bridge was validated using static and modal analysis. The static analysis yielded the pre-stress in the main cables as 734MPa which is within 2% of the design pre-stress of the main-cables. Also, the dynamic validation yielded natural frequencies and mode shapes for the first eight longitudinal bending modes within 5% of the experimental modes reported in literature [8].

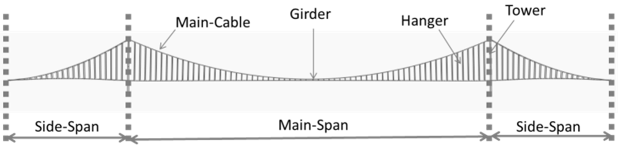

Fig. 2: FE Model of the Great Belt East Bridge

3. VIBRATION BASED DAMAGE IDENTIFICATION (VBDI)

3.1. Vibration Parameters

The vibration based damage identification methods use vibration characteristics to monitor the performance of the structure. It is an effective strategy for low-cost continuous monitoring. The methods are distinguished based on the basis of the structure property used for monitoring. The most common parameters used are for the changes in natural frequencies, in mode shapes, in mode shape derivatives, and in modal strains. The properties monitored are acceleration data and strain data for the structure subject to unknown ambient excitation.

Natural frequencies can be defined as the frequencies at which a structure vibrates. When the frequency of the external load meets the natural frequency of a structure, resonance occurs. Natural frequencies are measured using accelerometers, followed by taking the Fourier Transform of the time domain response. On the other hand, mode shape for a particular mode number is defined as the deformation shape of the structure for that mode of vibration when excited at that resonant frequency. The mode shape is computed by double integration of the accelerometer data with respect to time.

The modal properties are a function of the condition of the structure. Hence, any change in the structure will be reflected by a change in these parameters. These parameters have a varying sensitivity to the physical changes and have their own merits and limitations. Some of the commonly used VBDI methods are mentioned below.

3.2. Enhanced coordinate modal assurance criterion method (ECOMAC)

The ECOMAC [6] metric can be computed by

$$ECOMAC(j) = \frac{1}{2N}\sum_{i=1}^{N}\left|\psi_i{}^*(j) - \psi_i(j)\right| \qquad (1)$$

where, $\psi_i{}^*$, and ψ_i, denote the i^{th} damaged and undamaged mode shape respectively, N, is the number of mode shapes and j, is the joint number. The highest peak in the ECOMAC plot indicates damage. The derivation of ECOMAC is given in [6].

3.3. Mode Shape Curvature Method (MSC)

The modal curvature which is the second derivative of the mode shapes is highly sensitive and hence ideal for the detection and isolation of damage. The central difference operator may be used to get the mode shape curvature (MSC) from the measured mode shapes [3]. It is given by:

$$\phi_i'' = \frac{\phi_{i+1} - 2\phi_i + \phi_{i-1}}{l^2} \tag{2}$$

where, ϕ is the mode shape curvature at i^{th} location, ϕ is the mode shape at particular location, and l is the distance between the sensor nodes.

3.4. Modal Flexibility Index Method (MFI)

Flexibility matrix of the structure is an inverse of the stiffness matrix and hence can be calculated precisely even with a few lower modes of vibration [6]. The flexibility can be computed by:

$$F = \sum_{i=1}^{N} \frac{1}{\omega^2} \psi_i \psi_i^T \tag{3}$$

where, ψ_i, denotes the i^{th} mode shape, N, is the number of mode shapes, and ω, is the diagonal matrix with natural frequencies of vibration.

The change in flexibility matrix computed from the first few modes of vibration for the damaged and undamaged structure can be a used for damage detection and isolation. A comprehensive explanation of MFI is given in [4].

3.5. Compound SHM method

The proposed methodology is a two-step methodology. In the first step, Modal Macro Strain (MMS) [9] measurements are used to isolate the damage, and in the second step a sensitivity-based model updating for damage detection and for determining the extent of damage is adopted.

The MMS is the average strain over the gauge length of the sensors. The measurement being an average of the strain over the gauge lengths is less susceptible to local stress/strain concentrations, and hence is more representative of the structural deformation of the entire structural member. MMS is more sensitive to damage than the mode shapes. Furthermore, it does not face any round-off errors and truncation errors, which are faced while computing the curvatures. Furthermore, the present hardware allows measurement lengths of several meters, which allows us to overcome local discontinuities which affect the damage detection method adversely. Mathematically, the MMS [10] is given by

$$\boldsymbol{\Psi_r} = \frac{\boldsymbol{M_r y_r}}{\boldsymbol{EI_r}} \tag{4}$$

where, M, is the modal moment, EI, is the modal flexural rigidity, Ψ, is the modal strain, and y, is the distance from the neutral axis for the r^{th} mode.

