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The Application of Improved Genetic Algorithm on Damage Identification for Frame Structure

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Abstract

Genetic algorithm was used to identify the damage of frame structure. Stiffness coefficient damage factor is selected as design variable, and the weighted array difference value between inherent frequency and vibration mode of structure calculated and measured. According to the difficulty in selecting crossover rate and mutational rate for fundamental algorithm, the process of selection operator, crossover operator and mutation operator was improved. All operators were operated on parent individual. Crossover rate and mutational rate were set for 100%. Punishment function was applied for keeping the difference among individuals. The improved genetic algorithm can conserve the better individual in parent and keep off fall into local optimum. Through a 3-story frame with single variable damage and multiple variables damage study, the results showed that the improved genetic algorithm can identify the damage location and degree.

Keywords: *improved genetic algorithm, inherent frequency, vibration mode*

1. Introduction

Structures after put into service will be subjected to influences from the surroundings, or to external accidental loads such as earthquakes and impacts. The mechanical properties in materials will also change after years of service, and thus, structure detection is necessary for assessment of internal damages [1, 2]. The overall structure performance is usually assessed by testing the static or dynamic response under given load. Dynamic test is more commonly used than static test, since data acquisition is more convenient and structure damage is less likely. During damage analysis, the correlation between the intrinsic parameters and the response of a structure is used to back-calculate the performance parameters using the tested response. Damage analysis is essentially a problem of parameter identification and can be solved using optimization algorithms.

The genetic algorithm (GA) is an intelligence optimization algorithm [3] proposed in 1970s. GA does not involve complex mathematical knowledge, or require that the function be differentiable and continuous. As it can handle complex target functions and constraints, GA is applied to solve various optimization problems [4-7]. GA is also outstanding in system identification and damage identification.

GA was improved to diagnose damages in fixed-fixed beams [8]. GA was also applied into structural damage identification and programming, and the damages in a three-span continuous bridge was analyzed [9]. Hierarchical GA was used to monitor multiple damages in structures [10]. The improved damage identification factor and GA were used to study structural damage identification with the presence of noise, and the results were validated with simply supported beams and continuous beams as examples [11]. Intelligence optimization algorithms including GA were also used in structural damage identification [12-14].

GA in structural damage identification is superior over routine optimization algorithms in simple clues, clear ideas and simple operation. However, for specific problems, GA is

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also faced with limitations such as slow convergence, occurrence of prematurity, and occurrence of local optimization [15]. Because of crossover and mutation during the process of convergence, the basic GA may damage the otherwise identified better individuals in the parent generation. Regarding this problem, in this study, the selection operator, crossover operator and mutation operator were separately applied into the parent generation. Then the identified individuals were ranked by quality, and the better individuals were included into a new generation. This algorithm improved the optimizing efficiency from the perspective of operation flow. Then the improved algorithm was applied into damage identification in a frame structure.

2. Damage Identification in Frame Structure

2.1. Structural Damage Identification Algorithm and Principles

The damage in one component will change the mechanical parameters (e.g. stiffness) of the whole structure, and thus change the inherent frequency and the corresponding vibration mode that characterize the dynamic performances of the structure. The inherent frequency and vibration mode are closely correlated with the mass distribution and stiffness of the structure. If the damage is only stiffness deterioration, direct measurement of structural stiffness is very difficult, and the static methods may even induce further internal damage. Thus, dynamic signals are usually measured to back-calculate whether the component stiffness at one position has changed or is severely damaged.

If a structure is a system with n degrees of freedom (DOF), the mass matrix under undamaged state is M, which is usually a diagonal matrix, and the stiffness matrix is K.

Where

$$M = \begin{pmatrix} m_{11} & 0 & \cdots & 0 \\ 0 & m_{22} & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & m_{nn} \end{pmatrix}$$

$$K = \begin{pmatrix} k_{11} & k_{12} & \cdots & k_{1n} \\ k_{21} & k_{22} & \cdots & k_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ k_{n1} & k_{n2} & \cdots & k_{nn} \end{pmatrix}$$

The corresponding n inherent frequencies are $\omega_1, \omega_2, \cdots \omega_n$, the n vibration mode vectors are $\phi_1, \phi_2, \cdots \phi_n$, where $\phi_i = (\phi_{i1}, \phi_{i2}, \cdots \phi_{in})$. After damage, the stiffness of the structure changes and the stiffness matrix K is changed to K' .

$$K' = \begin{pmatrix} \alpha_{11}k_{11} & \alpha_{12}k_{12} & \cdots & \alpha_{1n}k_{1n} \\ \alpha_{21}k_{21} & \alpha_{22}k_{22} & \cdots & \alpha_{2n}k_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \alpha_{n1}k_{n1} & \alpha_{n2}k_{n2} & \cdots & \alpha_{nn}k_{nn} \end{pmatrix}$$

Where α_{ij} ($0 < \alpha_{ij} \le 1$) corresponds to the damage factor of k_{ij} in the stiffness matrix, the values of α_{ij} correspond to different damage degrees of k_{ij} , when α_{ij} approaches 0, the damage is severe, and this segment will be withdrawn from service. When $\alpha_{ij} = 1$, no damage occurs at this position.

