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Damage Detection of Single Tapered Poles Using APSO Algorithm

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ABSTRACT: In this paper, the damage detection of single tapered poles is studied. Structural damage is identified using an optimization-based method. In this method, the APSO is used to detect the location and severity of the damage. The objective function for detecting the damage is a correlation coefficient based on natural frequencies. In order to accelerate the calculation of the natural frequencies of the structure, the iterative method is used. In this paper, the damage induced into the structure is simulated as reduction of the stiffness matrix of the element in a finite element modeling of the structure and also in order to match the real situation, damages. To evaluate the efficiency and robustness of the proposed method in detecting damage of tapered poles, two numerical examples, including a police surveillance camera pole and a water storage pole under different damaged scenarios with considering measurement noise, are examined. In the first and second examples, structures are divided by 15 and 25 elements, respectively, with the uniform moment of inertia. The results show that the proposed method is capable of detecting both the location and severity of the damage properly, despite the complexity of some damage scenarios. Therefore, the algorithm can be used to detect the damage of other structures.

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1- Introduction

Minor damage in the elements of structures can lead to catastrophic failure if not identified and repaired in a proper time. Therefore, it is very important to identify the location and severity of the damage. Finding this damage through diagnostic methods such as visual inspection or local experimental methods is not always possible. To overcome this issue, optimization-based damage detection techniques were developed [1-3].

2- Optimization Form of Damage Detecting Problem

The occurrence of damage in a member or an element can reduce the stiffness and mass of that member or element, which leads to changes in the modal characteristics of structures such as modal frequencies. In this study, it is assumed that damage only reduces the stiffness of the element. Reverse methods are able to determine the location and severity of the damage by comparing the structural response before and after the damage. For this purpose, reverse methods generally use optimization methods to find the vector of failure variables that minimizes the correlation index between structural responses before and after damage [4]. In this study, an efficient correlation-based index (ECBI) is used as following [3]:

$$ECBI(X)=\frac{1}{2}\left[\frac{\left|\Delta F^{T}.\delta F(X)\right|^{2}}{\left(\Delta F^{T}.\Delta F\right)\left(\delta F^{T}.\delta F(X)\right)}+\frac{1}{nf}\sum_{i=1}^{nf}\frac{min\left(f_i(X),fd_i\right)}{max\left(f_i(X),fd_i\right)}\right] \quad (1)$$

Consequently, the damage detection process can be expressed as an optimization problem (2):

$$X^{T}=\{x_1,x_2,\dots,x_{ne}\} \quad \text{to Maximize } ECBI(X)$$
$$\text{Subjected to: } X^{l}\le X\le X^{u} \quad (2)$$

3- PSO Optimization Algorithm

PSO is one of the well-known optimization algorithms which is extensively used in engineering problems [5, 6].

3- 1- APSO

In order to increase the convergence rate, and efficiency of PSO, APSO was introduced [7].

4- Numerical Example:

For simulation of real-time conditions and considering errors of laboratory instruments to measure the responses of a damaged structure, the responses of the damage structure are estimated by considering some noise based on the results of the analytical model.

$$R_{ni}=R_i\left(1+rand\times noise\right) \quad (3)$$

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In Equation (3), R_i is the exact value of the structural response is. rand is a random value in the range [-1,1]. noise Indicates the amount of noise and for modal frequencies is equal to 0.15% of the i^{th} component of the analytical response of the damaged structure [8]. The damage detection problem is solved with the assumption of 10 different noises, and the best and worst answers are reported. Due to the use of APSO optimization algorithm to identify the location and severity of the damage, the parameters of this algorithm include ω_{min}, ω_{max}, c1 and c2 are assumed to be 0.4, 0.9, 1.5 and 1.5, respectively. Also, 300 particles are considered to search feasible space. The stop criterion of the algorithm is a compound criterion that includes a termination criterion and a convergence criterion. The convergence criterion is that if in 5 consecutive repetitions the difference between the results of consecutive repetitions is less than 1e-7, the algorithm will be stopped and the criterion limits to 100 iterations.

4- 1- Water Tank Taper Pole

Figure 2 shows the actual and schematic of the water tank taper pole. The cross-section of this base is tubular and its diameter decreases in height. Its inner and outer diameters at the bottom of the section are 1200 and 1170 mm, respectively, and its inner and outer diameters at the top of the section are 600 and 570 mm, respectively. The thickness of this section is constant in length and is equal to 15 mm. The length of the pole is 10,000 mm. This section is made of steel. Its modulus of elasticity is equal to 206 GPa and its Density is equal to 7850 kg/m^3 . Also, the mass of the tank and the water inside it is considered to be 1000 kg.

In order to check the accuracy and speed of the frequencies obtained from the matrix repetition method, these frequencies are compared with the Eigenvalues method. This problem has been solved with both methods and by dividing the structure into 10, 20 and 30 elements. Frequencies related to the first 3 vibrational modes along with the required time of each method, are presented in Table 1. In Table 1, the minimum time is assumed to be 1, and the other times are calculated based on it. According to the results, it is clear that the frequencies resulting from the two methods are completely consistent, and as expected, the matrix repetition method acquired a reduction calculation time of 10 to 20 percent rather than the Eigenvalues method. In addition, the higher the degree of freedom of the system, the lower the ratio.