Flexural Rigidity for a beam structure is the product of the Young's Modulus (Material Property) and the Second Moment of Area for that section (Property of the Structure). Thus, any change in material behavior, or sectional behavior of the structure due to damage will be reflected by a change in the flexural rigidity, which can be detected by the change in the modal strain at the location of the damage.

Once the damage is isolated, the extent of damage is determined in the second step. The second step uses the natural frequencies for the model updating process which is concisely explained in [11], where, ε_n, given by

$$\boldsymbol{\varepsilon_n = S_n\, \delta\theta_n} \tag{5}$$

is the difference in the measure natural frequencies at the n^{th} iteration, $\delta\theta_n$ is the change in updating parameter (flexural rigidity), and $S_{i,j}$ is the Sensitivity Matrix for the i^{th} mode and the j^{th} updating parameter and is given by

$$\mathbf{S}_{i,j} = \frac{\partial \lambda_{ci}}{\partial \theta_j} = \boldsymbol{\varphi}_i^T \left[\frac{\partial \mathbf{K}}{\partial \theta_j} - \lambda_{ci} \frac{\partial \mathbf{M}}{\partial \theta_j} \right] \boldsymbol{\varphi}_i \tag{6}$$

where, $\boldsymbol{K}$ is the system stiffness matrix, $\boldsymbol{M}$ is the system mass matrix, λ_i is the i^{th} natural frequency of the structure, and ϕ_i is the i^{th} mode shape vector

Hence, knowing the change in frequency and the mode shapes, the damage extent can be determined iteratively, by reducing the error in the target and the iterative natural frequencies.

3.6. Limitations of Vibration Parameters

The major limitation of the use of vibration parameters is the drop in performance in presence of measurement noise and changes in the ambient conditions.

The natural frequencies of the structure are a global property of the structure and hence each sensor measures all the natural frequencies of the structure. Due to this redundancy, the effect of measurement noise in the frequency measurements is negligible. Unfortunately, natural frequency changes are not able to localize the damage. Mode shapes are more local properties and may be used for damage isolation. But, due to the lack of redundancy it is not possible to offset the measurement noise from the mode shape measurement. Furthermore, this noise gets amplified during the numerical integration process [2]. This poses a very interesting challenge for the signal-processing community in order to reduce the errors in measurement and also the amplification during numerical integration through the use of intelligent algorithms and proper signal processing.

The vibration parameters are sensitive to ambient condition changes. The changes in natural frequencies particularly due to the temperature changes may be higher than the changes due to damage [2]. Thus, it is of utmost importance to estimate the natural frequencies with high precision. The use of Fourier Transform, although computationally efficient way for the estimation, may lead to some errors. More sophisticated high-resolution techniques may be applied for the estimation of natural frequencies than the use of Fourier Transform. This is another interesting problem which may be tackled through co-operation between the Structural Engineers and Signal Processing Engineers.