With the damage identification based on dynamic test signals, K is the original stiffness matrix of the known structure. If the damage factor is α_{ij}, the stiffness matrix after damage is K' , and the mass matrix M does not change.

$$\left|K' - \omega^2 M\right| = 0 \tag{1}$$

The inherent frequencies after damage are $\omega_{c1}, \omega_{c2}, \cdots \omega_{cn}$, the corresponding vibration modes are $\phi_{c1}, \phi_{c2}, \cdots \phi_{cn}$. From structural mode tests, the inherent frequency and vibration mode after damage are $\omega_{m1}, \omega_{m2}, \cdots \omega_{mn}$ and $\phi_{m1}, \phi_{m2}, \cdots \phi_{mn}$ respectively. The damage factor is determined to be α_{ij} , so that the dynamic parameter from computation infinitely approaches the measured value, which is the process of damage identification.

2.2. Target Function for Damage Identification in a Frame Structure

An n-layer frame structure is showed in Fig. 1. The horizontal stiffness from top to low layers is $k_1, k_2, \cdots k_n$ respectively. Usually lumped-mass method is used to lump the mass onto the floors, which are $m_1, m_2, \cdots m_n$ respectively (Fig. 1).

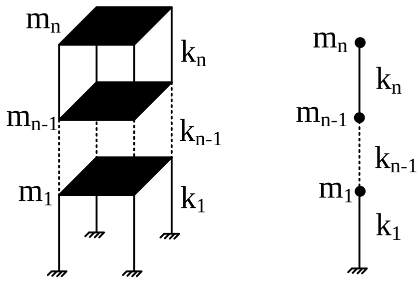

Figure 1. Sketch of the Frame Structure

The mass matrix M is a diagonal matrix, and the elements on the major diagonal lines represent the masses at all layers, other elements are all 0, and the stiffness matrix K is:

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & \cdots & 0 \\ -k_2 & k_2 + k_3 & -k_3 & \ddots & \vdots \\ 0 & -k_3 & k_3 + k_4 & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & -k_n \\ 0 & 0 & 0 & -k_n & k_n \end{bmatrix}$$

To show more clearly, the physical meaning is clearer, and the stiffness between horizontal layers can be reduced.

The stiffness coefficients at all layers after damage are $\alpha_1 k_1, \alpha_2 k_2, \cdots, \alpha_n k_n$ respectively, which is substituted into the original stiffness matrix K to form a post-damage stiffness matrix K'.

Then the problem of damage identification is equal to the determination of damage factor α_i, so the computed dynamic characteristic parameter is consistent with the measurements. This becomes a process of optimized selection, with the following target functions:

$$F_{\min}(\alpha_1,\alpha_2,\cdots\alpha_n)=\sum_{i=1}^{n}a_i(\frac{\omega_{ci}-\omega_{mi}}{\omega_{mi}}+\sum_{i=1}^{n}b_i(1-MAC(\phi_{ci},\phi_{mi})) \tag{2}$$

$$MAC(\phi_{ci},\phi_{mi})=\frac{\left|\phi_{ci}^{T}\square\phi_{mi}\right|^2}{(\phi_{ci}^{T}\phi_{ci})(\phi_{mi}^{T}\phi_{mi})} \tag{3}$$

Where a_i is the weight of i-order inherent frequency and b_i is the weight of i-order vibration mode vector, $MAC()$ is the modal confidence criterion.

Constraints:

$$0<\alpha_i\leq 1 \tag{4}$$

$$MAC(\phi_{ci},\phi_{mi})\geq 0.9 \tag{5}$$

3. Improved GA and Program Implementation

3.1. Improvement of Flow of GA

The flow of the basic GA is as follows:

Step 1. Based on the designed variables, generate an initial population made up of N individuals.

Step 2. Compute the adaptive values of individuals, and apply a punishment operator to the individuals not obeying the constraint. Decide whether the termination condition is met. If yes, terminate. Otherwise, enter Step 3.

Step 3. Apply the selection operator onto the individuals, and select those with higher adaptive values into the next step.

Step 4. Apply the crossover operator.

Step 5. Apply the mutation operator and return to Step2.

