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Damage assessment of structures from changes in natural frequencies using genetic algorithm

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Abstract. A method is presented to detect and assess the structural damage from changes in natural frequencies using Genetic Algorithm (GA). Using the natural frequencies of the structure, it is possible to formulate the inverse problem in optimization terms and then to utilize a solution procedure employing GA to assess the damages. The technique has been applied to a cantilever beam and a plane frame, each one with different damage scenario to study the efficiency of the developed algorithm. A laboratory tested data has been used to verify the proposed algorithm. The study indicates the potentiality of the developed code to solve a wide range of inverse identification problems in a systematic way. The outcomes show that this method can detect and estimate the amount of damages with satisfactory precision.

Key words: genetic algorithm; damage assessment; inverse problem; finite element method; natural frequency; stiffness reduction factor.

1. Introduction

Techniques to detect damage in a structure and to evaluate their residual life time are very important to assure the structural integrity of operating plants and structures. Damage to structure may be caused under service conditions as a result of the limited fatigue strength. They may also be due to mechanical defects, as in the case of turbine blades of jet turbine engines. Another group involves cracks, which are inside the material: they are created as a result of manufacturing processes. Sometimes the extent and location of damage can be determined through visual inspection. But visual inspection technique has a limited capability to detect damage, especially when damage lies inside the structure and is not visible. So an effective and reliable damage assessment methodology will be a valuable tool in timely determination of damage and deterioration state of structural member.

Methods based on modal analysis have several advantages over alternative techniques due to the fact that the modal parameters depend only on the mechanical characteristics of the structure and not on the excitation applied, and furthermore, that theoretically the structure can be represented by measurements taken at a single location. So in most of the studies of dynamic methods for damage identification, researchers have restored to the change in natural frequency as the diagnostic tool.

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Frequencies can be measured more easily than mode shapes, and as a result they are less affected by experimental errors. In damage detection problem two objectives have to be attained: the location of damage and its magnitude or severity. From the changes in natural frequencies the inverse problem related to damage detection may be posed to determine the location and percentage damage.

One class of damage location and assessment procedure, which has attracted considerable interest recently, is that based on the alteration of the vibration characteristics of structures when damage occurs. Sanayei *et al.* (1986) presented a method to detect damage, which is simulated through stiffness reduction under static load. For this method, applied force and measured displacement should be at some DOF in the structure. Wu *et al.* (1992) used the pattern matching capability of a neural network to recognize the location and the extent of individual member damage from the measured frequency spectrum of the damaged structure. Narkis (1994) treated the dynamics of a cracked, simply supported uniform beam for either bending or axial vibrations. The author simulated the crack by an equivalent spring, connecting the two segments of the beam. Barai and Pandey (1995) applied neural network based damage detection on bridge truss configuration after carrying out both static and dynamic analysis of structure. Mares and Surace (1996) described a technique to identify the location and quantification of the extent of the damage with genetic algorithms, by using the residual force method, which is based on conventional modal analysis theory. A general cracked prismatic element of 12 coupled degrees of freedom for a Timoshenko beam was developed by Gounaris *et al.* (1996) for dynamic analysis of a cracked prismatic beam to identify the location and magnitude of a surface crack. The main advantage of this method was its sensitivity and resolution because of the use of coupled vibration response. The main limitation of this method is one has to made assumptions that there is a single edge nonpropagating crack. Nikolakopoulos *et al.* (1997) showed the dependency of the first two structural eigenfrequencies on crack depth and location by the use of contour graph form. To identify the location and depth of a crack in a frame structure, one only needs to determine the intersecting point of the superposed contours that correspondence to measured eigenfrequency variations caused by the crack presence. Ruotolo and Surace (1997) used the modal parameters of the lower modes for the non-destructive detection and sizing of cracks in beams. They used a finite element model of the structure to calculate the dynamic behavior, to formulate the inverse problem in optimization terms and then to utilize a solution procedure employing genetic algorithm. Chondros *et al.* (1998) developed a consistent continuous cracked beam vibration theory with single-edge and double-edge open cracks. Fracture mechanics methods were used to model the crack as a continuous flexibility in the vicinity of the crack region investigating the displacement field. Friswell (1998) demonstrated a damage detection method using genetic algorithm on a simulated beam and an experimental plate. Cerri and Vestroni (2000) addressed the problem of identifying structural damage affecting one zone of a beam using measured frequencies. The beam model has a zone in which the stiffness is lower than the undamaged value. Suh *et al.* (2000) determined the location and depth of crack by just measuring eigen frequencies of the structure. They utilized hybrid neuro-genetic technique for this purpose. Feed-forward multi-layer neural networks trained by back propagations are used to learn the input (the location and depth of crack) and output (the structural eigen frequencies) relation of the structural system. Genetic algorithm is used to identify the crack location and depth minimizing the difference of measured frequencies with the trained network. Morassi (2001) presented a method, which deals with the identification of a single crack in a vibrating rod based on the knowledge of the damage-induced shifts in a pair of natural frequencies. Yongyong *et al.* (2001)

presented a genetic algorithm based shaft crack detection technique based on finite element method. They have suggested that the finite element model of the shaft crack need to be study deeply, so that the model simulates the real system more reasonably and higher accuracy of the detection can be expected. Krawczuk (2002) presented a paper that uses the wave propagation approach combined with genetic algorithm and the gradient technique for damage detection in beam-like structures. The objective function used by the author was based on differences between measured and calculated dynamic responses in the frequency domain. Liu and Chen (2002) proposed a computational inverse technique for identifying stiffness distribution on structures using structural dynamics response in the frequency domain. They applied Newton's method to search for the parameters of stiffness factor inversely. Au *et al.* (2003) described a procedure for detecting structural damage based on a micro genetic algorithm using incomplete and noisy modal test data. They showed the effectiveness of using frequencies and both frequencies and mode shapes as the data for quantification of damage extent.

