Structural Damage Identification Based on Wavelet Analysis and Particle Swarm Optimization

Deqing Guan[1,a] , Yungang Liu[2,b], Qinchang Wang[3,c]
[1,2,3]College of Civil Engineering, Changsha University of Science & Technology, Changsha, China
[a]491596452@qq.com, [b]1601376939@qq.com, [c]976371682@qq.com

Keywords: damage identification; continuous wavelet transform; particle swarm optimization
Abstract. In order to identify the multiple damage of the structure, this paper presents a method of structural damage identification based on wavelet analysis and particle swarm optimization(PSO). Firstly, analyzing dynamic characteristics of the finite element model to obtain the strain mode, then continuous wavelet transform is carried out for the strain mode, and the damage location of the structure is identified according to the modulus maximum of the wavelet coefficient, on this basis, using the natural frequency and the vibration mode before and after the structural damage construct the objective function, and then using PSO algorithm optimize the objective function to obtain the damage degree of the structure. Finally, a numerical example is given to demonstrate the effectiveness of this method in identifying structural damage.

Introduction

In the process of long time working, civil engineering structures will be faced with the problem of structural damage accumulation due to the influence of various external factors and natural factors. If the structural damage can't be detected and dealt with in time, the structure will be destroyed and catastrophic consequences will be brought about. Therefore, It is very necessary to obtain the damage information about the structure through the health monitoring technology.

In recent years, damage identification methods based on structural dynamic characteristics and dynamic response have become the hot and difficult research at home and abroad[1]. Among them, the wavelet analysis has good localization and multiresolution characteristics, and can be used to analyze and identify the local damage information which is difficult to be found in other methods of structural dynamic response. It has been widely used in the field of damage identification. Ovanesova used several numerical examples to demonstrate the ability of wavelet to detect structural crack damage[2]. Zhong used the stationary wavelet transform to identify the defects of simply supported beams[3]. Solis have carried on the continuous wavelet transform to the modal form vector difference before and after the structural damage, and the structural damage position is identified by the variation of the structural mode[4]. The above literature shows that wavelet analysis is sensitive to structural damage, but it is difficult to quantify the damage of the structure accurately. With the use of intelligent optimization algorithm in the field of structural damage identification, the damage degree of the structure is well quantified[5]. Compared with other intelligent algorithms, the PSO algorithm has the advantages of large searching area, simple program implementation, fast convergence velocity and little parameter setting, so it has been widely used by scholars. Qian proposed a hybrid optimization algorithm based on particle swarm optimization to identify the layered damage in the composite structure[6]. Shirazi proposed an adaptive multi-level optimization method based on particle swarm optimization algorithm to identify multiple damage of structure[7]. However, when the PSO algorithm is used to identify the structural damage, the small damage will be neglected due to the interference of the adjacent units. In addition, with the increase of the number of units, the computational complexity of the algorithm will increase exponentially and the iteration convergence slows down, which even leads to the algorithm failure. To sum up, aiming at the advantages and disadvantages of wavelet analysis and PSO algorithm in identifying structural damage, this paper proposes a "two-stage method" to identify structural damage, that is, the damage location is identified by wavelet analysis, and the PSO algorithm is used to quantify the damage degree of the damage location. This method make up for the use of a single method to identify structural damage defects.

Identification of Structural Damage Position

Wavelet Singularity. When the wavelet function is the first derivative of a smooth function, that is $\psi(t)=d\theta(t)/dt$, where $\theta(t)$ satisfies $\int_{-\infty}^{\infty}\theta(t)dt=1$ and $\theta(t)$ is the high order infinity of $1/(1+t^2)$,the continuous wavelet transform is defined as Eq.(1).

$$W_x(a,t)=x(t)*\psi_a(t)=x(t)*(a\frac{d\theta_a}{dt})(t)=a\frac{d}{dt}[x(t)*\theta_a(t)]. \tag{1}$$

For a certain scale a, the maximum point of $W_x(a,t)$ along the t axis corresponds to the inflection point of $x*\theta_a(t)$, that is, the point of mutation of $x(t)$.