Since in damage detection problems, the damaged structure frequencies are acquired by laboratory work and sensors data collection, it is necessary to show that due to the tapered cross-section of the element (variable moment of inertia) and Assuming the average element inertia in solving finite element method, the obtained answers from the finite element method lead to a similar result to the laboratory work. Therefore, to solve this issue, it is considered that if the number of elements increases, due to the decrease in element length and no noticeable change in cross-sectional area in each element, the frequency response obtained from the finite element method is the same as the response obtained from the sensors. It is assumed that the frequencies calculated by dividing the structure by 200 elements indicate the actual frequencies of the structure. The first 5 modes of natural frequencies of the structure are calculated by dividing the structure by different number of elements and to evaluate the accuracy of the calculated frequencies, the calculated frequency error is obtained by Equation (4).

$$er_i = \frac{1}{NM}\sqrt{\sum_{j=1}^{NM}\left(\frac{\omega_{ij}-\omega_j^{exact}}{\omega_j^{exact}}\right)^2} \tag{4}$$

In Equation (4), NM represents the number of modes, ω_{ij} is the frequency of the j^{th} mode and ω_j^{exact} is the exact value of the frequency of the structure in the j^{th} mode. The graph of the error rate versus the number of elements is shown in Figure 1.

Table 1. comparison matrix repetition and Eigenvalues methods results

Number of Elements	Times ration (Eigenvalues method / matrix repetition method)	first 3 modes Frequencies
10	5.43	1.55
		9.19
		26.09
20	7.08	1.55
		9.24
		26.25
30	9.77	1.55
		9.25
		26.28

Table 2. Damage scenarios for the water tank taper pole

scenario No. 2	
Damage Percentage (%)	**Element Number**
25	**4**
30	**20**

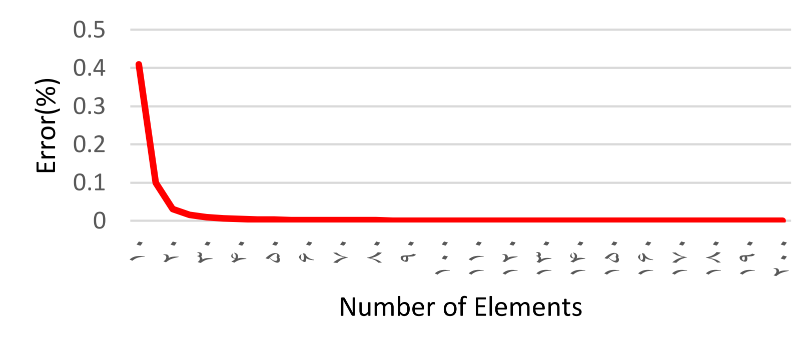
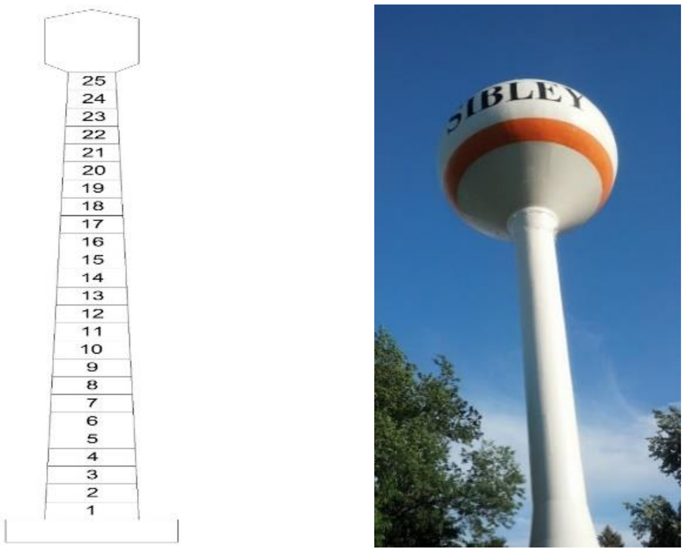


Fig. 1. percentage error of calculated frequencies to the exact frequency



b) schematic a) actual

Fig. 2. Water tank taper pole

Figure 1 shows the acceptable convergence of the calculated frequency to the exact value where the elements number is more than 50 elements. Based on the Figure 1, the calculated error frequency value for 15 elements (the minimum number of elements considered for this example) is about 0.09%, which is less than the noise (0.15%) considered to solve problems and therefore there will be no problem in detecting damage.

In order to calculate the frequency by the finite element method, water tank taper pole is divided into 25 elements of equal length according to Figure 2.

For this example, 3 damage scenarios are considered which briefly, only the damage scenario No. 2, is presented in Table 2.