From the past research work, it is understood that damage may be detected in a better way if natural frequency is considered as an input of the structural response. Some of the researchers have used neural network for damage detection, which has many disadvantages, like difficult to train the network, chances of getting tapered in local minima. A robust damage assessment methodology must be capable of recognizing patterns in the observed response of the structure resulting from individual member damage, including the capability of determining the extent of damage. In the application to the detection of damage in structures, the aim is to formulate an objective function in terms of parameters related to the physical properties and state of the structure. The objective function must be formulated in such a way that the maximum value is obtained when evaluated with the true parameters. In the formulation of an objective function presented in this paper, the parameters used are "stiffness reduction factors". Each factor corresponds to the reduction in the stiffness of one of the elements from which the structure is composed as compared to the counterpart in the integral (undamaged) structure. This objective function incorporates a vector, which, being formulated in terms of the stiffness matrix of the damaged as opposed to the integral structure differs from the conventional definition. Here plane stress and frame problem are considered for demonstration, which shows the effectiveness of the algorithm for both the cases. Experimental data obtained from the literature has been used to verify the accuracy of the proposed technique. This approach has the advantage that the more reliable genetic search algorithm can be employed to identify more reliably the presence, location and extent of damage in the structure.

2. The genetic search procedure

Genetic algorithms are stochastic search algorithms based on the mechanics of natural selection and natural genetics, which is designed to efficiently search large, non-linear, discrete and poorly understood search space, where expert knowledge is scarce or difficult to model and where traditional optimization techniques fail. Algorithm 1 illustrates the process of GA.

Algorithm 1: (Genetic algorithms).

1. Create initial population of fixed size.
2. Evaluate 'Fitness' of each individual population.
3. Repeat.

4. Select parents for ‘gene pool’.
5. ‘Offspring’: crossover (parents 1, 2).
6. Mutation (‘offspring’).
7. Replace (population, ‘offspring’).
8. Fitness evaluation of each individual in population.
9. Until (stopping criterion).
10. Report the best individual.

The main differences between GAs and traditional optimization methods can be summarized as follows:

- GAs work with a string-coding of variables instead of the variables
- The GA works with a population, which represents numerical values of a particular variables
- GA operators exploit the similarities in string-structures to make an effective search
- GAs work with a population of points instead of a single point
- Multiple optimal solutions can be captured in the population easily, thereby reducing the effort to use the same algorithm many times
- GAs only require the use of an objective function
- Only probabilistic rules of selection are used with GAs.

A simple genetic algorithm consists of three basic operations, these being reproduction, crossover and mutation. The algorithm starts with the randomly generated initial population. The members of this population are usually binary strings called chromosomes. The binary coding system formally allows the use of positive numbers only. Particular elements of chromosomes are called genes. In these, strings are coded values of a variable, or variables, which can be a solution of the problem of interest in a relevant search space. These variables are then used to evaluate the corresponding fitness value, this being the objective function. In the next step chromosomes are appropriately selected for reproduction. The selection processes can be carried out in various ways. In practice one of the following methods would be used:

- Deterministic selection
- Random selection.

Irrespective of the adopted selection method the actual number of selected members will be a function of the fitness of the members. Thus individuals with higher fitness will achieve more copies. After reproduction the process of crossover is undertaken next. There are many ways of implementing this idea. Generally crossover with one, or many, crossover points can be used and these points are then selected randomly, usually using roulette wheel statistics. In this way certain portions are exchanged between selected *parent* chromosomes, and so two new *children* strings are created. A crossover with two points is illustrated below. In this example two crossover points, and the exchanged parts of the parents have been randomly selected. The genetic form of the two children strings depends on the direction of crossover, with crossover between the two parents potentially in either direction, as shown in Fig. 1 by the double-headed arrows.

Taking Parent I (Fig. 1) as an example it can be seen that the full chromosome is given by 100101001111010. In Fig. 1, this is divided into three parts, namely, 10010, 10011, and 11010. Alternatively, one might choose to divide the chromosome differently, perhaps like this: 1001, 0100111, and 1010. However, in the present case, it was decided to work with equal part lengths, as

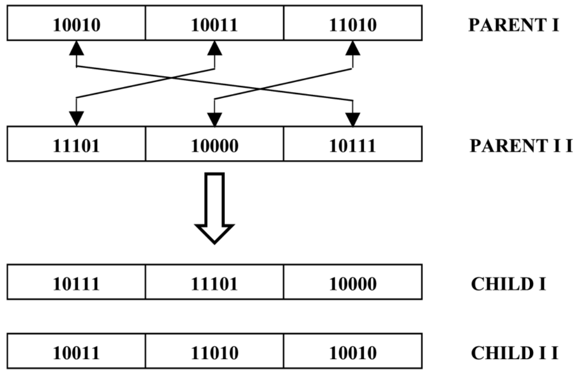


Fig. 1 Crossover with two points

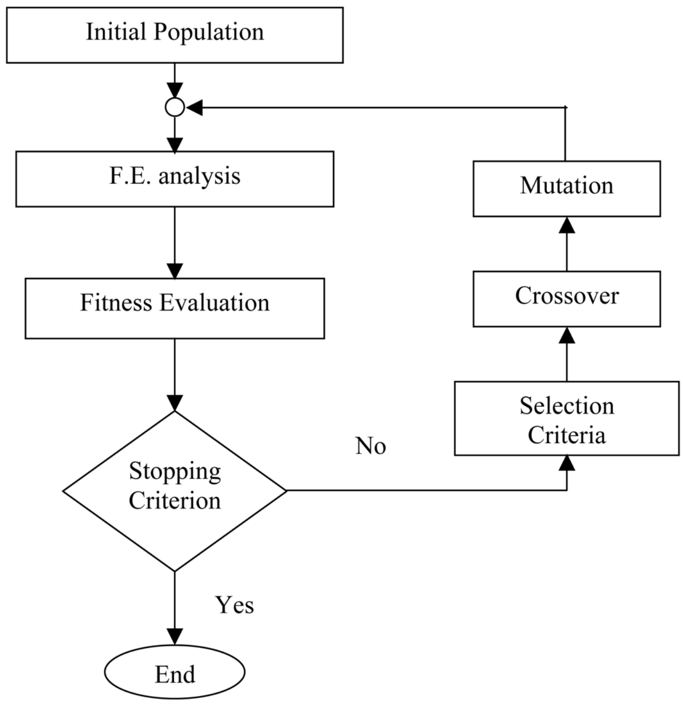


Fig. 2 Flowchart of genetic algorithm

per the first division strategy in which five bit parts were chosen. A similar approach is applied to Parent II so that it becomes 11101, 10000, and 10111, as shown above. Therefore, in each case, there is a fifteen-bit string divided into three five-bit parts. The crossover points are defined here as being after five and ten and this gives rise to the crossover strings, as shown in the diagram above, in which Children I and II are generated by means of exchanged five-bit parts from the two parents.

