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A Model-Based Method for Damage Localization and Qualification in a Cable-Stayed Bridge

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Abstract **-** To propose an effective optimization-based model updating and damage detection method, not only a damage-sensitive cost function is required, but also a strong and stable optimization algorithm should be employed. This paper is aimed at presenting a method in which both the mentioned challenges are considered for damage identification in cable-stayed bridges. For this purpose, the damage detection problem is formulated as a modal flexibility-based model updating approach and it is solved utilizing Democratic Particle Swarm Optimization (DPSO) algorithm. DPSO is a modified version of the standard PSO algorithm, which is developed for presenting a tackle the drawbacks of the original PSO algorithm in terms of increasing the algorithm's speed as well as decreasing the premature convergence rate. The efficiency of the method is demonstrated by studying different damage patterns on the numerical model of a cable-stayed bridge. Almost all the obtained results indicate the good performance of the proposed method for the damage localization and quantification of the cable-stayed bridge using only the first several modes' data.

Keywords**:** Structural Damage Detection, Cable-stayed Bridges, Democratic Particle Swarm Optimization algorithm (DPSO), Modal flexibility matrix

1. Introduction

Damage occurrence is inevitable in all structural systems such as buildings and bridges during their lifespan. In the past decades, different types of damage have been observed and recorded in the engineering structures, which resulted in major financial losses. In most cases, damage can be detected and modified by preliminary studies of the current condition of the structures, and they can be protected against the spread of damage or collapse. Damage can be happened due to various reasons such as environmental erosion, fatigue, severe and sudden shocks derived from earthquakes, etc.[1] To identify damage levels, evaluate, and estimate the lifespan of structures, structural health monitoring (SHM) has been utilized. Damage localization and quantification programs are the main parts of SHM plans as basic data. SHM has been performed in both local and global methods. Due to limitations and high expenses of local methods for damage diagnosis, the global methods provide researchers to do SHM based on properties of structures and their vibration characteristics such as natural frequencies and mode shape vectors. Indeed, any changes in physical characteristics of structures such as changes in structural stiffness can be used to detect damage in them. The main goals of global methods of damage detection are identifying damage at the earliest stage, locating damage precisely, quantifying the severity of the damage, and predicting the remaining lifetime of the structure. Limited studies have been reported on utilizing SHM in cable-stayed bridges in the following.[2] Ni et al studied the possibility of using measured dynamic characteristics of the bridge for damage identification. The modal flexibility of matrices of the three-dimensional finite element model of the bridge was extracted and the relative flexibility change between the undamaged and damaged states was formulated as an index to localize damage.

In addition, the effects of temperature alternation and traffic loading were regarded.[3] The temperature impacts on modal parameters of a cable-stayed bridge were assessed by Li et al. They showed that the temperature does not affect mode shapes considerably, while it influences the natural frequency of a cable-stayed bridge.[4] Talebinejad et al employed four damage detection methods on the Quincy cable-stayed bridge: Enhanced Coordinate Modal Assurance Criterion, Damage Index Method, Mode Shape Curvature Method, and Modal Flexibility Index Method were used to locate damage. Also, they extracted mode shapes and natural frequencies of damaged and undamaged structures by using ANSYS numerical model of the bridge. The results revealed the advantages and disadvantages of damage identification methods.[5] The probabilistic neural network based on simulated noisy modal data was used for damage localization in the cable-stayed

Ting Kau bridge by Zhou et al. They found that in noise levels less than 0.1, the probability of identifiability can be greater than 85%.[6] Parka et al investigated the effects of changes in wind velocity and traffic-induced on dynamics characteristics of Ting Kau bridge and analyzed the relationship between wind velocity and modal parameters.[7] Casciati and Elia focused on identifying damage in a cable-stayed bridge in Italy by localizing reduction in stiffness and using artificial bee colony and firefly algorithms for optimization issues. They compared both algorithms in terms of convergence and computational burden.[8] Due to the large scale and complexity of the cable-stayed bridges, and the need for testing cost-effective methods for damage identification based on structural vibration, it is vital to present and examine different methods on these structures. For this study, a two-dimensional cable-stayed bridge was selected to identify damage by defining the damage quantification as a updating model approach with modal data, solving the problem by the Democratic Particle Swarm Optimization (DPSO) algorithm, and considering a cost function.

