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Article

Damage Detection Based on Recorded Damaged Natural Frequencies Using Binary Bat Algorithm

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Abstract: The health monitoring system cycle for a structure has a significant impact on damage detection. The life cycle of a structure can be improved through the implementation of effective damage detection techniques. This is because the identification, prevention, and repair of damaged structural elements can be conducted with precision and speed. This study suggests a technique for identifying structural components that have been damaged. This approach involves comparing the recorded natural frequency to its actual natural frequency for all potential damage scenarios. The Modal Assurance Criterion (MAC) has been used to compare these two natural frequency values, while a binary value is used to indicate whether an element has been damaged or not. Two types of structures are considered: (1) shear building structures and (2) plane truss structures. Several damage scenarios are used to test the accuracy of the proposed method. According to the results, the binary bat algorithm in conjunction with MAC produces accurate results for the two categories of structures examined under several kinds of damage scenarios, such as single, double, and multiple damage.

Keywords: damage detection, binary bat algorithm, modal assurance criterion

1. Introduction

The healthiness of infrastructures tends to decline over time due to environmental influences and lack of proper maintenance. As a result, the structure will experience a loss of strength or stiffness. Therefore, damage detection of structures is one of the important issues for civil infrastructure monitoring systems. Several techniques can be employed to identify structural damage, such as the damage locating vector [1], mode shape curvature approach [2], strain energy [3], and some methods that combine optimization algorithms with other criteria to enhance the ability to locate damaged members in various types of structures [4-8]. Many applications have implemented methods for damage detection in various types of structures such as [9-11]. Gao et al. (2007) used flexibility-based damage locating vector method for experimental verification of three-dimensional truss structure [9]. Based on the result, The DLV method can effectively identify damage with a small number of sensors and modes. Ji and Qian (2008) applied the damage locating vector for a spatial steel braced-frame model [10]. Seven scenarios of damage, which are located at brace and connection damages, were simulated. It has been shown that the damage locating vector method is effective when the extent of the damage reaches a specific threshold. Experimental verification and comparison of damage detection methods that rely on changes in mode shapes, including mode shape curvature (MSC), modal assurance criterion (MAC), strain energy (SE), modified Laplacian operator (MLO), generalized fractal dimension (GFD), and Wavelet Transform (WT), have been conducted by Radzieński and Krawczuk (2009) [11]. To experimentally compare the proposed damage detection methods, an

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aluminum plate featuring two riveted stiffeners was tested. One of the conclusions show that WT is the most effective, noise independent and versatile for damage detection method. Several damage detection methods belong to the category of second level damage detection, which focuses on identifying the precise location of a damaged member in a structure. Damage detection of structure can be classified into several levels of identification [12]: (a) level 1: determine if there is damage to the structure, (b) level 2: locate the damage of the structure, (c) level 3: first and second level, and determining the loss of the strength, and (d) level 4: first, second, third level, and predicting the remaining lifetime of the structures.

This research suggests a second-level structural damage detection method that involves the comparison of recorded natural frequencies with actual natural frequencies. The method involves identifying the location of the damaged members. The recorded natural frequencies are first obtained beforehand by considering all potential structural damage before comparing with the actual natural frequencies. The binary bat algorithm and Modal Assurance Criterion (MAC) are then employed to compare the recorded natural frequencies with the actual natural frequencies. As it stated before, the goal of the proposed method is to locate the damaged members/elements of a structures. In order to find out the ability of the proposed method, there are two different types of structures considered.