In the basic GA, the selection operator, crossover operator and mutation operator are in series relation. The results show that at a very high crossover rate, the crossover operation damaged the relatively good individuals after selection operation. Also a very large mutation rate also damaged the previously identified better individuals. On the other hand, a too small crossover rate or mutation rate did not work effectively, and the convergence was slowed down. Based on this, the GA was improved, and the flow after improvement is showed in Fig. 2.

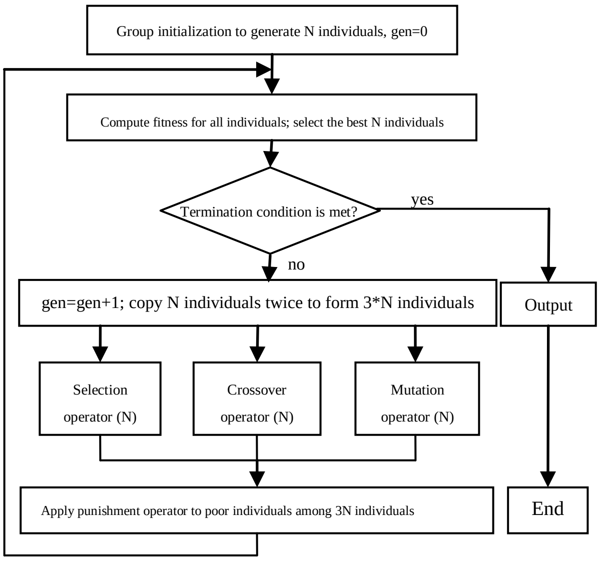

Figure 2. Flow of Improved GA

In the flow of the improved GA, the individuals in the parent generation are self-copied twice before application of operators. Then each copy is applied with the selection, crossover and mutation operations. The 3*N* individuals are gathered for computation of fitness and ranking. The best *N* individuals are included into a new generation. At this moment, the crossover rate and the mutation rate were both regarded as 100%. Thereby, these *N* relatively good individuals from the parent generation will not be damaged by the subsequent operations, which utmost reserve the optimal individuals.

3.2. Improved Punishment Operator

If the individuals from the parent generation are not largely different, or the solution space is overly concentrated, then this algorithm may very likely fall into a local optimal solution. Besides the individuals not obeying the constraint, those with high similarity are also applied with the punishment function, which reserves the optimal individuals and reduces the adaptive values of other individuals. The similarity between individuals is expressed as Hamming distance. For two individuals X_i and X_j (length of chromosomes = *m*), then their Hamming distance is computed as:

$$\left\| X_i - X_j \right\| = \sqrt{\sum_{k=1}^{m} \left(x_{ik} - x_{jk} \right)^2} \tag{6}$$

During the operations, the designed variables in the chromosomes may differ in order of magnitude. Then to make the punishment operator more effective, the difference between two individuals can be rewritten as:

$$dis(X_i, X_j) = \sqrt{\sum_{k=1}^{m} \left(\frac{x_{ik} - x_{jk}}{x_{jk}} \right)^2} \tag{7}$$

When $dis(X_i, X_j) < L$, the fitness between two individuals is compared, and the individual with low fitness is treated with the punishment function.

$$F_{\min}\left(x_i, x_j\right) = Penalty \tag{8}$$

4. Case Study

4.1. Framework Model

A 3-layer steel frame structure (Fig. 1) is designed as follows: mass at each layers m_1=m_2= m_3=1.5×10^6 kg, stiffness k_1=10.0×10^6, k_2=9.5×10^6, and k_3=9.0×10^6 N/m.

Mass matrix:

$$M = \begin{bmatrix} 1.5 & 0 & 0 \\ 0 & 1.5 & 0 \\ 0 & 0 & 1.5 \end{bmatrix} \times 10^6 kg$$

Stiffness matrix:

$$K = \begin{bmatrix} 19.5 & -9.5 & 0 \\ -9.5 & 18.5 & -9 \\ 0 & -9 & 9 \end{bmatrix} \times 10^6 N/m$$

4.2. Single-Variable Damage Identification

We assume that the stiffness damage factors are $\alpha_1 = 1$, $\alpha_2 = 0.5$, $\alpha_3 = 1$,or namely, the horizontal stiffness coefficient at layer 2 is reduced by half. The mass matrix M is not changed, and the original stiffness matrix is:

$$K' = \begin{bmatrix} 14.75 & -4.75 & 0 \\ -4.75 & 13.75 & -9 \\ 0 & -9 & 9 \end{bmatrix} \times 10^6 N/m$$

Computations based on Eq. (1) were conducted on MATLAB: frequency ω_1 =0.9664, ω_2 =3.0011, and ω_3 =3.8806 rad/s, and the corresponding vibration mode vectors are:

$$\phi_1 = (1 \quad 2.8104 \quad 3.3284)^T$$

$$\phi_2 = (1 \quad 0.2610 \quad -0.5208)^T$$

$$\phi_3 = (1 \quad -1.6503 \quad 1.0930)^T$$

The above frequencies and vibration modes after damage were used as measurements, based on the flow in Eq. (2) and Fig. 2, a C program was compiled under VC++, and the improved GA was used to back-calculate damage factors α_1, α_2 , α_3 (to one digit). The weighting coefficients were all 1, and th e initial population size was 100. The optimized convergence process is showed in Fig. 3.

