COMPARATIVE STUDY OF VIBRATION BASED DAMAGE DETECTION METHODOLOGIES FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT
This paper presents a comparative study of vibration based damage detection methodologies for structural health monitoring. Three types of damage detection methodologies namely damage location assurance criterion (DLAC), modal strain energy change (MSEC) and iterative modal strain energy (IMSE) are considered in this study. These methods depend on the modal parameters obtained by performing modal analysis from the healthy and damaged structure. In this study, a two-dimensional truss is selected and a single element is damaged by reducing its stiffness. For the damage cases considered both the damaged element and damage severity is found. The effectiveness of these damage detection algorithms by using the minimal modal parameters is also studied. To perform modal analysis and to automate these damage detection algorithms MATLAB code is developed.

Key words: Damage Detection, Modal Analysis, DLAC, MSEC And IMSE

http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=7

1. INTRODUCTION
There is a rapid increase of construction activities in the field of civil engineering in the recent years due to urbanization. The structures are subjected to severe loading and their performance is likely to change with time. It is necessary for continuous monitoring of structures to check its performance. If any deviation found from its design parameters, appropriate maintenance is
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required. The life of the structure not only depends on initial strength but also on post construction maintenance. It is the reason that the necessity of structural health monitoring (SHM) is emphasized around the world.

SHM is a process in which certain strategies are implemented for determining the presence, location, and severity of damages and predict the remaining life of structure after the occurrence of damage. Damage identification is the basic objective of SHM. There are mainly four levels in damage identification classified by Rytter [1]:
Level 1: Determination that damage is present in the structure
Level 2: Level 1 plus determination of the geometric location of the damage
Level 3: Level 2 plus quantification of the severity of the damage
Level 4: Level 3 plus prediction of the remaining service life of the structure

Most currently used damage identification methods are visual or localized experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiography, eddy-current methods or thermal field methods [2]. All of these experimental techniques requires the vicinity of the damage location priori and that portion of the structure is readily accessible for inspection. These methods are time-consuming and also labor intensive, perhaps requiring both a trained field technician for performing tests and also a structural engineer to interpret results. Inspections are costly and this large expense is likely to affect the rate at which they are conducted. These methods become tedious when it comes to complex structures.

These limitations have led to the development of vibration-based damage detection (VBDD) methods. The changes in modal parameters or parameters derived from these quantities are being used as indicators of damage in VBDD methods. The basic idea of these methods is that commonly measured modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties, such as reductions in stiffness resulting from the flaw or damage in the structure, will cause detectable changes in these modal parameters. In this study, a two-dimensional truss is taken to which three types of VBDD methods are used to find the damaged element location and damage severity.

2. LITERATURE ON VIBRATION BASED DAMAGE DETECTION METHODS

The various methods under the VBDD methods are summarized by the researchers [3-5]. P. Cawley et al. [6] was a first researcher proposed to detect damage on two-dimensional structures based on natural frequency. It is shown how measurements made at a single point in the structure can be used to detect, locate and roughly quantify the damage. A.Messina et. al. [7] has proposed a new correlation coefficient termed the damage location assurance criterion (DLAC) similar to modal assurance criterion (MAC). The DLAC method compared the normalized natural frequency change in theory before and after damage occurrence with regard to the normalized natural frequency change identified from the measurement. The DLAC method is used only for single damage localization and quantification. Later, A.Messina et al. [8] proposed a new correlation coefficient termed the multiple damage location assurance criterion (MDLAC), improves the DLAC’s applicability for multiple-damage cases. This is achieved by differentiating a frequency-to-damage sensitivity matrix for the DLAC method in order to consider local element information.

The author Ewins [9] proposed MAC to detect the existence and the location of structural damage which is based on comparing mode shape vectors. One of the issue for MAC evaluation is that, as it only uses one pair of mode shape vectors in judgment, how to choose the appropriate mode for MAC calculation become a determinant. To overcome this,
Lieven & Ewins [10] proposed a coordinate modal assurance criterion (COMAC) that was later used by many other scholars. Shi et al. [11] extended the MDLAC method by using incomplete noisy mode shapes. With incorporating the derived mode shape sensitivity matrix, they found that the index of mode shape correlation has considerable potential in damage detection for a truss model.

Stubbs et al. [12] presented a pioneering work of using modal strain energy for damage localization. Shi et al. [13] discussed performance and robustness of the developed modal strain energy change (MSEC) method in locating the damage and to quantify the damage. This method is discussed with two examples widely-used European space agency truss structure and two-storey steel plane frame structure. Shu-Qing Wang et al. [14] develops a new method iterative modal strain energy (IMSE) for damage localization and severity estimation based on the employment of modal strain energy. This method is able to determine the damage locations and estimate their severities, requiring only the information about the changes of a few lower natural frequencies and its corresponding mode shapes.