2. Theory and method

2.1. Binary bat algorithm

The bat algorithm was initially proposed by [13]. This algorithm is derived from the "echolocation" characteristic shown by bats. The bat algorithm, as proposed by Mirjalili et al. (2014), is considered to perform better than other algorithms like genetic algorithms or particle swarm optimization [14]. The bat algorithm has many three key point features that can make it better than other optimization, such as frequency tuning, automatic zooming and parameter control [15]. The bat method, as proposed by Yang (2010) is governed by a general equation as follows [13]:

$$f_i = f_{min} + (f_{max} - f_{min})\beta \tag{1}$$

$$\boldsymbol{v}_i^{t+1} = \boldsymbol{v}_i^t + (\boldsymbol{x}_i^t - \boldsymbol{x}_*)f_i \tag{2}$$

$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \boldsymbol{v}_i^{t+1} \tag{3}$$

The variables in the equation are as follows: f represents the frequency, β is a random number between 0 and 1, $\boldsymbol{v}$ represents the velocity vector, $\boldsymbol{x}$ is the position vector, and $\boldsymbol{x}_*$ represents the best global location in that iteration. In addition to utilizing equations (1), (2), and (3), there are additional equations for updating the specific position of the bat locally as follows:

$$\boldsymbol{x}_{new} = \boldsymbol{x}_{old} + \varepsilon A^t \tag{4}$$

$$A_i^{t+1} = \alpha A_i^t \tag{5}$$

$$r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \tag{6}$$

where: A_i is loudness, r_i is rate of pulse emission, γ, and α are constant (for simplicity, usually taken $\gamma = \alpha$).

Equations (1) to equations (6) are employed for solving continuous problems involving real variables. However, in this example, binary variables are utilized instead. Hence, equations (1) to (6) are adapted for utilization in optimization while dealing with binary variables. The bat algorithm, which is an optimization tool for real variables, was modified by Mirjalili et al. (2014) to function as an optimization tool for binary variables [14]. This algorithm is more commonly referred to as the binary bat algorithm. A V-shaped transfer function has been used in this theory. The formulas utilized to modify the position and velocity are in accordance with equation (7) and equation (8).

$$V\left(v_i^k(t)\right) = \left|\frac{2}{\pi} arctan\left(\frac{\pi}{2}\right) v_i^k(t)\right| \tag{7}$$

$$x_i^k(t) = \begin{cases} \left(x_i^k(t)\right)^{-1}, & if\ rand < V\left(v_i^k(t)\right) \\ x_i^k(t), & rand \geq V\left(v_i^k(t)\right) \end{cases} \tag{8}$$

where $x_i^k(t)$ and $v_i^k(t)$ represent the position and velocity for-i bat at t-iteration in the k dimension, and $\left(x_i^k(t)\right)^{-1}$ refers to the complement of $x_i^k(t)$.

2.2. Modal Assurance Criterion

The Modal Assurance Criterion (MAC) is a quantitative measure used to determine the similarity between two vectors. Initially, MAC was employed to assess the precision of the modal vector derived from the experimental test in relation to the measurement frequency response function [16]. It is a statistical measure that compares expected and actual estimates of the modal vector. When the interval value of MAC is zero, no consistency is detected between the two vectors. However, when the value is 1, similarities and consistencies are observed. In this research, MAC was employed to compare the recorder's natural frequencies and actual natural frequencies of damaged structures, as per Equation (9).

$$MAC_i = \frac{|\{\varphi_r\}_i^T\{\varphi_a\}_i|^2}{(\{\varphi_r\}_i^T\{\varphi_a\}_i)(\{\varphi_r\}_i^T\{\varphi_a\}_i)} \quad (9)$$

2.3. Methodology

This study introduces a second-level damage detection method based on recorded natural frequency of all potential damages. The key innovation of this method, compared to others, is that the comparison data for the damaged structure under actual conditions comes from pre-recorded simulations. These simulations account for all possible damages in each element of the structure. The data obtained from the simulatuon will be used to compare it with actual natural frequency to be matched. The calculation of potential damage scenarios can be determined using the combination equation as specified in equation (10).

$$PDS = \sum_{i=1}^{n} C_i^n \quad (10)$$

where PDS is the possible damage scenario or the number of possible damage scenarios for a structure, C is the combination equation, i is the number of elements that are damaged and n is the total number of elements.

For example, if there is a plane truss structure, as shown in Figure 1, there are seven potential damage scenarios, as determined by equation (10). Table 1 shows the possible damage scenarios of the plane truss structure considered.