2. Methodology

2.1. Optimization Algorithm

Democratic Particle Swarm Optimization (DPSO) introduced by Kaveh and Zolghadr [9] was used as an optimization algorithm in this paper. DPSO is an enhanced version of the standard Particle Swarm Optimization (PSO) algorithm suggested by Kennedy and Eberhart[10], which had been inspired by the social behavior of animals such as insects swarming and birds flocking. PSO contains a group of particles that travel in the multi-dimensional search space randomly to find better positions with a velocity. Gradually, the particles converge to sub-optimal solution by updating their location each time. Although PSO has been used in different fields of science, it has some drawbacks: PSO has the inability of proper exploration, and this can lead to convergence easily. Thus, DPSO has been introduced to fix the PSO disadvantages. The main difference between PSO and DPSO is that the particles share their information in DPSO appropriately, in addition to being motivated by their preference and the best particles' suggestion.[11] It should be noted that using DPSO instead of PSO can improve the speed of the algorithm. The velocity of the DPSO is shown hereunder:

$$v_{i,j}^{k+1} = \chi[wv_{i,j}^{k} + c_1 r_1\left(xlbest_{i,j}^{k} - x_{i,j}^{k}\right) + c_2 r_2\left(xgbest_{j}^{k} - x_{i,j}^{k}\right) + c_3 r_3 d_{i,j}^{k}] \quad (1)$$

where w is the inertia weight for previous iteration's velocity and χ is a parameter for dissuading divergence behavior shown as Eq. (2), respectively.

$$\chi = \frac{1.6}{\left|2-(c_1+c_2)-\sqrt{(c_1+c_2)^2-4(c_1+c_2)}\right|} \quad (2)$$

$v_{i,j}^{k}$ is the velocity of variable *j* of the *i*-th particle, $x_{i,j}^{k}$ is the current value of the *j*-th variable of the *i*-th particle, $xlbest_{i,j}^{k}$ is the best value of the *j*-th variable ever found by *i*-th particle, $xgbest_{j}^{k}$ the best value of the variable *j* experienced by the whole swarm so far. Eq. (1) includes three random constants named r_1, r_2, and r_3; these constant parameters are distributed uniformly in the range of (0,1). c_1 and c_2 are describing a particle's confidence rate in itself and the swarm, respectively. c_3 is a parameter that controls the weight of the democratic vector. $d_{i,j}^{k}$ is the *j*-th variable of the vector ***D*** for the *i*-th particle. The vector ***D*** shows the democratic impact of the other particles of the swarm on the movement of the *i*-th particle. The vector ***D*** has been represented as below:

$$D_i = \sum_{k=1}^{n} Q_{ik} \left(X_k - X_i\right) \tag{3}$$

in which X is the particle's position vector and Q_{ik} is the weight of the *k*-th particle in the democratic movement of the *i*-th particle and is obtained by the Eq. (4) hereunder:

$$Q_{ik} = \frac{E_{ik}\frac{obj_{best}}{obj(k)}}{\sum_{j=1}^{n} E_{ij}\frac{obj_{best}}{obj(j)}} \tag{4}$$

where *obj* is the objective function value, and obj_{best} is the value of the objective function for the best particle in the current iteration. *X* is the position vector of the particle; *E* is the eligibility parameter. To minimize, problem *E* can be defined as :

$$E_{ik} = \begin{cases} 1 & \frac{obj(k)-obj(i)}{obj_{worst}-obj_{best}} > rand \cup obj(k) < obj(i) \\ 0 & else \end{cases} \tag{5}$$

where obj_{worst} stands for the values of the objective function for the worst particles, and obj_{best} is the values of the objective function for the best particles in the current iteration. After defining the velocity vector by Eq. (1), the new positions of the particles in the DPSO algorithm are determined as:

$$x_{i,j}^{k+1} = x_{i,j}^{k} + v_{i,j}^{k+1} \tag{6}$$

in which the time interval is equal to 1.0 and therefore the velocity vector can be added to the position vector.