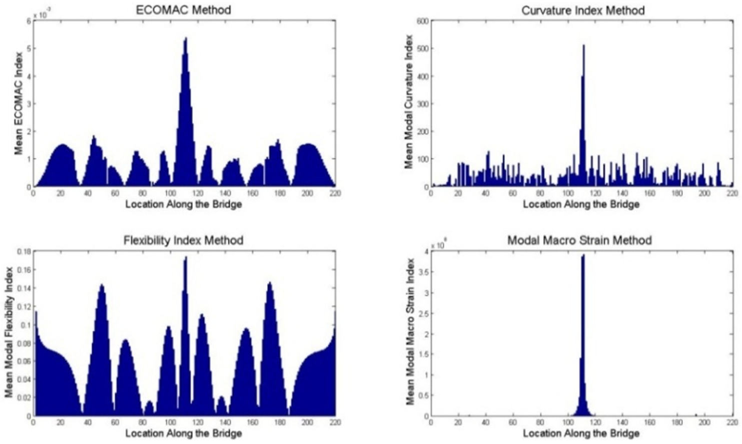

Fig. 3: Performance of Damage Isolation Methods

4. ANALYSIS RESULTS AND DISCUSSIONS

The performance of the various parameters of the four methods introduced in Section 3 can be assessed in terms of their ability to isolate damage successfully. The isolation method is considered to be successful, if the value of the corresponding parameter at the damage location is the highest. The damage was introduced at various locations and the ability of the methods was validated. In this paper, the results obtained for the damage isolation at the mid-point (beam element 110) using the four methods are presented in Fig. 3. It is noted that in these analyses 221 sensor nodes were assumed. For this case the damage was introduced by reducing the flexural rigidity of a single element by 82%. Analyses have demonstrated that the MMS method is able to detect low damage extents (i.e., 20% reduction in the flexural rigidity) in the absence of measurement noise. However, a higher degree of damage is assumed, to facilitate the comparison of the four methods, for which the performance of the above methods has already been validated [6, 13]. As can be seen in Fig. 3, all four methods were able to isolate the damage successfully. However, the relative difference in the peak corresponding to the damage location and the other locations is highest for the MMS method, while it is the lowest for the MFI method.

4.1. Determination of Damage Extent

The damage extent is determined using the sensitivity based model updating technique [12]. A level of damage extent is assumed to initiate the iterative process. For every iteration the error is reduced until the expected convergence is achieved (0.05% relative error). The natural frequencies and mode shapes are used for the determination of the extent of damage. Fig. 4 shows the convergence plot.

The use of a two-step methodology reduces the number of updating parameters or unknowns in the equation for the updating problem. This simplifies the problem and reduces the computational load.

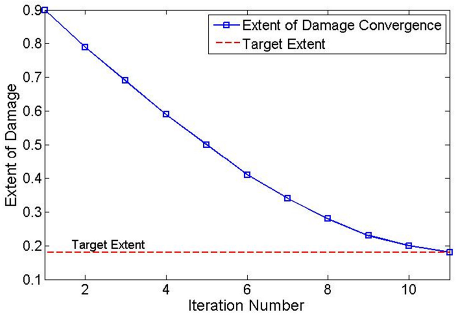

Fig. 4: Convergence of Damage Extent

5. COMMUNICATION CHALLENGES

The present study was undertaken without considering any network limitations. The study assumes perfect communication link, no data loss, and perfect time synchronization. Traditionally, tethered sensor networks have been employed in order to fulfill the aforementioned application demands. But due to the large installation costs and the lack of flexibility, their use has been limited [15]. On the other hand, the use of wireless networks for data transfer promises to be a low cost alternative for SHM. It reduces the installation cost and also the maintenance cost. Furthermore, it makes the network flexible, and engineers can change the network layout easily according to the application demands. But the employment of these wireless networks also poses some significant challenges which are highlighted in this section.

The network lifetime is a prime concern and stumbling block for commercial deployment of wireless networks for long term monitoring. The typical lifetime of wireless nodes is of the order of several months, while that of the structure is several decades [13].

The other key issue which is of importance is the delay in the time of data collection to its transfer to the sink node and then the post processing. Unfortunately, due to the complexity of the network, and the amount of data, it takes several minutes for the monitored data to be collected at the sink node and the required processing to take place. This delay makes the use of such networks for real time applications difficult. The other issues of significance for SHM applications are the ability for high sampling rates with low jitter, and time synchronized sampling of data, and data fidelity. In addition, the SHM system is expected to work even during natural hazards, like earthquakes, tsunamis, etc. Hence, the network design should have a certain level of redundancy and fault tolerance in order to ensure functioning even in extreme scenarios.

Attempts have been made by researchers in both fields to overcome some of the highlighted issues [14, 15]. Although this work has yielded encouraging results, more work needs to be done for complete replacement of tethered networks with WSN.

6. CONCLUSIONS

A novel compound SHM method, as well as some signal processing and communication challenges for achieving a robust methodology are presented in this paper. The performance of the compound SHM method is compared to some other established damage detection techniques through numerical simulation on a validated FE model of a long span bridge. The study indicates that the proposed two-step methodology performs better than other methods studied. It combines the benefits of the use of long gauge strain sensors and accelerometers and allows us to have reliable damage isolation and damage diagnosis.

However, in order to make the methodology more robust, issues related to signal processing and communication highlighted in the paper need to be addressed in detail.

The work so far in this field has yielded encouraging results, but still there is a scope for improvement in performance. Hence, the signal-processing community has to collaborate with the structural engineers to understand the issues and specific requirements of the application and replace of tethered networks by WSN.

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