The final process is mutation. Here a particular gene in a particular chromosome is changed randomly. In this context *0* is changed to *1*, and vice versa. The process of mutation rarely occurs in nature, and so for this reason the probability of chromosome mutation is necessarily kept to a very low level when using genetic algorithms.

Genetic algorithms have been frequently accepted as optimization methods in various fields, and have also proved their excellence in solving complicate, non-linear, discrete and poorly understood optimization problem. The genetic algorithm method is also very attractive in comparison with classical methods because it does not require a solution search within the whole solution space. Instead the algorithm starts from a small initial population of approximated solutions and converges rapidly from thereon. This is why GA is used to solve the inverse problem of damage assessment. Fig. 2 depicts this idea clearly.

3. Working principles of GAs

3.1 Coding

In order to use GAs to solve any problem, variables are first coded in some string structures. Binary-coded strings having 1's and 0's are used here. The length of the string is usually determined according to the desired solution accuracy. It is not necessary to code all the variables in equal sub-string length. The length of a sub-string representing a variable depends on the desired accuracy in that variable.

In this study, the candidate solution searched is the damage configurations, which are location of damage and amount of damage. They are all numerical parameters. So, bit strings are used to encode the candidate solution. The string length is taken in the present case as 10.

3.2 Fitness function

Generally, a fitness function is first derived from the objective function and used in successive genetic operations. For maximization problems, the fitness function can be considered to be the same as the objective function. For minimization problems, the fitness function is an equivalent maximization problem chosen such that the optimum point remains unchanged.

The fitness value is computed for each individual in the population and the objective is to find the individual that has the highest fitness for the consideration problem. In this study, the fitness function used is the RMS of the difference between the actual outputs and the computed results using the FEM.

$$g(\tilde{R}) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(f_i^m - f_i^c)^2} \tag{1}$$

Where, n is the number of natural frequencies, f^m and f^c are the measured frequency and the computed frequency respectively. $\tilde{R}$ is a vector representing the state of damage of the structure, and is given by

$$\tilde{R} = [r_1 r_2 r_3 \ldots r_n]^T \tag{2}$$

Where,

$$r_i \in [0, 1] \tag{3}$$

This is the simplest objective function that can be formulated for the damage assessment problems through an optimization task, as the difference between the natural frequencies are taken into account. It is obvious that when $g(\tilde{R})$ is minimized and the global minimum is reached, the damage state vector can be a reliable estimate of the true damage state of the structure. This function can be maximized as:

$$F(\tilde{R}) = 1/g(\tilde{R}) \tag{4}$$

4. GA operators

4.1 Reproduction

Reproduction is usually the first operator applied on a population. In this works, the classical ‘roulette wheel’ methods combined with the ‘elite’ strategy are implemented. During roulette wheel selection, two mates are selected for reproduction with probability values in direct proportion to their fitness values. Therefore, the fitter individuals will contribute a greater number of offspring in the succeeding generation. Meanwhile, the elite strategy force the best individual of the current generation always survives in the next generation.

4.2 Crossover

The ‘crossover’ operation is a process by which new individual (children) are created from existing ones (parents) during reproduction. In this work, to assure each sub string corresponding to various parameters has equal chance for crossover, ‘two-point’ crossover is implemented with a probability of Pc by choosing two random points in the selected pair of strings and exchanging the sub strings defined by the chosen points (Fig. 1 illustrated this process).

4.3 Mutation

The role of the ‘mutation’ operation is to introduce new genetic materials (genes) to the chromosomes with a probability of Pm, thus preventing the inadvertent loss of useful genetic material in earlier phases of evolution. In our work, two-element swap mutation is implemented. Here a particular gene in a particular chromosome is changed randomly. In this context 0 is changed to 1, and vice versa. In this study mutation probability is kept 0.01, as the process of mutation rarely occurs in nature, and so for this reason the probability of chromosome mutation is necessarily kept to a very low level when using genetic algorithm.

5. Finite element formulation

5.1 Plane stress problem

The structure is analyzed here considering 2-dimensional plane stress formulation using 8-noded isoparametric element. The stiffness and mass matrix may be obtained from the following expressions:

$$[K] = h\iint_A [B]^T[D][B]\,dxdy \tag{5}$$

$$[M] = h\iint_A [N]^T\rho[N]\,dxdy \tag{6}$$

where $[K]$ and $[M]$ are the stiffness and mass matrix respectively, h is the thickness of the element, $[D]$ is the constitutive matrix and $[N]$ is the shape function. $[B]$ is the strain-displacement relationship matrix which may be expressed as:

$$[B] = \begin{bmatrix} \frac{\partial N}{\partial x} & 0 \\ 0 & \frac{\partial N}{\partial y} \\ \frac{\partial N}{\partial y} & \frac{\partial N}{\partial x} \end{bmatrix} \tag{7}$$

5.2 Plane frame problem

For the plane frame problem, the finite element concepts are used to formulate the displacement method of analysis treating the *member* of a framed structure as an *element*. A planar frame structure is modeled using two-dimensional beam elements having three degrees of freedom $(\delta x, \delta y, \theta z)$ per each node. The corresponding element stiffness matrix may be given by

$$[K_e] = \frac{EI_{zz}}{L^3}\begin{bmatrix} \beta L^2 & 0 & 0 & -\beta L^2 & 0 & 0 \\ 0 & 12 & 6L & 0 & -12 & 6L \\ 0 & 6L & 4L^2 & 0 & -6L & 2L^2 \\ -\beta L^2 & 0 & 0 & \beta L^2 & 0 & 0 \\ 0 & -12 & -6L & 0 & 12 & -6L \\ 0 & 6L & 2L^2 & 0 & -6L & 4L^2 \end{bmatrix} \tag{8}$$

$$[M_e] = \frac{\rho AL}{420}\begin{bmatrix} 140 & 0 & 0 & 70 & 0 & 0 \\ 0 & 156 & 22L & 0 & 54 & -13L \\ 0 & 22L & 4L^2 & 0 & 13L & -3L^2 \\ 70 & 0 & 0 & 140 & 0 & 0 \\ 0 & 54 & 13L & 0 & 156 & -22L \\ 0 & -13L & -3L^2 & 0 & -22L & 4L^2 \end{bmatrix} \tag{9}$$

where $\beta = A/Izz$, where Izz is the second moment of area about the local z-axis. L is the length of element e, and A is the cross-sectional area. E and ρ are the modulus of elasticity and mass density respectively.