2.2. Damage Detection Method

In this section, details of the proposed method for structural damage identification and quantification are presented. According to the free vibration equation of a system with *Ne* elements and *N* degrees of freedom, structural modal information (i.e. modal frequencies and mode shapes) can be obtained using Eq. (7):

$$K\varphi_i = \omega_i^2 M \varphi_i \tag{7}$$

where ***M*** is global structural mass and ***K*** is stiffness matrices. Also, $\boldsymbol{\omega_i}$ and $\boldsymbol{\varphi_i}$ are the natural frequency and mass-normalized mode shape vector for the *i*-th mode, respectively. Flexibility matrix, ***F***, is interpreted as the inverse of the stiffness matrix, which is written by using natural frequencies and normalized mode shape vectors as below:

$$F = \Phi \Lambda^{-1} \Phi^T \tag{8}$$

in which, $\boldsymbol{\Phi}$ and $\boldsymbol{\Phi^T}$ are the Mass-normalized mode shape matrix and its transpose, and $\boldsymbol{\Lambda}$ is a diagonal matrix that consists of the eigenvalues of free vibration problem as Eq. (9):

$$\Lambda = \begin{bmatrix} \omega_1^2 & 0 & \dots & 0 \\ 0 & \omega_2^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \omega_N^2 \end{bmatrix} \tag{9}$$

Also, the Mass-normalized mode shape matrix is extracted from Eq. (10) as below. Note that ***I*** indicates an identity matrix.

$$\Phi^T M\Phi = I \tag{10}$$

According to the Eq. (8), it can be realized that the flexibility matrix is less dependent on the number of considered modes shape in contrast to the stiffness matrix; It means that increasing the number of considered modes can reduce the effects of the natural frequencies on computing flexibility matrix.[12] Moreover, according to the mathematical properties of the flexibility matrix, the values of the diagonal members of the matrix provide useful and unique characteristics for forming the cost function based on "p" first mode shapes of flexibility matrix $\boldsymbol{F_p}$. Thus, vector Γ is defined as Eq. (11):

$$\Gamma = \{\Gamma_1, \Gamma_2, ..., \Gamma_{Ne}\}^T, \Gamma_j = F_p(j, j) \tag{11}$$

To estimate damage severities, vector Γ is used to determine the following cost function [13]:

$$f(d_1, d_2, \dots, d_{Ne}) = \| \Gamma_d - \Gamma_a \| = \sqrt{\sum_{i=1}^{Ne}(\Gamma_{d(i)} - \Gamma_{a(i)})^2} \tag{12}$$

which ‖ ‖ demonstrates the Euclidean norm, *a* and *d* indexes are related to the analytical model with different levels of damage (updating model) and the damaged model (monitored structure). Also, $d_1, \dots d_{Ne}$ are the unknown damage severities for element number 1 to *Ne*. In the analytical model of the damaged structure, the damage is assigned as the reduction in the stiffness matrix with unknown damage severities. hence, the stiffness matrix of *j*-th element in damaged state E_j^d, can be considered as below:

$$E_j^d = (1 - d_j)E_j \tag{13}$$

In the equation above, E_j is the stiffness matrix of *j*-th element in undamaged structure and d_j is unknown damage ratio for *j*-th element. Given that damage in each element is considered as a value between zero to 1, the cost function of optimizing inverse problem for damage detection can be written as below:

$$\begin{cases} Find\ d = \{d_1, d_2, ..., d_{Ne}\}^T \quad \rightarrow Minimize\ f \\ subject\ to: \quad 0 \le d_i \le 1 \end{cases} \tag{14}$$

To solve the aforementioned cost function, the DPSO algorithm is used.

2.3. Numerical Study

In this section, the efficiency of the proposed method is discussed by studying a two-dimensional cable-stayed bridge under different damage patterns. To create and simulate damage, the analytical model of the cable-stayed bridge was generated in Opensees [14] based on Karoumi's study. The bridge geometry is shown in figure 1; also, the properties of the materials, sections of the girder and pylons of the bridge are presented in Table 1.

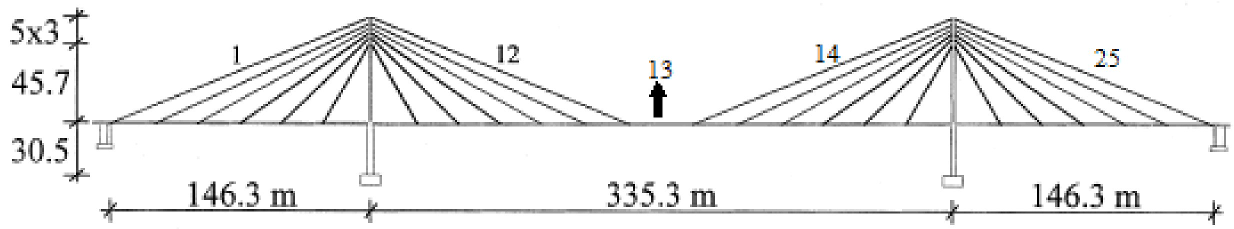

Fig. 1: Elevation of the studied cable-stayed bridge [15] with a specific number of each element

