Damage Identification of Frame Structure by Wavelet-Genetic Algorithm

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***Abstract*—This article takes the frame structure as the research object, and combines wavelet analysis with genetic algorithm for structural damage identification. Firstly, wavelet analysis is used to identify the structural damage location and the number of damaged units, then the genetic algorithm is used to identify the structural damage degree. The numerical simulation results show that this method can not only identify the damage location effectively, but also accurately identify the damage degree.**

Keywords-wavelet; genetic algorithm; damage identification; plane frame

I. INTRODUCTION

The frame structure is widely used in the current building engineering. If the frame structure is damaged and accumulated to a certain degree, it will seriously threaten people's personal and property safety. Therefore, it is of great practical significance to effectively identify the damage of frame structures when the degree of damage is relatively small. At present, structural damage identification is a very active research field in structural engineering. For the damage identification of the structure, it mainly includes two aspects: the location of the damage and the degree of the damage.

The concept of wavelet transform was proposed by J.Morlet in 1974. Wavelet transform is the localization analysis of time and frequency, and it can focus on any signal details. Through the calculate function making the muti-scale analysis it resolves many difficult problems which Fourier transformation cannot solve, it is known as “mathematical microscope”. Nowadays, wavelet analysis has been widely used in the field of structural damage identification. Raghavendrachar [1] used wavelet transform to detect the damage of concrete continuous beam model, it is proved that the wavelet transform is very sensitive to local damage. Hong [2] adopted cracks in the beam as the research object, using the wavelet singularity theory, by the wavelet coefficient modulus maxima to accurately determine the damage location of the beam. E.Douka [3] to take the transverse crack cantilever beam as the research object, through the continuous wavelet transform of the basic mode of vibration, identified the damage location and the depth of the crack. Shi Licheng etc[4] first used curvature mode method of wavelet transform on the damage identification of continuous steel box girder.

Genetic algorithm was proposed by Professor J.Holland in 1975 , who was inspired by the theory of biological evolution, and the solution of the problem was obtained by simulating the process of biological evolution. The main advantage of the genetic algorithm is that the objective function can be discontinuous, it without the need of gradient information and has strong robustness. Based on these remarkable advantages, genetic algorithm has been widely used and studied. By constructing a series of fitness function, many scholars have applied the genetic algorithm to the field of structural damage identification, and have achieved satisfactory results. Nobahari [5] using genetic algorithm combined with MDLAC index, identified the damage of the cantilever beam. Yu L [6] introduced the zero mutation rate factors to the genetic algorithm, the numerical simulation results consistent with the actual situation of the damage structure. Koh [7] determined the structural parameters by testing the excitation and response, and the parameters were identified by the local search function of the genetic algorithm. H.Y.Guo [8] established the finite element model of the cantilever beam, and combined with the evidence theory and genetic algorithm, using the two stage method to identify the structural damage. The results show that this method can get better results. Chou [9] constructed the objective function by using the theory of static displacement and the difference of measured values in the truss bridge model, and verified the effectiveness of the method.

Wavelet analysis has the advantages of fast, accurate and convenient operation, but it is not accurate enough to quantitatively identify structural damage degree. Genetic algorithm has excellent global search ability, but in the case of unknown number of damage units, the variables of the objective function is a very great number, it will lead to the genetic algorithm to solve the time is too long, and the results of large errors and other consequences. Based on the above considerations, this paper adopts the method of combining wavelet analysis and genetic algorithm. The method uses wavelet analysis to identify the damage location and the number of damage elements, damage element number as the number of variables in the objective function of the genetic algorithm, so the number of optimization variables is reduced. Then the genetic algorithm is used to identify structural damage degree.

II. PRINCIPLE OF WAVELET-GENETIC ALGORITHM

A. *Damage Location Identification Based on Wavelet Transform*

For any signal $f(t) \in L^2(R)$,and the base wavelet function $\psi(t)$ satisfy the wavelet permissibility condition.

The continuous wavelet transform of $f(t)$ is defined as:

$$WT_f(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty} f(t)\psi^*\left(\frac{t-b}{a}\right)dt \quad (1)$$

In the formula, $a,b,t\in R$ and $a\neq 0$; a is a scale factor that reflects the frequency information of the signal ,and b is a translation factor that reflects the time information of the signal, $\psi(t)$ is called basic wavelet, $\psi^*(t)$ is the complex conjugate function of $\psi(t)$ .With the change of wavelet transform, the characteristics of multi resolution is presented,local features of the function can be highlighted by the continuous wavelet transform both in time domain and in frequency domain.

