Intelligent non-destructive technique for crack existence inspection in a structure using Particle Swarm Optimization (PSO)

Saad Al-Wazni¹ and Ahmed YAZain-ul-abideen²

¹,² Lecturer at Civil Eng. Dept., Faculty of Eng. at University of Kufa, Najaf, Iraq

* Corresponding author: Email address: saad.alwazni@uokufa.edu.iq

Abstract. Increasing cost of erection and maintenance of modern structures becomes need new method of crack investigations before catastrophic failure is happened. A proposed technique for non-destructive inspection of crack in a structure is presented using standard Particle Swarm Optimization (PSO) method. The vibration properties, natural frequencies and mode shapes, of the structure are included in the non-destructive proposed technique. The new technique of crack inspection is verified in a steel clamped beam structural model. The crack position and size are considered and two cases of crack scenarios are adopted in this study. The crack is presented in the FE model as a reduction in the stiffness of specified elements. The dynamic analysis of the FE model is implemented using ANSYS-APDL software. The proposed technique includes a subroutine created by high technical level language in MATLAB software. This new technique exhibits robust and satisfactory performance of inspection the position and size of crack in the adopted structural model.

Keywords: Vibrations of structures, intelligent nondestructive techniques, crack investigation, Particle Swarm Optimization.

1. Introduction

Intelligent nondestructive techniques are modern methods to evaluate the integrity and reliability of the structural system in many engineering disciplines. The information of crack coordinates and size in the structure is main skill of the intelligent nondestructive techniques. The crack in the structure changes the stiffness of the system. These changes of the structural properties alter the vibration characteristics of the structure. By using the vibration properties (modal frequencies and mode shapes) of the structure, the nondestructive technique is effective. In this technique, the operational system data of structure could be extracted without the need for dissociation of the structure [1].

This study developed new technique using Particle Swarm Optimization (PSO) to extract the information of crack in the structure. The PSO optimization method has solved complex non-convex problems in hyperspace [2]. Nowadays, The PSO is implemented to include large scale problems with significant efficiency in solve difficult optimal. In the specified complex problems, the PSO exhibits better than Genetic Algorithms [1]. Kennedy and Eberhart explored the idea of the PSO method during were modeling the social behavior of artificial life, like as birds flocks, fish schooling and bee collections..etc [2].
In the PSO method, the target function is very important to get the global optimal in the convex and nonlinear problems. Nanda et al. (2012) adopted technique to investigate the crack in a cantilever steel structural model using PSO with incremental swarm size [3]. The change in the natural frequencies of the structure was only included in their target function without and with noise. They improved that the PSO effective method in damage investigation. Vaez and Fallah (2017) presented a hybrid technique for crack detection using PSO with Genetic Algorithm (GA) and carried out it on three types of steel thin plate structural numerical model only in their study [4]. They used fitness function included the error in the modal frequencies and mode shapes and verified their approach with several crack scenarios without and with noise. They concluded that PSO method improved their hybrid technique with GA to investigate the crack in the structure. As well as, Wei et al (2018) proposed technique for crack investigating using modified PSO [5]. They implemented their technique on three types of structures; beam, truss and plate and reported that PSO is robust to detect crack in the structure.

In this study, the standard PSO with all parameters designed in different values is adopted in the new proposed technique. Also, the modal mode shapes were included in the adopted target function as well as the modal frequencies of the structure. Also, the weights of the parameters in the target function are studied. Those important modifications of the PSO technique and fitness function are main contributions in this research.

2. Particle Swarm Optimization (PSO)

A real simulation of the Particle Swarm Optimization method is a flock of birds in a searching for food. The target of the swarms is to find the position of the more food. In fact, each bird is going to do random search and it will keep the bushy location of food it experiences. Furthermore, all birds can memorize the acquaintance about their best exploration of positions, then each bird is leaded by its detection and by best position notified by the others. So, by changing the direction of their course to travel somewhere between two positions, the birds will detect the region by overflying positions of most focus and finally is going to dragged to the bushy position [2].

The PSO algorithm is implemented for all type of optimization problems with low effort of calculations. The Genetic Algorithm (GA) method is close to the PSO method, but, the PSO is more robust [1]. As well as, The GA optimization has binary system counter to the PSO method has real parameters to simplify the computations.