Table 1. All possible damaged scenarios of a plane truss structure with 3 elements

No	Possible scenarios	Damaged member	Damaged type
1	S1	1	Single damage
2	S2	2	
3	S3	3	
4	S4	1, 2	Double damage
5	S5	1, 3	
6	S6	2, 3	
7	S7	1, 2, 3	Triple damage

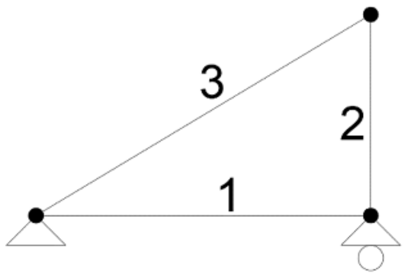

Figure 1. A plane truss structure with 3 elements

The binary value represents the existing damage of an element. A binary value of 1 indicates that the element has been damaged, while a binary value of 0 indicates that the element is not damaged. An example of a binary application to ascertain whether an element is damaged is illustrated in Table 2.

Table 2. An example of a binary value that is used to identify the damaged members

No	Binary value	Damaged members
1	[1 0 0]	1
2	[1 0 1]	1,3
3	[0 1 1]	2,3

It is important to mention that, in this study, the stiffness reduction value is utilized as a measure of the damaged element, and a similar stiffness reduction value is applied to each damaged element. Table 1 is used to initially calculate and record the natural frequencies of buildings for all scenarios. These frequencies are then compared with the natural frequencies of structures that actually exist. The two natural frequencies are evaluated using the MAC, and the outcome of this evaluation is referred to as the fitness value. Equation 10 represents the fitness equation under consideration.

$$fitness = \frac{1}{MAC(\omega_r, \omega_a)} \quad (11)$$

The function MAC is used to compare two vectors. ω_r represents the natural frequency of a situation where elements experience damage (recorded), whereas ω_a represents the actual natural frequency. The function aims to minimize the fitness values; therefore, the MAC value is placed in the denominator.

This research conducted two case studies to evaluate the efficacy of the proposed method. The first case study involved a shear building structure, while the second case study focused on a plane truss structure consisting of seven elements. The MATLAB R2022b application was utilized to develop all the calculations and functions necessary for analysis and computations [17,18].

3. Results and discussion

3.1. Result

3.1.1. Case 1: Shear building

A shear building with 4-stories was considered as the first study case. Figure 2 shows the stiffness and mass values of each story. Four damage scenarios have been examined, ranging from single damage to multiple-story damaged. It is important to mention that the damage value in the initial case study is exemplified by a 30% reduction in story stiffness, resulting in a residual stiffness value of 70% for the damaged story. The damage scenarios employed are illustrated in Table 3. Scenario 1 (S1) is a single damage scenario in which the stiffness of the third story decreases by 30%. Scenario 2 (S2) is a double damage scenario in which the stiffness of the first and fourth stories decreases by 30%. Scenario 3 (S3) and scenario 4 (S4) are multiple damage scenarios in which the stiffness of stories 1, 2, and 4 decreases by 30% in scenario 3 (S3) and the stiffness of stories 1, 2, and 4 decreases by 30% in scenario 4 (S4).

According to equation (10), there are a total of 15 potential damage situations. Table 4 shows the potential damage situations for the first case study. As previously stated, the numbers 0 and 1 signify the presence or absence of a decrease in stiffness on the story. A value of 0 signifies that there is no reduction in the stiffness of the story, whereas a value of 1 shows a reduction in story rigidity. As an illustration, the possible damage scenario-9 is represented by the sequence [0 1 0 1], indicating a reduction in stiffness on the 2nd and 4th stories.