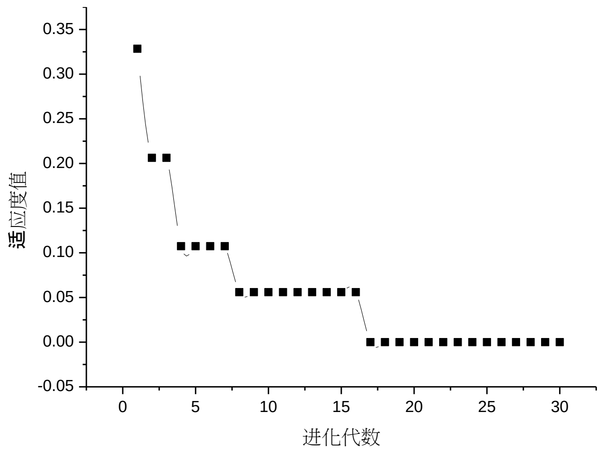

Figure 3. Convergence in Single-Variable Damage Identification

After 16 iterations, it converges to, and the corresponding optimal individual is (Fig. 3):

$$X = (\alpha_1 \quad \alpha_2 \quad \alpha_3) = (1.0 \quad 0.5 \quad 1.0)$$

Clearly, for single-variable damage identification, the improved GA is good at finding the global optimal solution. After repeated tests, the optimal solution did not change.

4.3. Multi-Variable Damage Identification

We suppose the stiffness in 3 layers is damaged at $\alpha_1 = 0.6$, $\alpha_2 = 0.7$, $\alpha_3 = 0.8$, namely the stiffness was reduced to 60%, 70% and 80% of the original levels. Then the stiffness matrix is:

$$K' = \begin{bmatrix} 12.65 & -6.65 & 0 \\ -6.65 & 14.85 & -7.2 \\ 0 & -7.2 & 7.2 \end{bmatrix} \times 10^6 N/m$$

The computations showed that after damage, frequency ω_1=0.9139, ω_2=2.6331, ω_3=3.8338. The corresponding vibration mode vectors are:

$$\phi_1 = (1 \quad 1.7138 \quad 2.0749)^T$$

$$\phi_2 = (1 \quad 0.3384 \quad -0.7615)^T$$

$$\phi_3 = (1 \quad -1.4131 \quad 0.6853)^T$$

Similarly, the above inherent frequencies and vibration modes were used as measurements, and the GA was used to find the damage factors α_1, α_2, and α_3. The optimized convergence process is showed in Fig. 4.

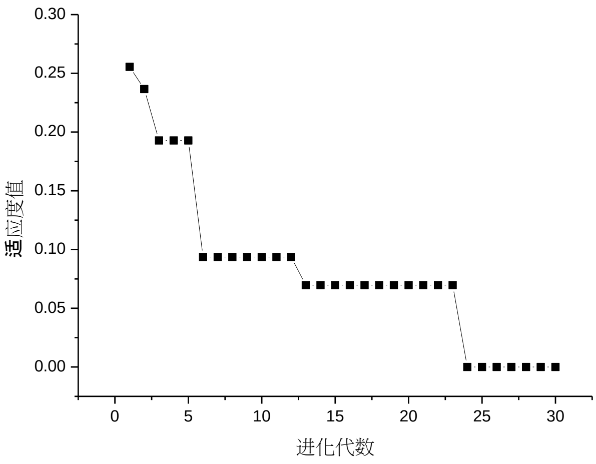

Figure 4. Convergence in Multi-Variable Damage Identification

The optimal solution after convergence is:

$$X = (\alpha_1 \quad \alpha_2 \quad \alpha_3) = (0.6 \quad 0.7 \quad 0.8)$$

The above two cases show that for both single- and multi-variable damages, the optimized convergence processes of the improved GA are similar as it can well identify the positions and degrees of damages.

In practical engineering, the mass matrix and stiffness matrix of a structure are known, and its inherent frequency and vibration mode are identified via dynamic test. If the stiffness coefficient damage factors are, then the genetic algorithm is used to find the optimal solution. The structural damage situation is assessed.

5. Conclusions

The genetic algorithm was applied into damage identification in structures, and the basic genetic algorithm was improved. The case study shows that the improved genetic algorithm applied into damage identification in a frame structure can well identify the positions and degrees of damages.

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