We take an example of a frame structure with one layer and one span, the unit damage is simulated by the reduction of the stiffness of the structural element. If the structure is damaged at a certain location, we consider the bending stiffness of the structure in a certain section to be reduced. On the left and right sides of the damage section: $EI(v^+)=EI(v^-)$, but the internal force equilibrium condition and deformation compatibility condition of the structure should be satisfied:

Vertical displacement:

$$w(v^+)=w(v^-) \quad (2)$$

Rotation:

$$\frac{dw(v^+)}{dx}=\frac{dw(v^-)}{dx} \quad (3)$$

Bending moment:

$$EI(v^+)\frac{d^2w(v^+)}{dx^2}=EI(v^-)\frac{d^2w(v^-)}{dx^2} \quad (4)$$

Shear force:

$$EI(v^+)\frac{d^3w(v^+)}{dx^3}=EI(v^-)\frac{d^3w(v^-)}{dx^3} \quad (5)$$

Because $EI(v^+)\neq EI(v^-)$, according to formula (4) can be obtained: $\frac{d^2w(v^+)}{dx^2}\neq\frac{d^2w(v^-)}{dx^2}$,it suggests that the second derivative of the basic vibration mode of structure's damage cross section is discontinuous. The rotation mode can be transformed into the continuous wavelet transform, the modulus maxima of the wavelet coefficients will appear in the damaged section to identify the location of the damage.

B. Damage Degree Identification Based on Genetic Algorithm

In the use of genetic algorithm to solve the problem, each of the possible solutions are encoded into a individual, a number of individuals formed a group. At the beginning of the genetic algorithm, some individuals are randomly generated. According to the fitness function, each individual is evaluated, and a suitable value is given. Based on the fitness value, the individual is selected to reproduce the next generation. The selection operation embodies the principle of "survival of the fittest", high fitness individuals are selected for reproduction, and low fitness individuals will be eliminated, then selected individuals through crossover and mutation operator are combined to generate a new population. The new population is superior to the last generation because of some excellent characters of the last generation, so it is more in the direction of the better solution. Therefore, the genetic algorithm can be regarded as a process of gradual evolution of a group composed of feasible solutions.

In structural damage identification, the inherent frequency belongs to the structure of the whole property. If using the change of inherent frequency to identify structural damage, the damage location and degree of damage identified by the change of the same inherent frequency may be different. Vibration mode belongs to the local properties of structure, the higher accuracy of the vibration mode data in the actual operation is difficult to obtain. If only using the modal data as the identification parameters, the error of the identification results can be caused by the inaccurate measurement of the vibration data. Based on the above considerations, the objective function is constructed by weighting the frequency error and the mode error, as follows:

$$J=F_\omega\sum_{i=1}^{m}\left(\frac{f_i^{test}-f_i^{cal}}{f_i^{test}}\right)^2+F_\varphi\sum_{i=1}^{n}\sum_{j=1}^{k}\left(\varphi_{ij}^{test}-\varphi_{ij}^{cal}\right)^2 \quad (6)$$

In the formula, F_w, F_ϕ is a weighted factor of frequency and vibration type, respectively. In this paper, the value is 1. f_i^{test} , f_i^{cal} is the structure of the measurement and calculation of the n order frequency, φ_{ij}^{test}, φ_{ij}^{cal} is the structure of the measurement and calculation of the n order vibration mode. m to participate in the assessment of the frequency order number, n to participate in the assessment of the vibration mode number, k is the number of nodal displacement.

In this article, structural damage is expressed by unit stiffness reduction factor, and the design variable of the objective function is the element stiffness reduction factor. After wavelet analysis, the number of damage units is determined as the number of design variables. The damage is defined as less than 50% of the damage degree. Therefore, the value range of the design variable is: $0<\alpha_i\leq 50$.

C. Damage Identification Based on Wavelet-genetic Algorithm

First of all, using the finite element theory, the finite element model is established, the rotation of structural modal parameters is obtained by Lanczos method, using DB3 wavelet to carry on the continuous wavelet transform of the rotation mode, the damage location is identified by the wavelet modulus maxima. Then the objective function is constructed by using the error of frequency and vibration mode, using damage unit number as the number of variables in the objective function. Through genetic algorithm to minimize the objective function, we can identify the degree of damage.

III. NUMERICAL SIMULATION ANALYSIS

We take an example of a frame structure with one layer and one span, as shown in Figure I. The beam and column use the rigid connection, and both are uniform bar, the column is fixed to the ground. The length of the beam and column is $4000mm$,the section dimension is $200 \times 250mm$,elastic modulus: $E = 2.07 \times 10^{11} N/m^2$,density: $\rho = 7800 kg/m^3$, poisson ratio: $\mu = 0.3$ .The finite element model of structure is established by ANSYS, the frame is divided into 600 units, the center spacing of each unit is 20mm,B points and C points respectively corresponding to unit 200th and unit 400th.This article assumes that frame structure with three different levels of small damage, The damage units are unit 100 (distance A point 2000mm), unit 250 (distance B point 1000mm), unit 450 (distance C point 1000mm),The damage degree is 5%, 10%, 15%, respectively.