The comparison of damage detection methodologies namely DLAC, MSEC and IMSE are considered in this study for damage localization and quantification of damage severity on a two-dimensional truss model.

3. METHODOLOGIES FOR DAMAGE DETECTION

In this section, the methodologies for damage detection using DLAC, MSEC, and IMSE algorithms are explained.

3.1 Damage location assurance criterion algorithm

In the DLAC algorithm, the damaged element location and damage severity directly depend on the DLAC value obtained. The DLAC value for jth element is given by,

\[
DLAC(j) = \frac{|(\Delta f)^T \cdot \delta f_j|^2}{((\Delta f)^T \cdot (\Delta f)) \cdot ((\delta f_j)^T \cdot (\delta f_j))}
\]

Where, \(\Delta f\) = measured frequency vector for a structure with damage of unknown size or location

\(\delta f_j\) = theoretical frequency change vector for damage of a known size at location j

Hence, \(\Delta f\) and \(\delta f_j\) are two vectors of dimension n. Both \(\Delta f\) and \(\delta f_j\) vectors are normalized with respect to the structure’s health frequencies.

Where, \(\Delta f = \{\Delta f_1, \Delta f_2, \Delta f_3, \ldots \ldots \ldots \Delta f_n\}\)

\(\delta f_j = \{\delta f_{j1}, \delta f_{j2}, \delta f_{j3}, \ldots \ldots \ldots \delta f_{jn}\}\)

\(\Delta f_i = (f_{i,observe} - f_{i,health})/f_{i,health}\)

DLAC values lie in the range 0 to 1, with 0 indicating no correlation and 1 indicating an exact match between the patterns of frequency changes. The location j giving the highest DLAC value determines the predicted damage site. The DLAC value for all the elements is found for damage cases, ranging from 0 to 100 % loss of stiffness till the perfect match is found.
3.2. Modal strain energy change algorithm

The MSEC algorithm is a two-step process. In the first step damaged element is predicted and later damage severity is computed. The steps in the MSEC algorithm are:

(i) The modal strain energy (MSE) of the \( j \text{th} \) element and the \( i \text{th} \) mode before and after the occurrence of damage is computed as,

\[ \text{MSE}_{ij} = \phi_i^T K_j \phi_i \quad \text{and} \quad \text{MSE}^d_{ij} = \phi_{di}^T K_j \phi_{di} \]

Where, \( \phi_i \) represents the \( i \text{th} \) mode of the structure; \( K_j \) represents the stiffness matrix of \( j \text{th} \) element.

The terms having subscript or superscript ‘d’ in this method refers to values obtained from the damaged structure.

(ii) The modal strain energy change ratio (MSECR) is an indicator for damage localization computed as,

\[ \text{MSECR}^i_j = \frac{|\text{MSE}^d_{ij} - \text{MSE}_{ij}|}{\text{MSE}_{ij}} \]

Where, \( j \) and \( i \) denote the element number and mode number respectively

(iii) If the MSE for several modes are considered together, the \( \text{MSECR}^i_j \) of the \( j \text{th} \) element is defined as the average of the summation of \( \text{MSECR}^i_j \) for all the modes normalized with respect to the largest value \( \text{MSECR}^i_{\text{max}} \) of each mode.

\[ \text{MSECR}_j = \frac{1}{m} \sum_{i=1}^{m} \frac{\text{MSECR}^i_j}{\text{MSECR}^i_{\text{max}}} \]

Therefore, the element \( j \) with maximum \( \text{MSECR}_j \) value is the damaged element.

(iv) Suppose damage exists in the structure in only element \( p \),

\[ \text{MSEC}^i_j = -2 \alpha_p \sum_{r=1}^{m} \frac{1}{\lambda_r - \lambda_i} \phi_r^T K_p \phi_i \phi_i^T K_r \phi_r, \text{ where } r \neq i. \]

Where, \( \lambda = \) eigen frequency of structure

\[ \alpha_p = \text{damage severity in element } p \]

\[ \text{MSEC}^i_j = \text{MSE}^d_{ij} - \text{MSE}_{ij} \]

From the above equation damage severity of the damaged element is computed.

3.3. Iterative modal strain energy algorithm

The IMSE algorithm is a two-step process. In the first step damaged element is predicted and later damage severity is computed by using an iterative procedure.