In the majority of the works aimed at diagnosing the state of damage of a beam, the structure is considered to be affected by single damage; only very few studies assure the presence of two damage, while the possibility of multiple damage is almost invariably ignored. Focusing attention on this last aspect, a mathematical model can be obtained by using the finite element method, assuming that the various cracks do not interact with each other and that all components that make up the structure is potentially damaged. Subsequently, the entire structure is represented using elements of a stiffness matrix, which is a function of amount of damage and is given by

$$[k] = [k(\tilde{R})] \tag{10}$$

$\tilde{R}$ is the vector representing the state of damage of the structure as given by Eq. (2).

Eq. (10) is used to locate and assess the damage for both plane stress and plane frame problem.

5.3 Calculation of natural frequency

Using the stiffness and mass matrix, the eigen value problem for free vibration case may be written as:

$$\left|[K] - \omega^2[M]\right| = \{0\} \tag{11}$$

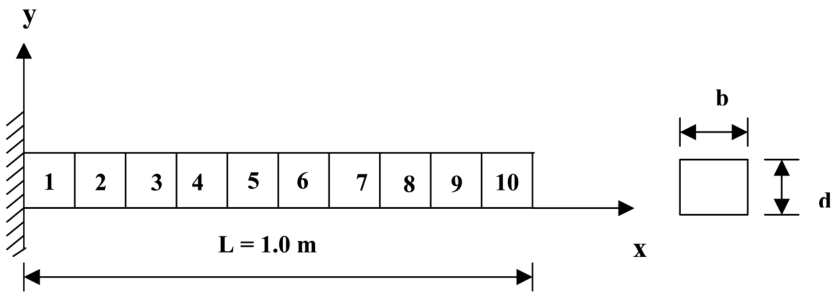
Where, ω is the eigenfrequency of the structure. The above analysis serves to identify the location and percentage of damage in a structure by measuring the eigenfrequency variations.

6. Numerical examples and results

The computer codes developed in the present study with formulation outlined before are applied on two different types of structural system such as on a cantilever beam and a plane frame. The calculated first three and first six mode natural frequencies are used as input response. Element damage is defined as a reduction in stiffness of the element. In the present study damage at single location and multiple locations in structure are found out. After some trials with, the genetic search was set up as follows; a population size of 50 for single damage case and 300 to 500 for multiple damage case; a cross over probability of 0.9; a mutation probability of 0.01; a string length of 10. Due to random nature of genetic search, for each damage scenario the simulations were run five times to evaluate the probability that the optimization procedure would converge to the same solution.

6.1 Example 1: Damage on a cantilever beam

A simple cantilever beam is considered in the present analysis to demonstrate the efficiency and robustness of the developed algorithm. The dimensions of the beam are shown in Fig. 3. The first three and six mode natural frequencies are calculated and used in the objective function for a comparison of the results.



b = 0.20 m d = 0.20 m $E = 2\times10^8$ kN/m^2 $\rho = 78.5$ kN/m^3 $\mu = 0.25$

Fig. 3 Cantilever beam problem

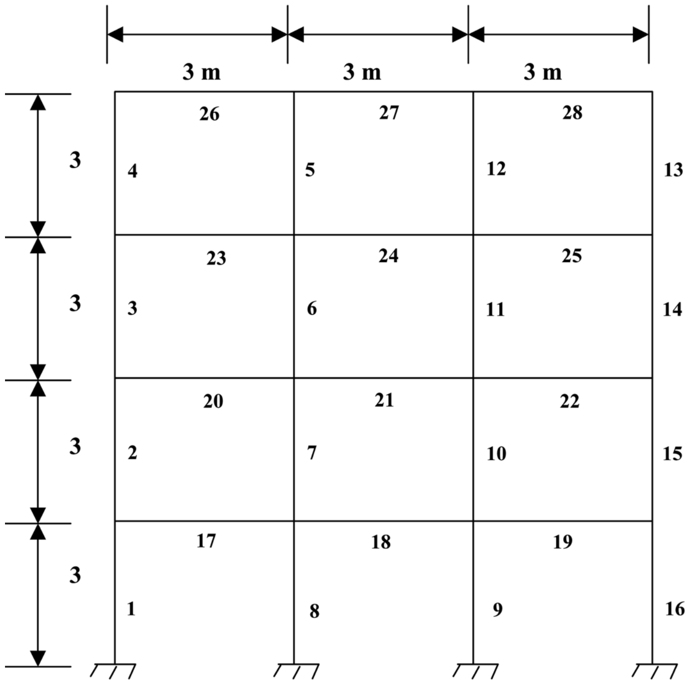
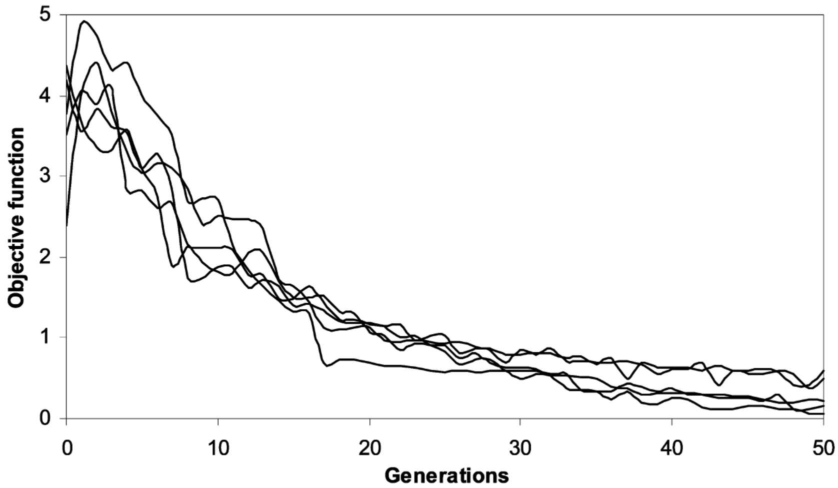