Strain Mode. Structural damage usually leads to unequal stiffness EI on both sides of the damaged area, but the displacement, rotation and bending moment on both sides of the damage area will still meet the conditions of deformation coordination and internal force equilibrium, as shown in equations (2), (3) and (4), respectively.

$$\omega(\upsilon^+)=\omega(\upsilon^-). \tag{2}$$

$$\frac{d\omega(\upsilon^+)}{dx}=\frac{d\omega(\upsilon^-)}{dx}. \tag{3}$$

$$EI(\upsilon^+)\frac{d^2\omega(\upsilon^+)}{dx^2}=EI(v^-)\frac{d^2\omega(\upsilon^-)}{dx^2}. \tag{4}$$

The relation between strain and rotation, as in Eq. (5).

$$\varepsilon=K\frac{\partial\theta}{\partial x}. \tag{5}$$

Where x is the coordinate of the length direction; θ is the rotation; K is a constant.

Since $EI(\upsilon^+)\neq EI(\upsilon^-)$,then $\left(d^2\omega(\upsilon^+)/dx^2\right)\neq\left(d^2\omega(\upsilon^-)/dx^2\right)$, this shows that the structural strain mode produces a mutation in the structural damage region. From the Saint-Venen principle we can see that the strain mode away from the damaged area is basically unchanged. Therefore, the strain mode of the structure can be transformed by continuous wavelet transform, and then the structural damage position can be identified according to the modulus maxima of wavelet coefficient.

Quantification of Structural Damage

PSO Algorithm. In 1995, Kennedy and Eherhart proposed the PSO algorithm based on the similarity between the behavior rules of the birds and the optimization problem[8]. The algorithm treats the individual as a particle, assuming that in a M-dimensional target search space, there are N random particles to form a population. At each iteration, the particle updates its velocity v and position x by dynamically tracking the individual extremum p and global extremum g, until the optimal solution is found in the complex solution space.

$$v_{im}^{k+1}=w*v_{im}^k+c_1r_1\left(p_{im}^k-x_{im}^k\right)+c_2r_2(g_{im}^k-x_{im}^k). \tag{6}$$

$$x_{im}^{k+1}=x_{im}^k+v_{im}^k. \tag{7}$$

Where $i=1,2,\cdots,N$, $m=1,2,\cdots,M$; c_1,c_2 are learning factors, $c_1=c_2=2$; r_1,r_2 is a uniform random number in the range $[0,1]$; $v_{im}\in[-v_{\max},v_{\max}]$, $v_{\max}=x_{\max}-x_{\min}$;k is the current iteration number of steps.

Application of PSO Algorithm. In this paper, the damage degree of the structure is initialized into a group of random particles, and the value of the constructed objective function min*F* is used to judge the property of the particle position. In the target search space, the particle updates its velocity *v* and position *x* by dynamically tracking the individual extremum *p* and the global extremum *g*, until the objective function min*F* gets the global minimum. At this point, the location of the particles is the global optimal solution, that is, the degree of structural damage.

$$\min F = F_1\sum_{i=1}^{m}\left(\frac{f_i^{test}-f_i^{cal}}{f_i^{test}}\right)^2 + F_2\sum_{i=1}^{n}\sum_{j=1}^{u}(\varphi_{ij}^{test}-\varphi_{ij}^{cal})^2 . \qquad)8($$

Where F1 and F2 is the weighting factor, $F_1 = 0.3$, $F_2 = 0.7$;*m* is the order of frequency; *n* is the order of modal; *u* is the node number ; f_i^{test} , f_i^{cal} is the i-th order frequency of the structure obtained by actual measurement and calculation, respectively; φ_{ij}^{test} , φ_{ij}^{cal} is the vibration mode of j-th node of i-th order modal of the structure obtained by actual measurement and calculation, respectively.

Numerical Simulation Analysis

Damage condition of frame structure. This frame structure uses Q235 steel, the length of the beam and column is 3000*mm*, the dimension of the cross section is: $300\times500mm$, density: $\rho = 7800kg/m^3$, Poisson ratio: $\mu = 0.3$.elastic modulus: $E = 2.1\times10^{11} N/m^2$. The frames are divided into 1000 units in order of A-B-C-D-E-F-G, B-H-F, and D-H-I, and assuming this frame structure has a 2%, 5%, 3%, 6%, 4% damage at units 160, 350, 520, 680 and 960, respectively. the model of the frame structure is shown in Fig. 1.