3.3.1 Steps for computing damaged element

The steps for computing damaged element are:

(i) Find the structural modal strain energy between the baseline structure and the damaged structure for the \( i \text{th} \) mode as

\[ c_i = (\phi_i)^T K \phi_i^* \]

Where, \( \phi_i \) denote the \( i \text{th} \) mode of structure and \( K \) represents stiffness matrix of structure. In this method, all the variables with superscript ‘*’ represents the values of damaged structure.
(ii) Find the elemental modal strain energy for the stiffness matrix $K_{in}$ for the $i^{th}$ mode as

$$c_{n,i} = (\Phi_i)^T K_{in} \Phi_i$$

(iii) Compute $b_i = \left( \frac{\lambda_i}{\lambda_i} - 1 \right) C_i$

Where, $\lambda_i$ denote the $i^{th}$ eigen frequency

(iv) The two damage severities $\bar{\alpha}_k^i, \bar{\alpha}_k^j$ are computed by considering different eigen frequency and its corresponding mode shape. Then, $e_k$ for each element is calculated as

$$e_k = \sum_{i=1}^{N_m} \sum_{j=i+1}^{N_m} |\bar{\alpha}_k^i - \bar{\alpha}_k^j|$$

Where, damage severity $\bar{\alpha}_k^i = (C_{n,i}^T C_{n,i})^{-1} C_{n,i}^T b_i$ ; $N_m$ is no. of elements

(iv) The damage indicator is re-defined to judge the existence of damage as follows,

$$e_k = \frac{\min(e_k)}{e_k}$$

The damaged element shows the $e_k$ value of 1.

3.3.2. Steps for computing damage Severity

The damage severity can be estimated iteratively as follows:

(i) Assume the damage severity to be zero initially, i.e., $\alpha^{(0)} = 0$, where superscript “0” denotes initial value. Then compute the mode shape $\Phi_i^{*(0)}$.

Where, $\Phi_i^{*} = \Phi_i^{*}(K^{*}, M) = \Phi_i^{*} ( K + \sum_{n=1}^{N_d} \alpha_n K_{in}, M )$

(ii) Estimated damage severity $\alpha^{(1)}$ using the computed mode shape $\Phi_i^{*(0)}$. The first iteration for estimating the damage severity is finished.

(iii) Compute the damaged mode shapes $\Phi_i^{*(j-1)}$ by using the estimated damage severity $\alpha^{(j-1)}$, and estimate the damage severity $\alpha^{(j)}$ by using $\Phi_i^{*(j-1)}$ for $j=2, 3$, sequentially.

(iv) Set the condition of iteration termination. Repeat Step (iii) until $\max \{ |\alpha^{(j)} - \alpha^{(j-1)}| \} \leq tol$, where tol is a pre-determinated threshold. For example, one can set tol to be 0.001 or 0.004, up to the precision of the severity estimation.

4. ANALYSIS AND DISCUSSION

The two-dimensional truss designed by G.Thulasendra et. al. [15] is considered in this study for damage detection. The properties of the truss members are Young’s modulus is $2.05 \times 10^{11}$ N/m² and mass density is 7834 Kg/m³. The cross-sectional area of the members are shown in Table 1 and the truss configuration is shown in Figure 1.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Members</th>
<th>Cross-sectional area in mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2,6,10,14,18,21</td>
<td>866</td>
</tr>
<tr>
<td>2.</td>
<td>1,4,8,12,16,20</td>
<td>677</td>
</tr>
<tr>
<td>3.</td>
<td>3, 19</td>
<td>141</td>
</tr>
<tr>
<td>4.</td>
<td>7, 15</td>
<td>203</td>
</tr>
<tr>
<td>5.</td>
<td>5,17</td>
<td>295</td>
</tr>
<tr>
<td>6.</td>
<td>9,13</td>
<td>388</td>
</tr>
<tr>
<td>7.</td>
<td>11</td>
<td>295</td>
</tr>
</tbody>
</table>

Table 1 Cross-sectional area for members of truss
Two damage cases are assumed for damage detection in this study. The damage is incorporated by reduction of stiffness in the element. The damage of 20% is assumed in both the cases. The damage cases considered are as follows:

Case (i): Damage of 20% in element 1 & Case (ii): Damage of 20% in element 8

To compute the modal parameters required for damage detection algorithms, finite element method based modal analysis is performed on a two-dimensional truss which is depicted in Figure 1. To perform modal analysis and to automate all the three damage detection algorithms which are used below, MATLAB codes are developed. In the absence of experimental modal parameters which are required in the damage detection algorithms, analytical values are considered in this study.