Table 1: Parameters for the cable-stayed bridge model defined in Fig. 1

Elements	Modulus of Elasticity (N/m^2)	Area (m^2)	Moment Inertia (m^4)	Weight (t/m)
Girder	2.0E11	1.11	1.29	19.64
Pylons above deck level	2.8E10	13.01	34.52	30.65
Pylons below deck level	2.8E10	18.58	86.31	43.78

Table 2: Section properties of cables

Number of Cables	Modulus of Elasticity(N/m^2)	Area (m^2)	Length (m)	Weight (t/m)
1,25	2.0E11	0.0362	158.13	0.398
2,11,15,24	2.0E11	0.0232	134.66	0.255
3,10,16,23	2.0E11	0.0204	111.64	0.225
4,9,17,22	2.0E11	0.0176	89.43	0.194
5,8,18,21	2.0E11	0.0136	68.80	0.153
6,7,19,20	2.0E11	0.0113	51.69	0.125
12,14	2.0E11	0.0372	158.12	0.409

For base materials of the cable-stayed bridge, *Concrete01* and *Steel01* materials provided by Opensees were used for concrete and steel elements. *ForceBeamColumn* element was utilized to model the girder and pylons of the bridge. In addition, cables were modelled using *Truss* elements with the *ElasticPPGap* material. All the details of the cable elements are presented in Table 2 based on the characteristics mentioned in Karoumi's study.[15]

Using the damage detection method such as Modal Flexibility Index Method (MFI) and Mode Shape Curvature Method (MSC),[12][16] the possible part of the bridge, which is highly probable to the damage occurrence, was estimated. Taking advantage of the link between Opensees software and MATLAB, the different values of modulus of elasticity (from *$E1* to *$E13*) were defined as variables and were assigned to the modulus of cables (No. 1 to 12) and the deck (No. 13) to create an updating model. It should be noted that half of the model was considered variable due to the perfectly symmetrical structure of the cable-stayed bridge. The other elements which exist in another half of the bridge participated in the analysis with their constant characteristics which were introduced in Tables 1 and 2. To assess the applicability of the method in detecting damage of the studied bridge, four damage patterns shown in Table 3 were regarded. The damage pattern (1) consists of a single damage scenario, while the rest of them (2),(3), and (4), are multiple damage scenarios in the bridge.

Table 3: Damage patterns and their severities in the bridge

Damage Pattern 1		Damage Pattern 2		Damage Pattern 3		Damage Pattern 4	
Element	Damage	Element	Damage	Element	Damage	Element	Damage
9	15%	2	25%	2	20%	4	15%
-	-	4	10%	5	20%	7	20%
-	-	-	-	12	20%	10	10%
-	-	-	-	-	-	12	15%

To identify damage according to the suggested method, three first modes of the bridge were used. Having a more precise SHM program and consider the impact of various issues such as climate changes, working with old equipment or sensors, different levels of random noises (i.e. 0%, 2%, 5%) were added to the input information.[17] Random noises were entered by using the following strategy:

$$\omega_i^{\alpha} = \omega_i \times (1 + \varepsilon R) \tag{15}$$

where ω_i^{α} is the *i*-th natural frequency contaminated by random noises, ω_i is the *i*-th natural frequency without considering noises. ε and *R* are the noise level and a random value between [-1 1] which is developed by MATLAB. In addition, the parameters selected for this algorithm are as follows: number of particles=150, number of iterations=500.

3. The Results and Discussion

The results related to damage diagnosis and quantification of the studied cable-stayed bridge and the defined damage patterns are presented in this part. Considering the symmetrical geometry of the structure and finding the part of the bridge where damage is most likely based on the damage index, half of the bridge was examined to identify the severity of the damage according to the proposed method. As a result of that, fewer unknowns were involved in solving the optimization problem, which results in more accurate responses and higher convergence speeds. As shown in figure 2, the method, including the DPSO algorithm with the presented cost function, illustrates an acceptable level of accuracy in measuring severities and location of damage in occurring both the single pattern (i.e. the damage pattern 1) and multiple damage patterns (i.e. damage patterns 2,3,4). In cases of high random noises, little damage can be observed in other (undamaged) elements; this can be rooted in using three first modes for damage identification. If we just considered the first mode data of the structure, these effects caused by input noises might not have occurred. Also, using the cost function obtained from the higher order of generalized flexibility matrix can eliminate these impacts and provide better results.