Fig. 4 A two dimensional frame

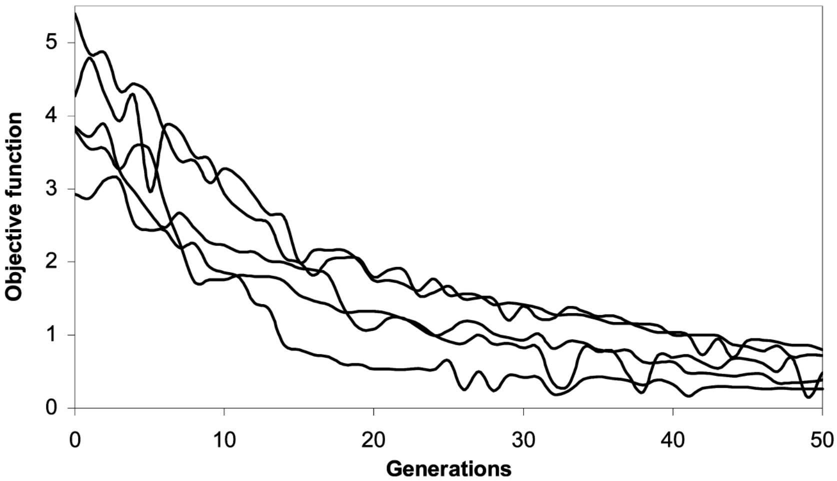
6.1.1 Case-1: Cantilever beam with single element damage

For the single damage case the population size is chosen on the basis of convergence criteria with random seed 0.125. Here two examples are considered. The first one is with the first three mode natural frequencies and the second one with first six mode natural frequencies for a comparison. The variation of the objective function with number of population size is shown in Fig. 5 and Fig. 6 for first three and first six natural frequencies respectively. The population size is chosen as 50 on the basis of the outputs plotted in Fig. 5 and Fig. 6 for the single damage case. The comparison of the output (Fig. 7) shows that the damage may be assessed more accurately while first six frequencies are used as input instead of first three frequencies.



(Damage in element 1)

Fig. 5 Single element damage case, using first three-frequencies

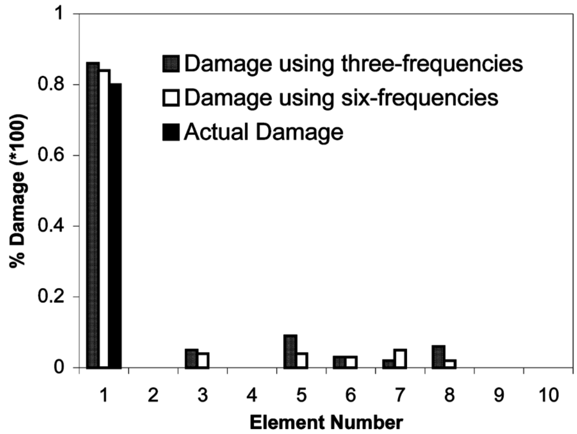


(Damage in element 1)

Fig. 6 Single element damage case, using first six-frequencies

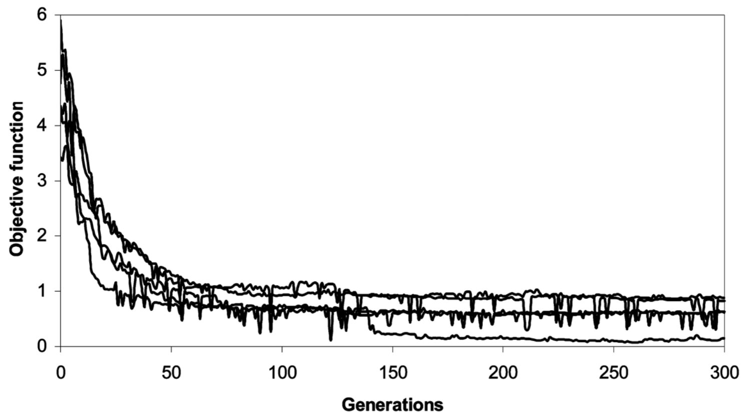
6.1.2 Case-2: Cantilever beam with two-element damage

In this case damage in two-elements i.e., element number 1 and 5 have been simulated using first three and first six natural frequencies. The variation of the objective function with number of population size is shown in Fig. 8 and Fig. 9 for first three and six natural frequencies respectively. The population size chosen is 300 on the basis of the results (Fig. 8 and Fig. 9) with random seed 0.15 .The comparison of the output is shown in Fig. 10, which shows that the accuracy of assessing damage in the structure increases with the increase of number of the measured frequencies.



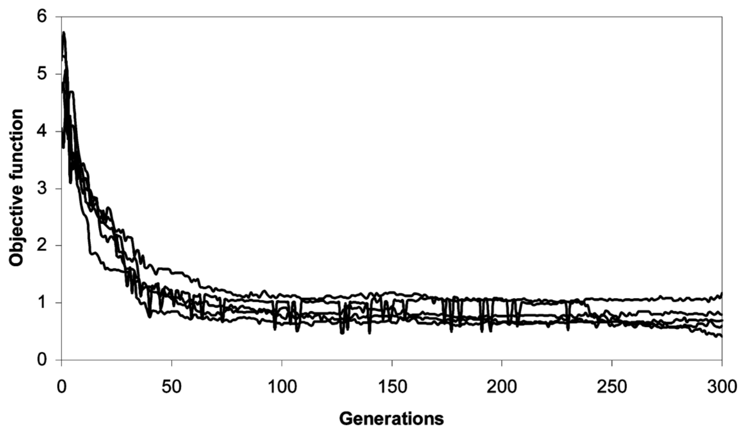
(Damage in element 1)