The PSO mimics the behavior of birds during searching for food. Here each bird indicates to a particle (solution from searching space) and the group of particles indicates to swarm. Each particle has location and velocity which are modified continuously. That's mean, the particle moves by two vectors, the first accelerates it to the best locally and the second to the best globally of the entire swarm. These two vectors of the particles are shown in the figure 1. Eventually, design the number of particle is more significant for exploring the precise optimal solution. In this study, the number of particle is designed to ten particles.

![Figure 1. Concept of modification of a particle in PSO searching space.](image-url)
The equation of modified velocity of the particles during the search is written in equation (1) [2]:

$$v_{i+1} = \omega \times v_i + c_1 \times r_1 \times (p_{\text{Local}} - p_i) + c_2 \times r_2 \times (p_{\text{Global}} - p_i)$$  \hspace{1cm} (1)

where $\omega$ is a variable changed dynamically which generates acceleration for the particle depends on the last iteration. The $p_i$ is the particle in the current time (solution). The $p_{\text{Local}}, p_{\text{Global}}$ are the local and global optimal solution during the iterations. The $c_1, c_2$ are constants represent the directions of the particle to the best weighted by random values locally and globally, respectively. Those constants are design within range between $[0, 4]$. $r_1, r_2$ are random number ranged between $[0, 1]$. The $v_i$ is the current velocity of the particle. The next better step of the particle is given by kinematic equation as equation (2):

$$p_{i+1} = p_i + \Delta t \cdot v_{i+1}$$  \hspace{1cm} (2)

where $\Delta t$ is the time incremental step of the particle movement in the searching space.

The proposed technique begins the iteration with random swarm of the particle. The convergence criterion controls the new generations of particles to get the global target. In this work, the convergence criterion is a specified number of iteration and the standard PSO was implemented.

3. Finite element analysis of the structural model

This study adopted Nanda et al (2012) structural model, the model was a steel clamped beam [3]. The structural model has length of 600 mm and material properties 200 GPa, 7800 kg/m$^3$, respectively. The finite element model was divided into 20 elements, as shown in figure 2.

![Figure 2](image_url)  \hspace{1cm} Figure 2. The adopted structural model [3].

Their study was included six natural frequencies extracted from the finite element analysis. This study carried out the numerical analysis using ANSYS-APDL software to extract the vibration properties [6], as shown in figure 3.

From figure 3, the first six natural frequencies and mode shapes are included and represented the translations of model nodes in z-axis without noise. The results of the analysis are very close and compared with the reference, as show in figure 4. The differences percentages in natural frequencies values are ranged (-0.000044) in the 1$^{\text{st}}$ mode and (-0.00383) in the 6$^{\text{th}}$ mode.

The single cracked state is included and the comparison of crack investigation in convergence of target function, between the study and the reference, is conducted to verify and exhibit the efficiency and powerful of the proposed technique.
Figure 3. Modal frequencies and mode shapes of the clamped beam.

Figure 4. The comparison in natural frequencies between the study and the reference [3].
4. Performance of new proposed technique

As mentioned previously, the existence of cracks in the structure changes its properties. This changes effects on the vibration properties of the structure. The comparison between the intact and cracked structure state could supply appropriate diagnosis.

The general dynamic response equation for the intact structure could be given in equation (3):

$$ M\ddot{u}(t) + Ku(t) = 0 $$

where \( M \), \( K \) are the mass and stiffness matrices, respectively and \( \ddot{u}(t) \), \( u(t) \) are the acceleration and displacement, respectively.

When crack occurred, the reduction in the stiffness of the local element and global structure is obtained. The changes in the eigenvalue problems are acquired, as shown in equations (4) and (5):

$$ (K - \omega_i^2 M)u_i = 0 $$

$$ (K_e - \omega_{i,e}^2 M)u_{i,e} = 0 $$

where \( \omega_i \), \( u_i \) represent the \( i^{th} \) modal natural frequency and mode shape, respectively. The symbol 'e' represents the cracked structure and \( i = 1,2,3,..., n \) is equal the few first frequencies.

These small changes in the properties need sensitive target function to gives accuracy and can gain the best global or very close to the optimum. Current study adopts fitness function includes two parts. The first one is the square of percentage differences between cracked and examined natural frequencies of the structure. The second term is the sum of the norm of the differences between cracked and examined relative nodes translation of the structure. The second term was not included in the target function which was used in the study of Nanda et al (2012) [3]. Those altering and adding in the fitness function are one of the important differences between this study and the reference. To verify the proposed new technique, two crack scenarios were adopted to simulate the cracks in the structural model. These two scenarios were carried out in the study of Nanda et al (2012) [3], and adopted here for comparative and verification.