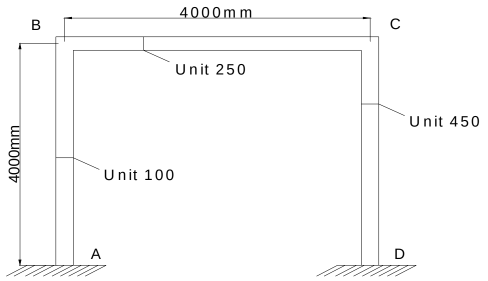

FIGURE I. FRAME MODEL

A. Damage Location Identification

Firstly, by using the Lanczos method, the modal analysis of the damage structure is carried out, and the rotation mode parameters are obtained. Then we use the Matlab wavelet toolbox function, use db3 wavelet as the mother wavelet, the rotation mode as the object to carry on the continuous wavelet transform. The wavelet coefficient diagrams as shown in Figure II, observed that the singular points of wavelet coefficients map the location corresponds to the damaged unit in the framework of the position (unit 100,unit 250 and unit 450).This is consistent with the hypothesis, thus, the structural location is identified. Moreover, the degree of damage can be judged qualitatively according to the degree of mutation in the figure.

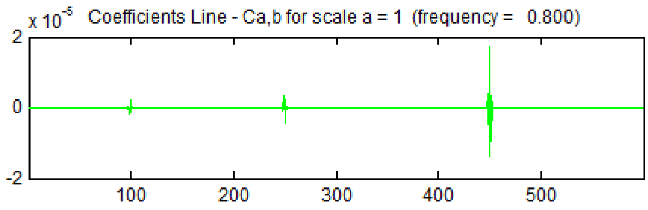

FIGURE II. WAVELET COEFFICIENT CHART

B. Damage Degree Identification

The number of damage units is determined by wavelet analysis, and the damage location is unit 100, unit 250 and unit 450, so the population size is set to 150.Coding method uses binary coding, six binary number represents a variable, the individual consists of three variables, so the total length of the individual is eighteen. The iteration number is 200 times, and the iteration termination condition is not updated for 50 consecutive times. The selection operator uses the optimal preservation strategy, so that the optimal individuals obtained so far can not be destroyed by genetic operators such as crossover and mutation. The crossover probability is 0.8 and the mutation probability is 0.08.Fitness function see formula (6), damage identification was performed by using the first 10 order dominant frequency and the first 2 order vibration mode, by minimizing the objective function to get the degree of damage. In the iteration process, the best fitness value and the mean fitness value of each generation are shown in Figure III. In the figure, the vertical coordinate indicates the fitness value, and the horizontal coordinate indicates the number of iterations. Final damage identification results are shown in Table I.

TABLE I. DAMAGE IDENTIFICATION RESULTS

Unit Number	No.100	No.250	No.450
Damage Identification(%)	4.9982	10.0003	15.0074
Assumed Damage(%)	5	10	15
Absolute Error(%)	-0.0018	0.0003	0.0074

The results shows in the Table I: the identification result of unit 100 is 4.9982%, the identification result of unit 250 is 10.0003%, the unit 450 is 15.0074%. Unit damage degree identification error is less than 0.01%, the identification error is extremely small, it shows that this algorithm is very accurate for the damage degree of the frame structure, and it meets the engineering requirements.

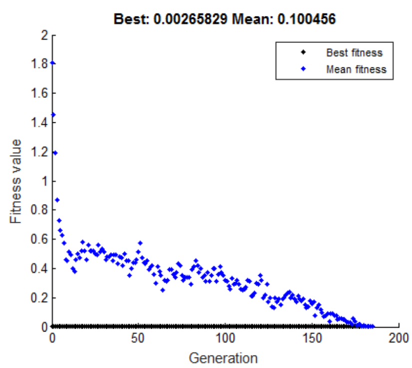

FIGURE III. FITNESS VALUE CURVE

IV. CONCLUSIONS

1) This paper adopted the method of combining the wavelet analysis and genetic algorithm for structural damage identification. The damage location is identified by wavelet analysis, and the damage degree is identified by the genetic algorithm. This method solves the problem that the wavelet analysis is not accurate and the design variables of the genetic algorithm are too many.

2) By establishing a finite element model of plane frame structure, this paper studied a layer of a cross plane frame structure containing three damage identified problems. Numerical simulation results proved that the wavelet-genetic algorithm not only can accurately identify the location of damage, but also accurately identify the degree of damage.

3) By using the finite element analysis, the rotation mode parameters of the structure were obtained, the continuous wavelet transform was carried out by using db3 wavelet to the parameters of the rotation mode. Then the wavelet coefficients were obtained, by the wavelet coefficients in the figure mutation position and degree of mutation, the damage location was accurately identified, and the size of the damage degree was qualitatively determined.

4) After determining the location of damage by wavelet analysis, the number of variables in the objective function of genetic algorithm is greatly reduced, and the number of variables is determined by the number of damage units after wavelet analysis. Then genetic algorithm was used to quantitatively identify the degree of damage. The objective function is constructed based on the weighted combination of frequency error and vibration type error, and the damage degree of the structure was identified accurately.

5) A simple frame structure was adopted as the study object, satisfactory results have been obtained for the damage identification, it is of practical significance for further damage identification research of complex structure.

ACKNOWLEDGMENT

The work is supported by National Natural Science Foundation of China (No.51378079)

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