Identify the Damage Location of the Frame Structure. Firstly, establishing the finite element model of frame structure and constructing the five damages mentioned above by the method of element stiffness reduction, then the strain mode is obtained by modal analysis. Then we use the db5 wavelet to carry on the continuous wavelet transform to the obtained strain mode, get the wavelet coefficient figure as shown in Fig. 2. As shown in Fig. 2, the wavelet coefficients are mutated at 160, 350, 520, 680 and 960 units, indicating that the structure has damage in these five units, consistent with the assumed damage condition of the frame structure.

Quantify the Damage to the Frame Structure. As we can see above, the structure is damaged only in units 160, 350, 520, 680 and 960, on this basis, constructing objective function by using the first 5 order natural frequency and vibration mode before and after structural damage, and then using PSO algorithm optimize the objective function, the damage degree of units 160, 350, 520, 680 and 960 is 0.0191,0.0521,0.036,0.0591,0.0388, as shown in Fig. 3. The optimization curve is shown in Fig. 4. The quantification relative error of the damage degree of the five damage units is less than 5%, which indicates that the PSO algorithm can effectively quantify the structural damage.

Conclusions

1.Wavelet analysis can make timely feedback on the instantaneous characteristics of the dynamic response signal, and it has good robustness to the noise, which makes the mutation characteristic of the signal easy to be manifested. So it can more accurately identify the small damage of the structure.
2.PSO algorithm does not depend on the nature of the damage problem and the characteristics of the structure. It shows a strong vitality and robustness in solving the complex nonlinear relationship between the natural frequency, the vibration mode and the degree of damage.
3.In this paper, wavelet analysis is used to identify the damage location of the structure, which reduces the dimension of the PSO algorithm in solving the optimization problem and avoids the PSO algorithm misjudgment the structural damage location. So that the calculation of PSO algorithm will be greatly reduced and the convergence rate will become faster. The numerical analysis shows that this method has high precision and efficiency to identify the damage of frame structure.
4.The structural damage identification method proposed in this paper has a reference value for

identifying the damage of the actual engineering structure. Firstly, with the instrument measured structure of the strain mode, the natural frequency and vibration mode and other data. Then the continuous wavelet transform is applied to the obtained strain mode data, and the structural damage position is identified according to the modulus maxima of the wavelet coefficient. Finally, the PSO algorithm is used to obtain the damage degree of the damage unit based on the measured natural frequency and vibration mode.

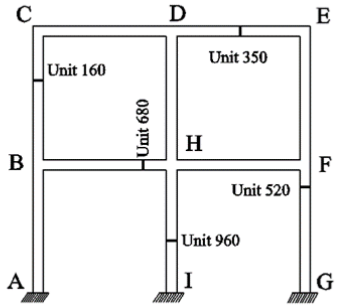

Fig. 1. Model of frame structure

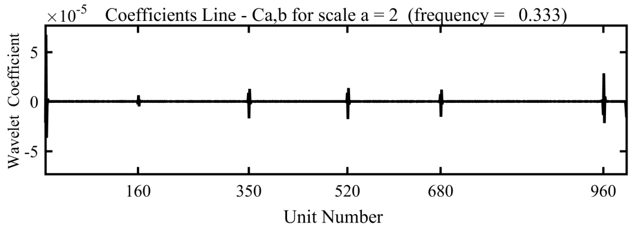

Fig. 2. Wavelet coefficient

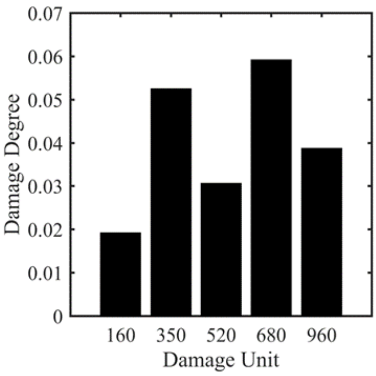

Fig. 3. Quantification of unit damage degree

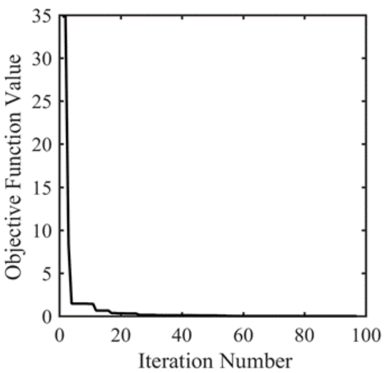

Fig. 4. Iterative optimization curve

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (51378079).

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