Fig. 7 Comparison of first three-frequencies and first six-frequencies



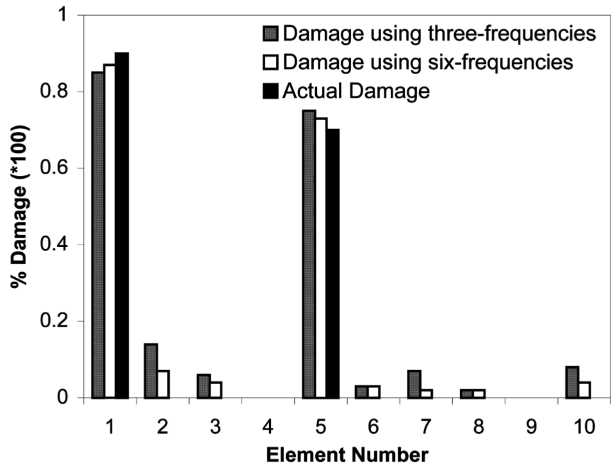
(Damage in element 1 and 5)

Fig. 8 Two-element damage case, using first three-frequencies



(Damage in element 1 and 5)

Fig. 9 Two-element damage case, using first six-frequencies

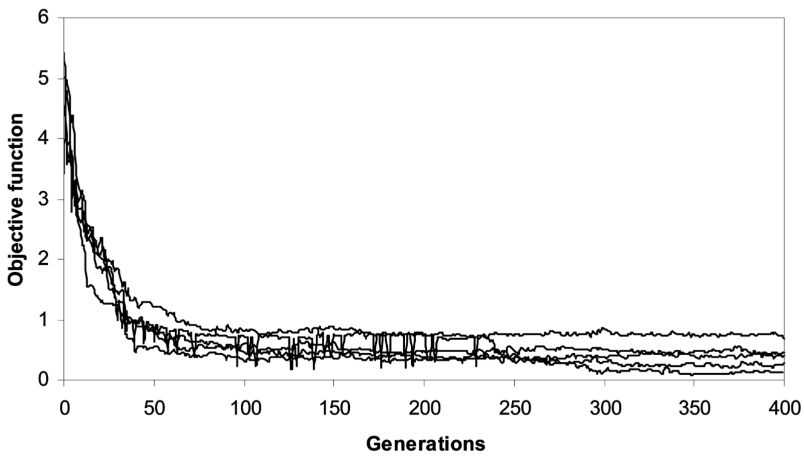


(Damage in element 1 and 5)

Fig. 10 Comparison of first three-frequencies and first six-frequencies

6.1.3 Case-3: Cantilever beam with three-element damage

Here damage in three-elements i.e., element numbers 1, 5 and 8 have been simulated, using the first three and first six mode natural frequencies. The variation of the objective function with number of population size is shown in Fig. 11 and Fig. 12 for first three and first six, natural frequencies respectively. The population size chosen is 400 on the basis of the results (Fig. 11 and Fig. 12) with random seed 0.15. The comparison of the output for three-frequencies and six-frequencies are shown in Fig. 13, which shows when six frequencies are used; it gives better result than three frequencies with an error less than 5 percent.



(Damage in element 1, 5 and 8)

Fig. 11 Three-element damage case, using first three-frequencies

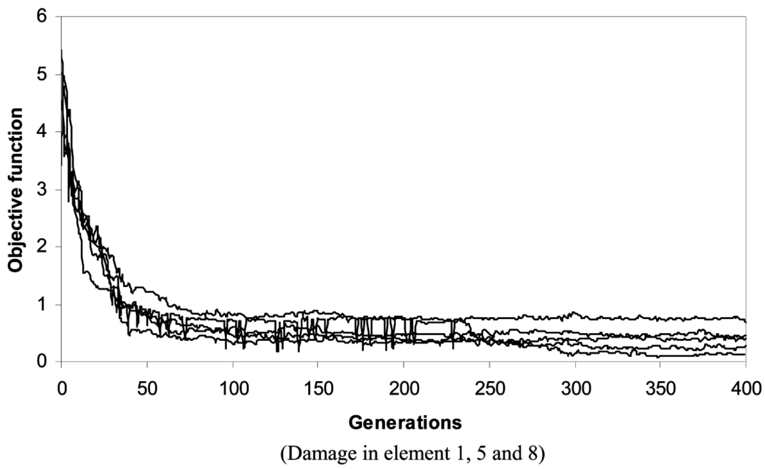


Fig. 12 Three-element damage case, using first six-frequencies

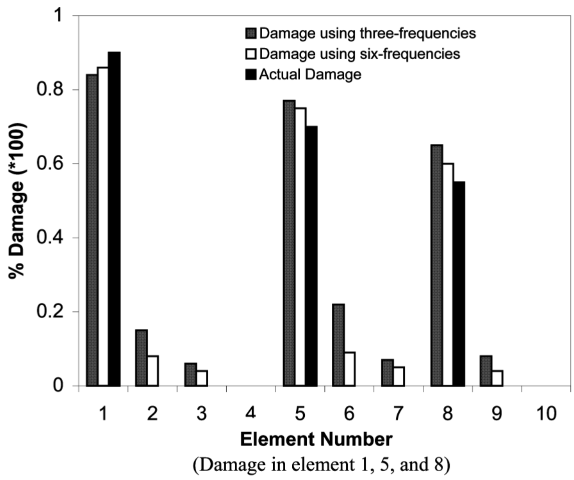


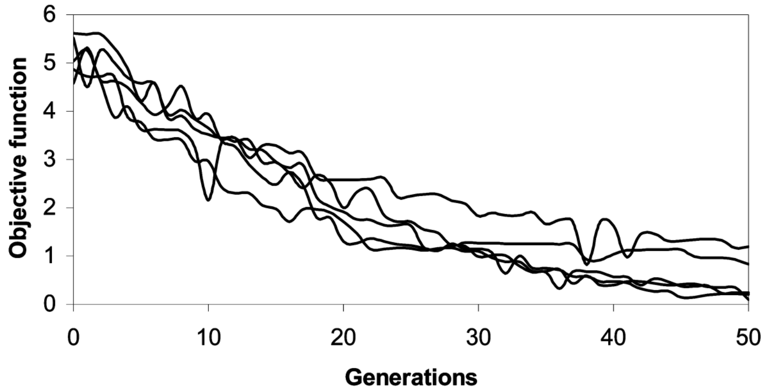
Fig. 13 Comparison of first three-frequencies and first six-frequencies

6.2 Example 2: Damage on a plane frame

A plane frame is considered in this case. The dimensions of the frame are shown in Fig. 4. The first three mode and six mode natural frequencies are calculated and used in the objective function to study the effectiveness of the proposed algorithm.

