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Systematic Review of Global Response Based Techniques of Structural Health Monitoring

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A detailed review of the global SHM techniques has been presented advantages and disadvantages of the techniques were also discussed in this paper. As compared to existing techniques, Global technique is most suitable. However, it is not sensitive for incipient damages but moderate to severe damages can be detected precisely. Though the global response based technique relies on some basic parameters like flexibility, stiffness, mode shape, modal damping etc. and is also found costly in application hence this technique have their limitations to apply to real structure. This technique is suitable for health monitoring of any civil, mechanical or aerospace structure and It is also realized that it should be updated so that it will be possible to monitor the complete health of structure used in present scenario. In the present scenario of developing age of any country it is very essential to monitor the life of the structure for present condition, performance and future usefulness of the structure. The health monitoring of a structure does not only provide the present condition of the structure but also provide sufficient information regarding the method of rehabilitation of the existing structure.
Keywords: Local Technique, Global Technique, Static Response, Dynamic Response

I. INTRODUCTION

There are various techniques of health monitoring and damage/crack detection in Civil Engineering Structures. Damage/crack detection in structure is based on fact that any crack/ damage changes the structural characteristics like frequencies, stiffness, flexibility, mode shape etc. resulting in changes in the structural response. Various investigators (Bhalla, 2004; Soh et al., 2000; Park et al. 2007; Zhao et. al. 2008; Shanker, 2009) reported that structural health monitoring techniques can be broadly classified into following two broad categories based on different kinds of structural characteristics or responses:

*A.*Global techniques
*B.*Local techniques
1) Global Techniques

Further global technique can be classified into two categories:

2) Global static response based techniques
3) Global dynamic response based techniques

a) Global Static Response Based Techniques: A static displacement technique based on static deformation was formulated by Banan*et. al.* (1994). In this technique static forces on the structure are applied and corresponding displacements are measured. The relationship between forces and displacements reflects the health of the structure. It is not necessary to select entire set of forces and displacements, instead force and displacement at critical section may be considered. However, to achieve the appropriate results, several load cases may be important to obtain sufficient information of the structural system. The resulting equations are solved iteratively to obtain a set of member constitutive properties or the structural parameters. Any change in parameters from the parameters at healthy state indicate the presence of damage/crack. Measurement of displacements on a large real-life structure is not an easy task since one needs to establish a frame of reference which requires the construction of a secondary structure on an independent foundation the applicability of this method, therefore, is limited. Further employing a number of load cases and computational approach is a time-consuming procedure. Similar technique was proposed by Sanayei and Saletnik in year 1996 based on static strain measurement. Although, in this technique strain measurement can be made with a much greater degree of precision, but is too tedious and expensive to enable a timely and cost effective assessment of the health of real life structures.

b) Global Dynamic Response Based Techniques: The basic underlining principle of these techniques is that the modal parameters like the frequencies, the mode shapes and the modal damping are the functions of the physical properties of the structure like mass, damping and stiffness. Hence, any change in the physical properties resulting from damage will cause detectable change

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in the modal parameters. On the basis of modal parameter employed, these techniques can be further divided into following four categories:

i) Based on frequency changes
ii) Based on mode shape change
iii) Based on modal damping change
iv) Based on updating structural model parameter

II. GLOBAL TECHNIQUESIN TERMS OF BASIC PARAMETERS

A. *Stiffness Changes*

Zimmerman and Kaouk (1994) proposed "change in stiffness method" based on changes in stiffness resulting from damage. This method identifies changes in structural stiffness matrix resulting from damage. The stiffness matrix [**K**] is determined from the mode shapes and the modal frequencies derived from the measured dynamic response of the structure, as

$$[K] = [M]\,[\Phi][\Omega][\Phi]^T[M] = [M]\left(\sum_{i=1}^{n}\omega_i^{\,2}\Phi_i\Phi_i^{\,T}\right)[M] \quad (1)$$

Where, [M] is the mass matrix, [Φ] the mode shape matrix and n the total number of the modes considered. Let [Δ***K***] represents the change in stiffness matrix due to damage. The indicator of damage in this method is a damage vector defined by

$$[D_i] = [\Delta K][\Phi_i] \quad (2)$$

Where, [D_i] is the i^{th} damage vector, obtained from the i^{th} mode shape vector [Φ_i]. The location of the damage is indicated by the row of the maximum parameter in the damage vector.