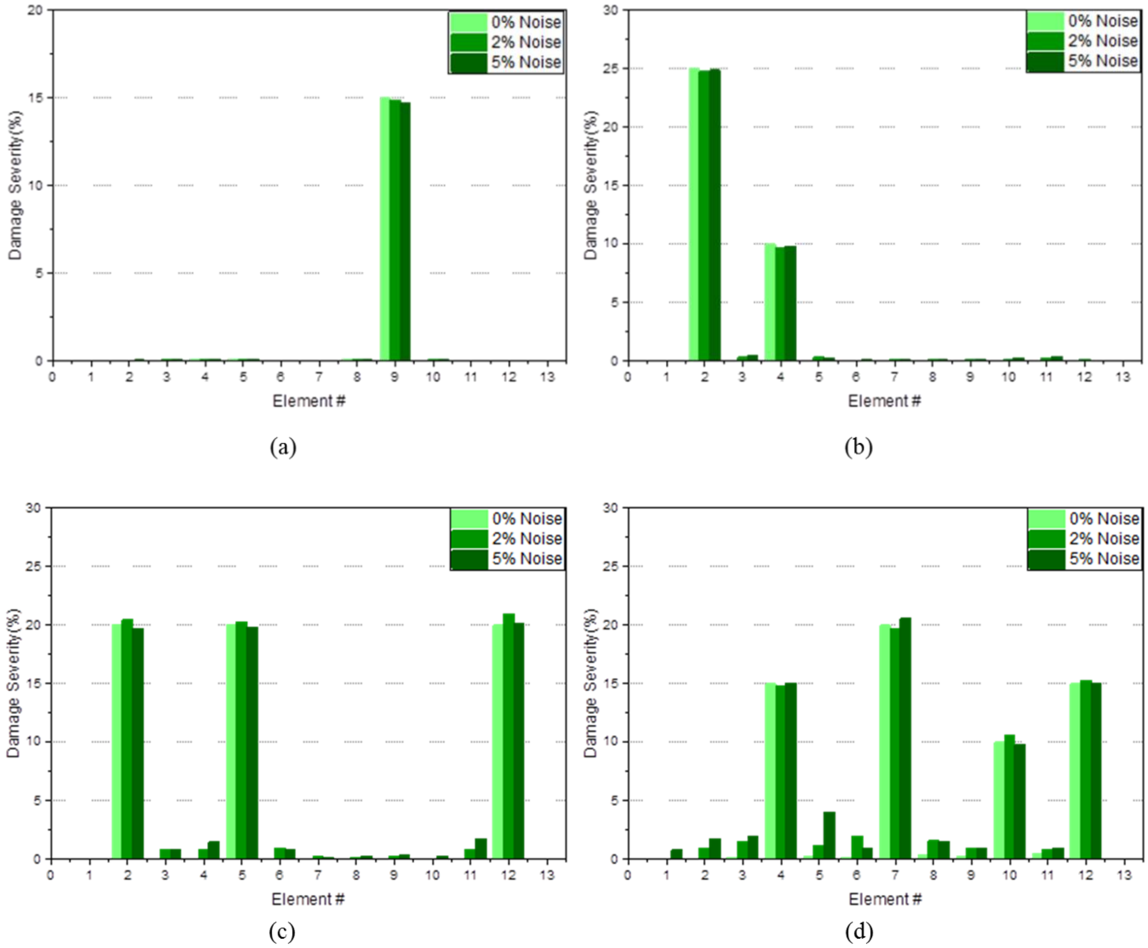

Fig. 2. Damage detection results of the studied bridge for the (a) damage pattern 1 (b) damage pattern 2, (c) damage pattern 3, and (d) damage pattern 4 with different noise levels

4.Conclusion

The main objective of this paper is to propose a method for damage detection in cable-stayed bridges. For this purpose, a model updating approach using Democratic Particle Swarm Optimization (DPSO) algorithm was utilized. To create the updating model and simulate an analytical model of the bridge, the link between Opensees and MATLAB was used and a cost function was defined based on the flexibility matrix to solve the problem. A numerical example of a cable-stayed bridge was studied by defining damage as the reduction in the stiffness matrix of damaged elements. Comparing the obtained results from the studied four damage patterns with the actual simulated damages indicated that the suggested method has sufficient accuracy in detecting damage though noisy inputs are fed.

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