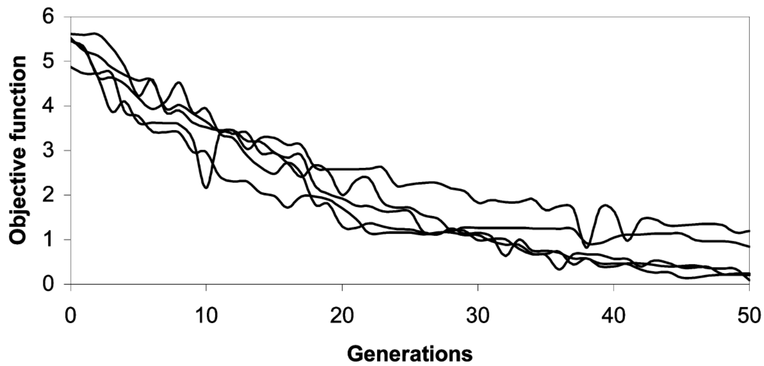
6.2.1 Case-1: Plane frame with single element damage

For the single element damage case, the population size is chosen on the basis of convergence criteria with random seed 0.125. Here two examples are considered. The first one is with the first three mode natural frequencies and the second one with first six mode natural frequencies for a comparison. The variation of the objective function with number of population size is shown in Fig. 14 and Fig. 15 for first three and first six natural frequencies respectively. The population size



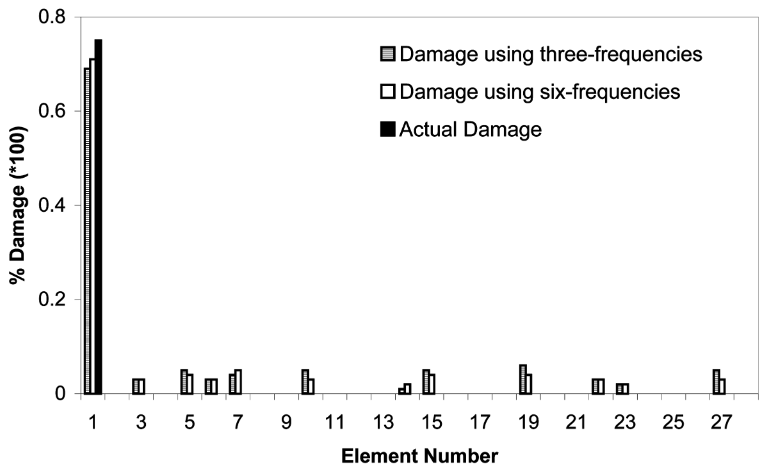
(Damage in element 1)

Fig. 14 Single element damage case, using first three-frequencies



(Damage in element 1)

Fig. 15 Single element damage case, using first six-frequencies



(Damage in element 1)

Fig. 16 Comparison of first three-frequencies and first six-frequencies is chosen as 50 on the basis of the outputs plotted in Fig. 14 and Fig. 15 for the single damage case. The comparison of the output (Fig. 16) shows that the damage may be assessed more accurately while first six frequencies are used as input instead of first three frequencies.

6.2.2 Case-2: Plane frame with two-element damage

In this case, damage in two-elements i.e., element number 1 and 8 have been simulated using first three and first six natural frequencies. The variation of the objective function with number of population size is shown in Fig. 17 and Fig. 18 for first three and six natural frequencies respectively. The population size chosen is 300 on the basis of the results (Fig. 17 and Fig. 18) with random seed 0.15. The comparison of the output is shown in Fig. 19, which shows that the accuracy of assessing damage in the structure increases with the increase of number of the measured frequencies.