This method is inflicted with major drawback. Higher modes are important in the estimation of the stiffness matrix, as can be seen from Eq. (1). Since, modal contribution to [K] increases as the modal frequency increases. Unfortunately, the dynamic vibration testing can yield only first few mode shapes. Hence, the estimated [K] is likely to be inaccurate.

B. *Flexibility Changes*

Pandey and Biswas (1994) were the first to propose the change in flexibility method. The basic principle in this approach is that damage in thestructure alters its flexibility matrix, which can be used to identify damage. The relative amount by which the various elements are altered is used to localize the damage. Like the change in stiffness method, mode shape vectors and resonant frequencies obtained from the dynamic response data (collected before damage and after damage) are used to obtain the flexibility matrices [***F***], which may be expressed as

$$[F] = [\Phi]\,[\Omega]^{-1}[\Phi]^{T} = \sum_{i=1}^{n}\left(\frac{1}{\omega^2}\right)\Phi_i\Phi_i^{\,T} \quad (3)$$

As can be seen from Eq.(3),[F] is proportional to the square of the inverse of the modal frequencies. Hence it decreases rapidly with increasing frequencies. Hence, only a few lower modes are required for accurate estimation of [F].The maximum of the values at a particular column $\overline{\delta_j}$ of [F] is taken as an index of flexibility for that particular degree of freedom (DOF). Any change in this parameter is indicative of damage at that particular DOF. In the case of a simply supported beam, the change is maximum at the damaged element. The amount of change is a measure of the severity of damage. Although the technique is an improvement over the change in stiffness method, the researchers did not investigate the case of multiple damage locations.

Aktan et al. (1994) suggested the use of measured flexibility as a structural condition to assess the relatively integrity of a bridge. Measured flexibility of bridges were compared to the static deflection subjected to a set of truck loads.

C. *Technique based on Strain Energy*

Stubbs and Kim (1994) developed the damage index method. The damage index β is calculated based on the strain energy stored in the structure when it deforms in particular mode shape. For the j^{th}location and the i^{th}mode, the damage index β_{ij} is defined as

$$\beta_{ij}=\frac{\left(\int_a^b[\Phi_i^{*''}(x)]^2dx+\int_0^L[\Phi_i^{*''}(x)]^2dx\right)\int_0^L[\Phi_i^{''}(x)]^2dx}{\left(\int_a^b[\Phi_i^{''}(x)]^2dx+\int_0^L[\Phi_i^{''}(x)]^2dx\right)\int_0^L[\Phi_i^{*''}(x)]^2dx} \quad (4)$$

where, $\Phi_i^{''}(x)$ and $\Phi_i^{*''}(x)$ are the second derivatives of the i^{th} mode shape corresponding to the undamaged and the damaged structures, respectively. . Here, *a* and*b* are the limits of a segment of a beam where damage is being evaluated. This technique has an advantage over other techniques (such as stiffness/flexibility approaches) in that it has specific criteria for determining whether damage has occur at a particular location. Farrar and Jauregui (1998) did a comparative study of the above techniques on a single structure, the I-40 Bridge over Rio Grande in Albuqueque, New Mexico, USA. The bridge had a maximum span length of about 50m and girder depth of about 3m. Damage was induced by means of a torch cut, at the middle of the 50m span and starting from the mid depth of web as a 600mm long by 10mm wide crack. It was then extended in three stages to the entire bottom half of the web and the bottom flange. The bridge was excited by a hydraulic shaker both in undamaged and damaged conditions to obtain the natural frequencies and the mode shapes. The major conclusions of their work are:

1) Standard modal properties such as mode shapes and resonant frequencies are not good indicators of damage. No noticeable change in the measured resonant frequencies and mode shapes (drawn through interpolation) was observed till the final level of damage.
2) All the methods identified the damage location correctly for the most severe damage case only.
3) In some of the methods, human judgmentis imperative to correctly identify the location of damage. If judgment is applied blindly, it would have been difficult to locate the damage.
4) When the entire sets of tests are considered, the damage index method is the one with the best performance.
5) Exact location of the damage is not predicable using any of the methods.