4.1. Damage detection using DLAC algorithm

For the 2 damage cases considered the DLAC algorithm is utilized for damage localization and damage severity estimation using the developed MATLAB code. Each damage case is solved separately first by using the initial 7 natural frequencies and later by using 14 natural frequencies for the truss depicted in Figure 1. The DLAC value nearer to 1 represents the damaged element. The severity varies from 0 to -1, '0' represents no loss of stiffness in element and '1' represents complete loss of stiffness in the element.
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The Figure 2 and Figure 3 shows the plot obtained from DLAC algorithm for damage case (i). In both the conditions by considering 7 and 14 natural frequencies in the DLAC algorithm, we can notice that damaged element 1 and damage severity of -0.2 is identified exactly. It is observed that the probability of damage of remaining elements is decreased i.e., the DLAC value is lesser for elements other than damaged one when more no. of frequencies are considered for damage detection.

Figure 3 DLAC plot for damage case (i) with 14 natural frequencies

Figure 4 DLAC plot for damage case (ii) with 7 natural frequencies
The Figure 4 and Figure 5 shows the plot obtained from DLAC algorithm for damage case(ii). While considering 7 natural frequencies in DLAC algorithm from Figure 4 we can notice that the element 6 & 7 are also having DLAC value very nearer to 1 but the element 8 has DLAC value of 1. So it is hard to tell the damaged element by seeing the bar graph but the damage severity of -0.2 is identified exactly while considering 7 natural frequencies. While considering 14 natural frequencies in DLAC algorithm from Figure 5 we can notice that the damaged element 1 and damage severity of -0.2 is identified exactly.

4.2. Damage detection using MSEC algorithm

For the 2 damage cases considered the MSEC algorithm is utilized for damage localization and damage severity estimation using the developed MATLAB code. Both the damage cases are solved by using this method using varying modal parameters. Each damage case is solved by considering MSEC computed by considering 10 modes for locating the damaged element and taking an average of damage severity computed using MSEC corresponding to 14 modes of damaged element, these parameters in damage detection is considered as “type 1 parameters”. Next, each damage case is solved by considering MSEC computed by considering 10 modes for locating the damaged element and taking an average of damage severity computed using MSEC corresponding to 21 modes of damaged element, these parameters in damage detection is considered as “type 2 parameters”.

The plot obtained from MSEC algorithm shows the maximum MSECR for the damaged element when compared to other elements. The severity varies from 0 to -1, “0” represents no loss of stiffness in element and “1” represents complete loss of stiffness in the element.
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We can observe from Figure 7 that MSECR computed by considering 10 modes were sufficient to identify the damaged element 1 but the average of damage severity computed using MSEC corresponding to 14 modes of damaged element shows the wrong damage severity with a very higher deviation from the actual damage severity.

Figure 7 MSECR plot for damage case (i) considering type 1 parameters

We can observe from Figure 8 that MSECR computed by considering 10 modes are sufficient to identify the damaged element 1 but the average of damage severity computed using MSEC corresponding to 21 modes of damaged element, shows the damage severity of -0.218 very nearer to actual damage of -0.2

Figure 8 MSECR plot for damage case (i) considering type 2 parameters
We can observe from Figure 9 that MSECR computed by considering 10 modes are sufficient to identify the damaged element 8 but the average of damage severity computed using MSEC corresponding to 14 modes of damaged element shows the wrong damage severity with a higher deviation from the actual damage severity.

We can observe from Figure 10 that MSECR computed by considering 10 modes are sufficient to identify the damaged element 8 but the average of damage severity computed using MSEC corresponding to 21 modes of damaged element shows the damage severity -0.25489 nearer to actual damage of -0.2

Figure 9 MSECR plot for damage case (ii) considering type 1 parameters

4.3. Damage detection using IMSE algorithm
For the 2 damage cases considered the IMSE algorithm is utilized for damage localization and damage severity estimation using the developed MATLAB code. In this method for damage localization, the damage location is selected in the case of two damage cases considered.

Figure 10 MSECR plot for damage case (ii) considering type 2 parameters
localization first 2 eigen frequencies and its corresponding mode shapes are taken. For damage severity estimation first eigen frequency and corresponding mode shape of it is considered.

The damage indicator has a value of 1 for the damaged element. The severity varies from 0 to -1, “0” represents no loss of stiffness in element and “1” represents complete loss of stiffness in the element.

From Figure 11 and Figure 12 we can observe that that damaged element and its severity is predicted accurately, for the damage case (i) and case (ii) respectively.

5 CONCLUSIONS
The conclusions drawn from this study are:
(i) All the three damage detection algorithms namely DLAC, MSEC, and IMSE have predicted the damaged element correctly for the damage cases considered.
(ii) The DLAC and IMSE algorithms are more accurate in damage severity estimation when compared to MSEC algorithm.
(iii) DLAC algorithm requires more modal parameters when compared to an IMSE algorithm for damage detection, and also requires more computational effort.
(iv) IMSE algorithm requires minimal modal parameters when compared with DLAC and MSEC algorithm both for damage localization and its severity estimation.

REFERENCES