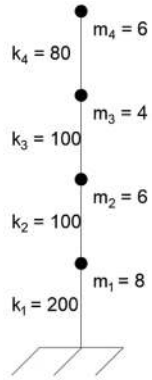

Figure 2. Shear building with four stories

Table 3. Damaged scenario for shear building

No	Scenario	Damaged story
1	S1	3
2	S2	1,4
3	S3	1,2,4
4	S4	1,2,3,4

Table 4. Possible damaged scenario for shear building

Possible scenarios	Story			
	1	2	3	4
1	1	0	0	0
2	0	1	0	0
3	0	0	1	0
4	0	0	0	1
5	1	1	0	0
6	1	0	1	0
7	1	0	0	1
8	0	1	1	0
9	0	1	0	1
10	0	0	1	1
11	1	1	1	0
12	1	1	0	1
13	1	0	1	1
14	0	1	1	1
15	1	1	1	1

The results of the proposed method are illustrated in Table 5. It is apparent that the proposed method is capable of accurately identifying the location of the story that is experiencing damage for all scenarios that are employed. The binary number results for the first scenario indicate a decrease in stiffness on the third floor. In contrast, the second scenario indicates a decrease in stiffness on the first and fourth floors. The third and fourth scenarios, on the other hand, indicate a decrease in stiffness on the first, second, and fourth floors, respectively.

Table 5. The result of proposed method for shear building

Scenarios/ Story	1	2	3	4
S1	0	0	1	0
S2	1	0	0	1
S3	1	1	0	1
S4	1	1	1	1

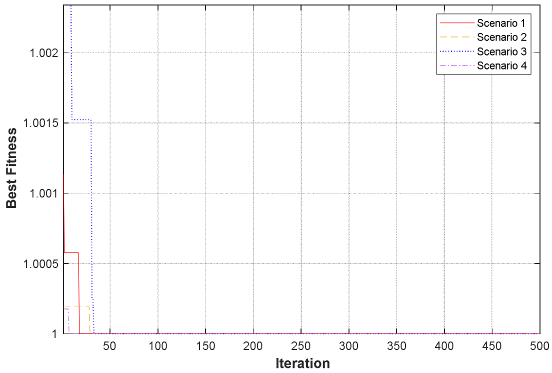

Figure 3. The fitness value of each iteration for all damaged scenarios (shear building)

Decreasing the fitness value for each iteration with all damaged scenarios can be seen in Figure 3. Based on Figure 3, the convergence results were obtained below 50 iterations for all damaged scenarios. This demonstrates that the algorithm employed is highly effective in achieving the optimum solution.

3.1.2. Case 2: A plane truss structure with 7-members

The second case study considered a plane truss structure with 5 nodes and 7 members, as shown in Figure 4. To indicate the extent of damage to the members, the stiffness value of the damaged members is decreased by 40%, resulting in a residual stiffness value that is 60% of the initial stiffness. The material's elastic modulus is determined to be 200,000 MPa, assuming a homogeneous cross-sectional area of 1785 mm². The assumption of this cross-sectional size value is made due to its negligible impact on the obtained results. There are a total of seven damage scenarios, as shown in Table 6. The plane truss structure consists of 7 members, which results in a total of 127 potential damage scenarios, as determined by equation (10). Several examples of potential structural elements that are damaged are illustrated in Table 7.

Table 6. Damaged scenario for plane truss structure

No	Scenario	Damaged members
1	S1	5
2	S2	4,6
3	S3	1,3,6
4	S4	2,3,5,7
5	S5	2,4,5,6,7
6	S6	1,2,3,4,6,7
7	S7	1,2,3,4,5,6,7

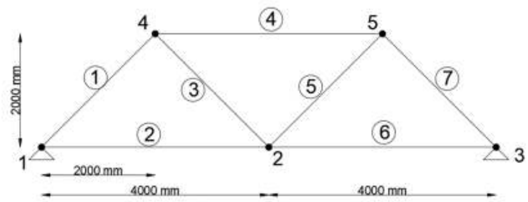

Figure 4. A plane truss structure with 5-nodes and 7-members

Table 7. Possible damaged scenario for plane truss

Possible scenarios	Member						
	1	2	3	4	5	6	7
1	1	0	0	0	0	0	0
2	0	1	0	0	0	0	0
3	0	0	1	0	0	0	0
...	...	...	...	...	...	...	...
17	0	1	0	0	0	1	0
18	0	1	0	0	0	0	1
19	0	0	1	1	0	0	0
...	...	...	...	...	...	...	...
45	0	1	1	0	1	0	0
46	0	1	1	0	0	1	0
47	0	1	1	0	0	0	1
...	...	...	...	...	...	...	...
124	1	1	0	1	1	1	1
125	1	0	1	1	1	1	1
126	0	1	1	1	1	1	1
127	1	2	3	4	5	6	7