Several other related publications can be found, reporting the use of improved techniques, modern wireless technology and high speed data processing (Singhal and Kiremiddjian, 1996; Skjaerbaek et al., 1998; Pines and Lovell, 1998; Aktan et al., 1998, 2000; Lynch et al., 2003a).However, in spite of rapid advancement in the hardware and software technologies, basic principle has not changed, which is to identify changes in the modal and structural parameters (or their derivatives) that are resulted from cracks/damages.

III. CONCLUSIONS AND LIMITATION OF GLOBAL TECHNIQUES

A. *Some of the critical issues associated with the global techniques are discussed below*

1) These techniques are dependent on either of analytical models or test data for detection and location of the damage. If these data sets are unavailable, they are impractical. It is very difficult to generate the original data of the existing structures.
2) These techniques are based on linear structural model. Behaviors of structure can be assumed linear for small loads, however it isnon-linear at failure level. Generally damage develops in structure at higher loads.
3) To monitor the health of very large and heavy structures like bridges and tall building, large number of sensors are required for monitoring, which may bea critical issue.
4) For small incipient level damages, it is tedious to differentiate between variation in the modal properties that resulted from damage and those changes resulting from changes in the measurements.
5) These techniques typically rely on the first few modes and the corresponding natural frequencies of the structures, which, being global, are not sensitive enough to be altered by localized incipient damages. It is for this reason that Farrar and Jauregui (1998) found that the global dynamic technique failed to identify damage location for less severe damage scenarios in their experiment. It could be possible that damage, just large enough to be detected by global dynamic techniques, is already critical for the structure in question.
6) These techniques demand expensive hardware and sensors, such as inertial shakers, self-conditioning accelerometers and laser velocity meters. For a large structure, the overall cost of such sensor systems could easily run into millions of dollars.
7) A major limitation of these techniques is the interference caused by the ambient mechanical noise, besides the electrical and the electromagnetic noise associated with the measurement systems. Incidentally, the ambient noise also happens to be in the low frequency range.

8) The precondition of a high fidelity ‘model’ of the test structure restricts the application of the methods to relatively simple structural geometrics and configurations. Since evaluation of stiffness and damping at the supports (often rusted out in service condition) is an intricate process, identification of suitable 'model' is relatively a difficult task in practice.
9) Most often the performances of these techniques degrade in multiple damage condition (Wang et al., 1998).

IV. NEED FORFURTHER RESEARCH IN GLOBAL TECHNIQUES

A. The following factsreinforces the requirement for further work for development of new global dynamic techniques

1) The global dynamic techniques depends upon the prior test data or analytical/numerical models to detect and locate the damages. It is not possible to predict the health of structure, if healthy state data/undamaged data are not available. Comprehensive research is needed to avoid dependency upon prior set data.
2) All damage-identification methods based on vibration based techniques depends upon linear structural models. A research is needed to account for the effect of non-linearity.
3) There is uncertainty associated with the number and location of sensors required to be installed on real structures to successfully detect and predict the location of damage. Comprehensive research is required to figure out the minimum number of sensors required for real-world implementation of technique. Prior knowledge of damage location should be mandatory for deciding location for installing sensors.
4) The global vibration techniques are unable to detect the incipient damages. Their response is poor in case of moderate damage. Due to this drawback, their application is limited. This fact is critical for the development of health monitoring techniques because users of these methods have assurance that the damage will be detected while the structure has ample stability to allow repair.
5) Accuracy in damage detection is completely dependent upon the accuracy in measurement of modal properties of the structures. It is found that the modal properties are subjected to fluctuations due to variations in the measurement. Hence it is difficult to conclude whether the observed changes are due to damage or due to variations in the measurement. This is the critical issue in vibration based techniques, and need to be explored further. For practical applications of the vibration based techniques on real life structures such as tall buildings, bridges, dams, and underground structures, it is required to reduce the dependence upon applied forces. Vibrations produced by existing loading system and ambient environmental conditions can be used for exciting the structure. This issue is required to be investigated further.
6) There are several vibration based techniques/methods to detect the damage and to predict the locations of damage developed and validated in the laboratory. Validation of all existing technique should be done on common structures and should be based on real measurements. Henceforth the advantages of these methods and their efficacy in locating the damage must be compared in a systematic manner. Farrar and Jauregui (1998) compared five vibration-based damage identification techniques that had been applied to chosen data sets.