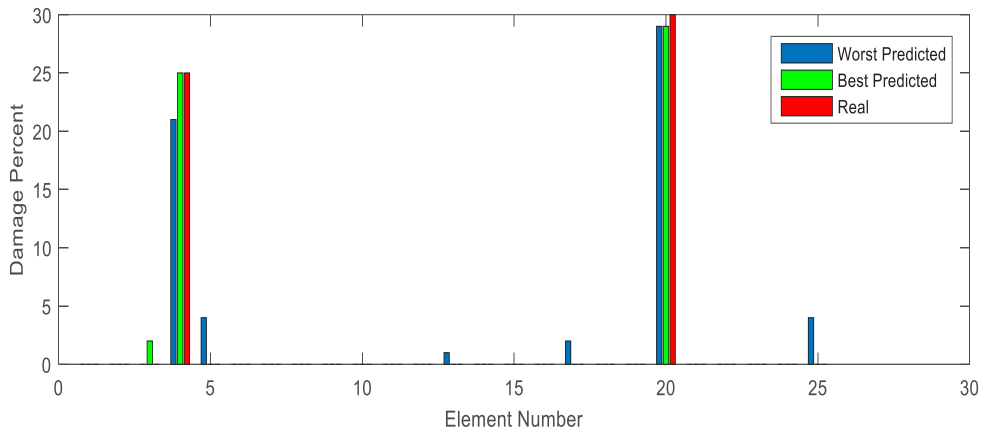


Fig. 3. damage detection results of APSO for scenario No.2

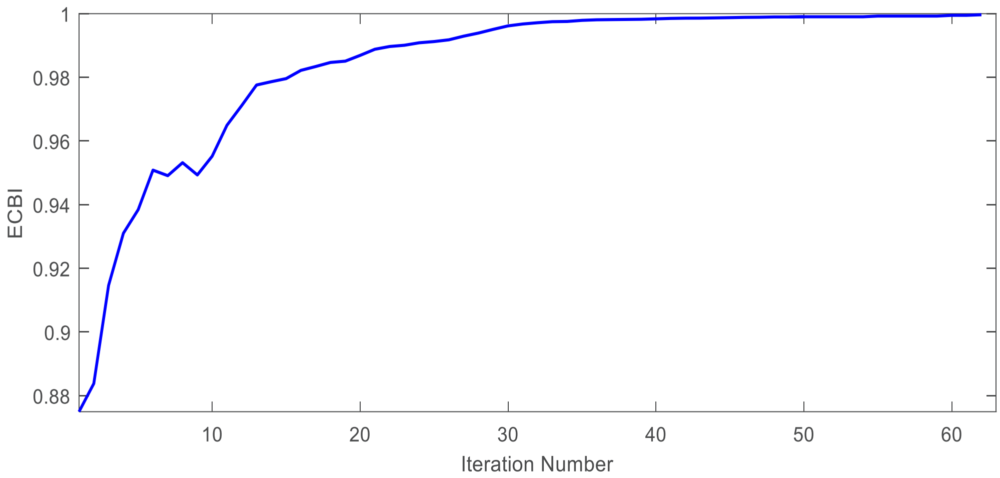


Fig. 4. Conversion history of APSO algorithm for water tank taper pole (Scenario 2)

Figure 3 shows the position and severity of actual damaged elements and the damaged elements recognized by the APSO optimization algorithm. Also, for more clarification and proving the efficiency of the algorithm, the best and worst predictions of APSO have been reported. Based on Figure 3, it can be seen that the algorithm has been able to detect not only all real damaged elements in the worst case detection, but also predict the severity of their damage with a small error percentage. All healthy elements that are misdiagnosed have a failure rate of less than 5%, which is also negligible due to noise. High convergence speed of the algorithm for the example, is depicted in Figure 4.

5- Conclusions

In this paper, a based natural frequencies method has been used for Damage Detection of tapered poles. In order to calculate the natural frequency of the structure, the matrix repetition method is used because of its high speed and very accurate in calculating the structural frequencies, rather than similar methods. And increased the frequency calculation speed about 7 times compared to the Eigenvalues method. For analyzing the variable inertia moment of tapered pole, the equivalent average inertia moment of each part is considered. Since the discontinuity in this method causes errors in calculations, the sensitivity of the number of selected elements on calculated frequencies investigated. According to the results, it is determined that the calculated error related to the selection of 15 elements (the minimum number of elements considered for damage detection problem) is about 0.09%, which is less than the intended possible noise. It is to solve problems and therefore there will be no problem in detecting the damage. APSO optimization algorithm is used to identify the location and severity of damaged elements, which showed good performance for identifying damaged members. In order to measure the efficiency of the method, two numerical examples with different failure scenarios were examined. To make modeling more consistent with reality, measurement error in calculated frequencies is considered as noise in all problems. In all scenarios, despite the complexity of some of them, APSO was able to find all the damaged elements even in its worst detection and predict the severity of their failure with a small error rate. In addition, all healthy elements that were misdiagnosed in some damage scenarios had a damage rate of less than 5%, which is negligible due to the noise. So, the proposed method also has the power to detect low-intensity failures (10% to 15%) as it can been seen Examples. Therefor based on these results, it can be concluded that the proposed method for detecting damage tapered poles is quite efficient and capable and can be used for other structures as well.

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