4.1. First crack scenario

In this case, a single crack created in the element no.3 at 75 mm close to the fixed support, as shown in figure 2. The crack was represented by reducing in the height of the cross section 10%, as listed in table 1.

| Crack Scenario | Element No. | Distance from support (mm) | Crack Size (%) |
|----------------|-------------|----------------------------|----------------|
| 1              | 3           | 75                         | 10             |
| 2              | 8           | 225                        | 10             |

The reduction in the height of the cross section reduced the stiffness of the structural model. Then, the vibration properties extracted for the cracked model, as listed in table 2.
Table 2. Modal frequencies of the clamped beam for intact, first and second crack scenario.

| Mode | Intact Freq. (Hz) | Cr.Sc.-1 Freq. (Hz) | Cr.Sc.-2 Freq. (Hz) |
|------|-------------------|---------------------|---------------------|
| 1    | 22.721            | 22.162              | 22.527              |
| 2    | 142.343           | 141.52              | 141.503             |
| 3    | 398.363           | 398.613             | 395.586             |
| 4    | 780.087           | 780.089             | 779.437             |
| 5    | 1288.396          | 1283.372            | 1273.994            |
| 6    | 1922.711          | 1908.959            | 1915.23             |

The proposed new technique using PSO method was written by subroutine in high technical language using MATLAB-software environment [7]. After executing the proposed technique to the adopted structural model with first scenario of crack, the target function history during total iteration of 250 is shown in figure 5. The precise solution was detected of the exact element number 3 and crack size of 0.1 of cross section height, as shown in figure 6.

Figure 5. Target function history for first crack scenario during iterations of the proposed new technique.
4.2. Second crack scenario
The crack in this scenario was created in the element no.8 at 225 mm from the support, as shown in figure 2. The crack size was the same value of 10%, as listed in table 1. The extracted modal properties for the cracked model are listed in table 2. The results of this case are shown in figures 7 and 8. From figures, the exact element number 8 and crack size of 0.1 of cross section height are explored.

From comparison between the current and Nanda et al [3] study, the better and quick convergence in the target function value was gained. The results show the efficiency and robustness of the proposed new technique.

Figure 6. History of crack number and size investigation for first crack scenario of the proposed new technique.
Figure 7. Target function history for second crack scenario during iterations of the proposed new technique.

Figure 8. History of crack number and size investigation for second crack scenario of the proposed new technique.
5. Conclusions
A new intelligent technique of non-destructive investigation of crack in a structure using Particle Swarm Optimization (PSO) is proposed. The new technique is based on vibration properties of the structure and included the mode shapes and natural frequencies. The steel clamped beam is adopted in this research study. The target function shows the high sensitivity during assessment of crack in the structure. The exact cracked element number and precise crack size are explored for two crack scenarios, near and far from the support. This new technique exhibits robust and satisfactory performance for investigating the location and size of cracks in the structural model. The experimental testing and other types of structure will study in the future works.

References
[1] Kennedy J and Spears WM 1998 Matching algorithm to problems: an experimental test of the Particle Swarm and some Genetic Algorithm on Multi Model Problem Generator Proc. IEEE Int. Conf. Evolutionary Computation USA.
[2] Kennedy J and Eberhart RC 1995 Particle Swarm Optimization IEEE Proc. Int. Conf. on Neural Networks IV (NJ-USA: Picataway).
[3] Bharadwaj N, Damodar M and Dipak K M 2012 Vibration based structural damage detection technique using Particle Swarm Optimization with incremental swarm size Int. J. Aeronautical & Space Science 13 no. (3) 323-31.
[4] Vaez S R H and Fallah N 2017 Damage detection of thin plates using GA-PSO algorithm based on modal data Arabian J. Science & Engineering (KSA: Springer) 42 Issue (3) 1251-63, doi.org/10.1007/s13369-016-2398-6, KSA.
[5] Wei Z, Liu J and Lu Z 2018 Structural damage detection using improved Particle Swarm Optimization J. Inverse Problem Science & Engineering (Tylor & Francis) 26 Issue (6)
[6] Academic ANSYS-Software, Inc, Release 14.0, http://www.ansys.com
[7] Academic MATLAB-Software, Release 10.0