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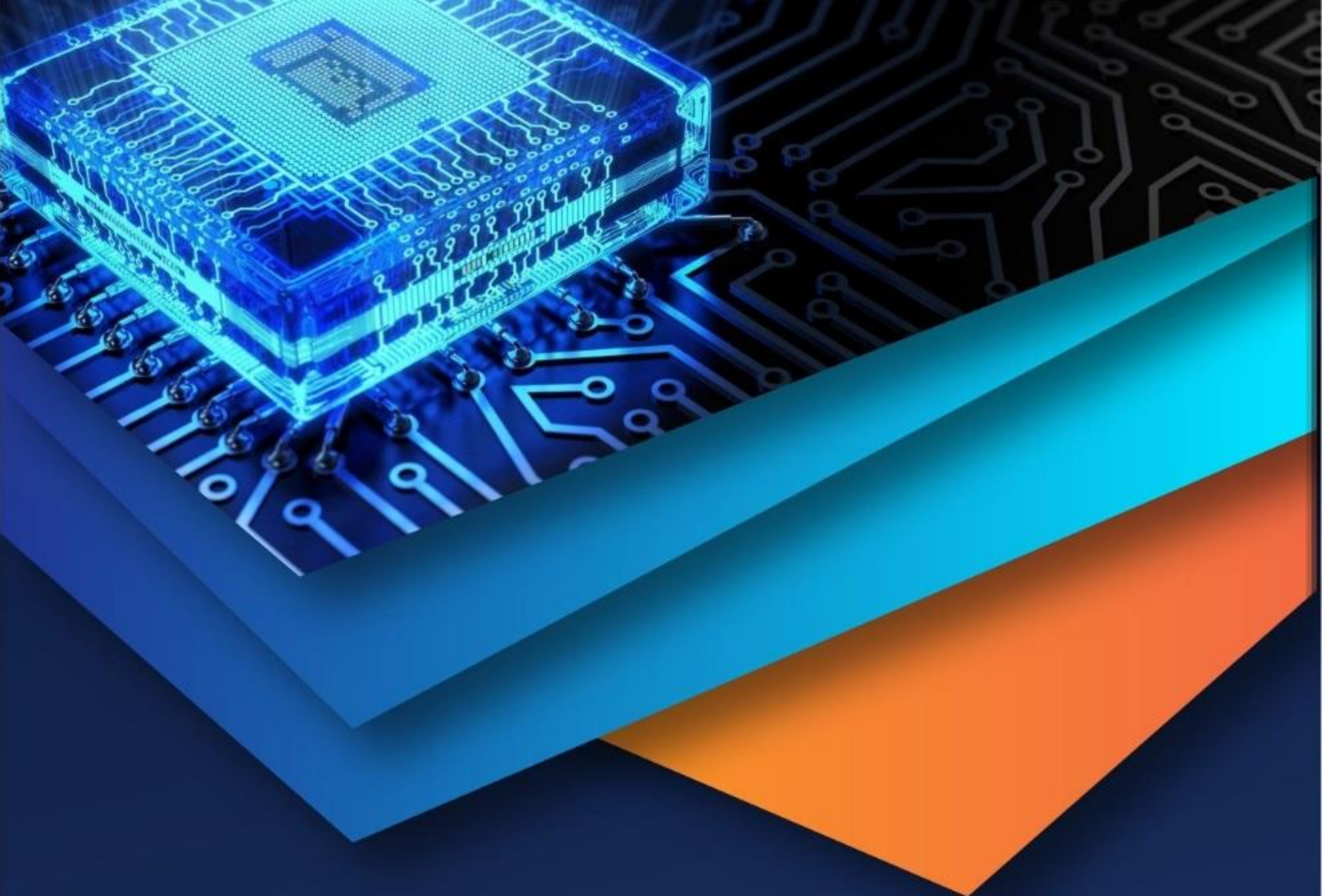

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