The results of the proposed method are displayed in Table 8, which clearly demonstrates the ability to accurately identify the precise location of damage members. This is demonstrated by the binary value allocated to each element. For example, in the damage scenario 5, the binary value obtained for members 1, 2, 3, 4, 6, and 7 is 1, but for element 5 it is 0. This indicates that elements 1, 2, 3, 4, 6, and 7 are the damaged members, but element 5 remained undamaged.

Table 8. The result of proposed method for plane truss

Scenarios	**Member**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
S1	0	0	0	0	1	0	0
S2	0	0	0	1	0	1	0
S3	1	0	1	0	0	1	0
S4	0	1	1	0	1	0	1
S5	0	1	0	1	1	1	1
S6	1	1	1	1	0	1	1
S7	1	1	1	1	1	1	1

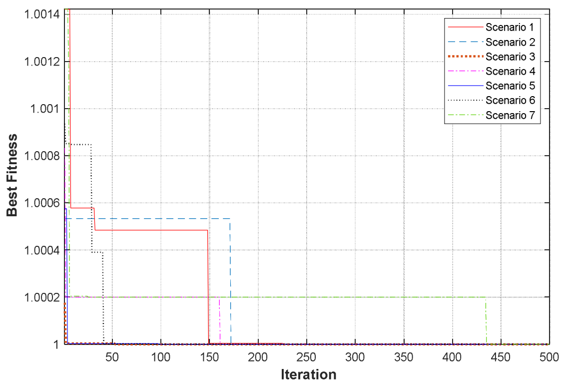

Figure 5. The fitness value of each iteration for all damaged scenarios (plane truss structure)

Figure 5 illustrates the decline in fitness value with each iteration. The optimum fitness value for each scenario indicates a perfect match between the natural frequencies of the actual structure (in its damaged condition) and the recorded structure (which was previously analyzed for its natural frequency value). In this case, the convergence is achieved in fewer than 200 iterations.

3.2. Discussions

Based on the results of the two case studies examined, the proposed method effectively predicts the location of damaged element of a structure. The combination of the binary bat algorithm and the MAC algorithm accurately identifies damage by representing binary values as indicators of the presence or absence of damage in each element. A key feature of this method is the use of pre-recorded natural frequencies for all possible damage scenarios, allowing highly precise damage prediction by comparing these pre-recorded frequencies with actual natural frequencies when calculating the MAC value. This positions the method as a second-level damage detection technique. Its performance is quite strong compared to other methods like the Damage Locating Vector (DLV), which can sometimes misidentify the location of damage in elements [4,5,19]. However, the method still has room for improvement, particularly through combining real and binary algorithms to not only detect the damaged element's location but also predict reductions in strength or stiffness. This could eventually make it a viable option for third-level structural damage detection.

4. Conclusion

This study presents a method for the second level of damage detection by analyzing the natural frequencies of all potential element damage scenarios. This approach employs a binary value to indicate the presence of damage in an element. At the same time, MAC is utilized to compare the natural frequency of structures that have experienced damage under actual conditions with the natural frequencies recorded from structures that have also experienced damage. This research focuses on two types of structures that serve as case studies: shear building structures with 4 stories and plane truss structures consisting of 7 members (elements). Several damage scenarios were considered to assess the effectiveness of the proposed method. In the case of the shear building, four damage scenarios were used, while for the plane truss structures, seven damage scenarios were considered. Based on the results obtained, the proposed method can precisely determine the location of damage to the structure by indicating which elements are damaged according to each damage scenario. Therefore, the proposed method could serve as an alternative method for second-level damage detection with the basis of recorded natural frequencies.

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