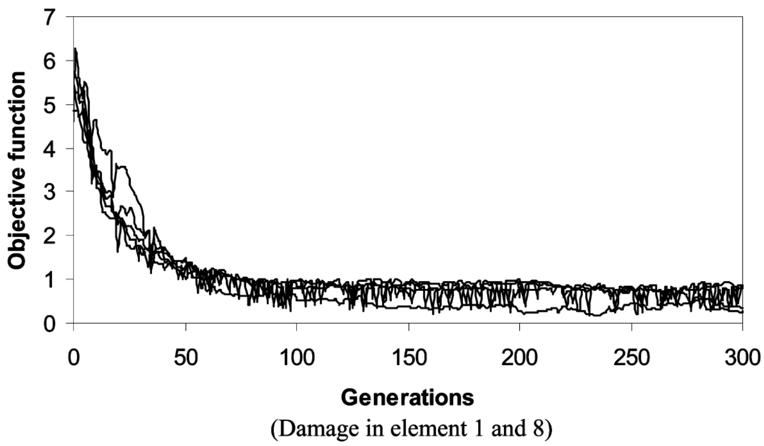


Fig. 17 Two-element damage case, using first three-frequencies

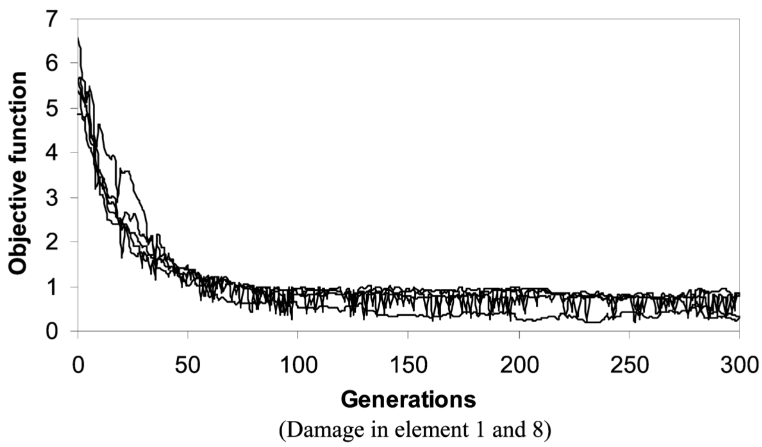
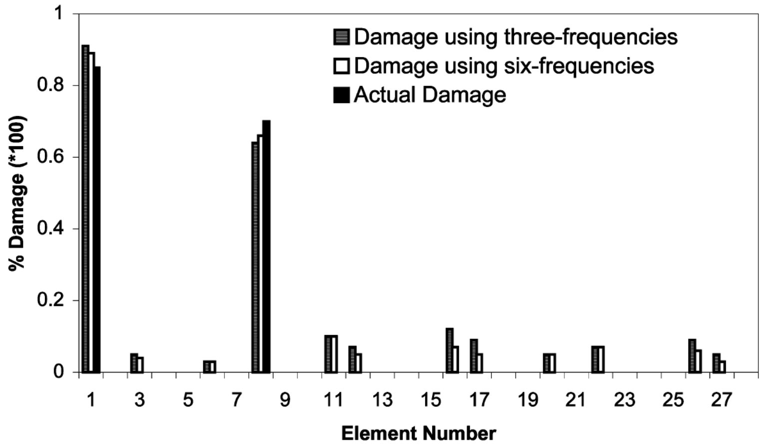


Fig. 18 Two-element damage case, using first six-frequencies

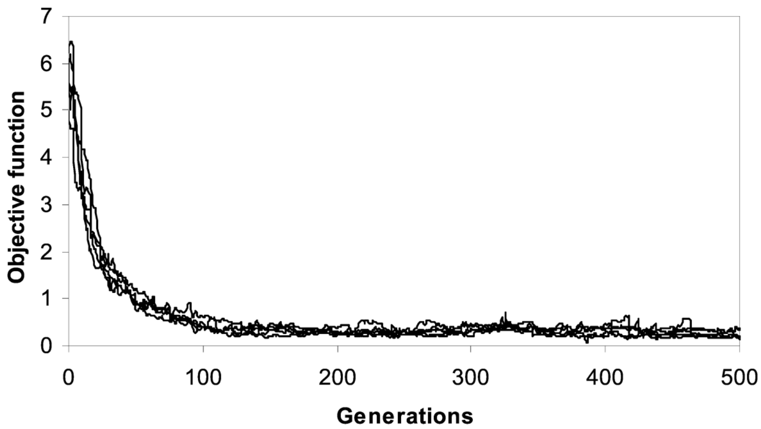


(Damage in element 1 and 8)

Fig. 19 Comparison of first three-frequencies and first six-frequencies

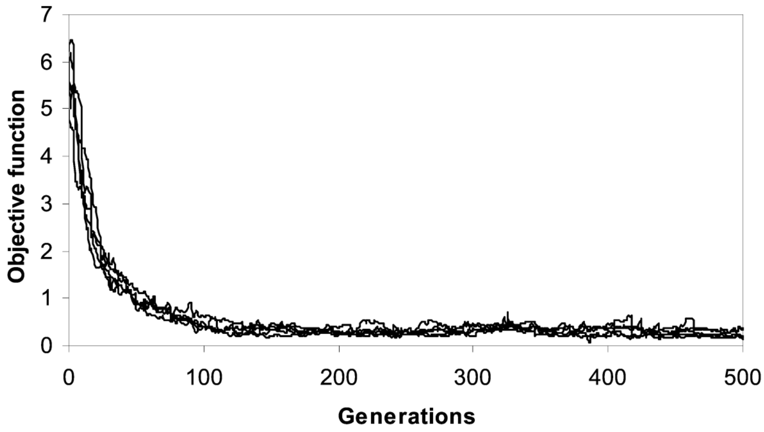
6.2.3 Case-3: Plane frame with three-element damage

For the three-element damage case, the population size chosen is 500 with random seed 0.14. In this case damage in three-elements i.e., element number 1, 8 and 10 have been simulated, using the first three mode and first six mode natural frequencies. The variation of the objective function with number of population size is shown in Fig. 20 and Fig. 21 for first three and first six, natural frequencies respectively. The comparison of the output for three-frequencies and six-frequencies are shown in Fig. 22, which shows when six frequencies are used; it gives better result than three frequencies with an error less than 5 percent.



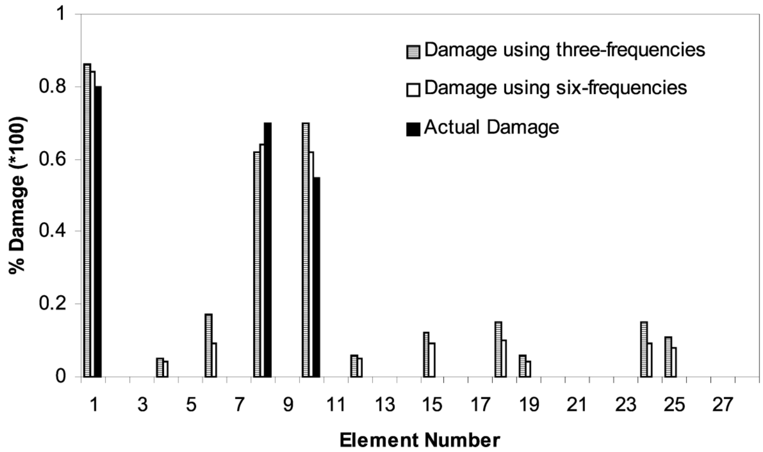
(Damage in element 1, 8 and 10)

Fig. 20 Three-element damage case, using first three-frequencies



(Damage in element 1, 8 and 10)

Fig. 21 Three-element damage case, using first six-frequencies



(Damage in element 1, 8 and 10)

Fig. 22 Comparison of first three-frequencies and first six-frequencies

6.3 Example 3: Validation of the proposed algorithm using test data

Measurements of first six natural frequencies before and after damage of a cantilever beam are reported by Yang *et al.* (1985). These data have been used by Hassiotis and Jeong (1995) to identify the damage with the Lagrange multiplier method. The experimental values of the change in the frequencies will be used here to test the algorithm presented in the foregoing sections. The subject of experiment was a cantilever beam 49.53 cm long, 2.54 cm wide and 0.635 cm thick as shown in Fig. 23(a). The beam was made of aluminium with Young's modulus of 7.1×10^7 kPa and mass density of 2210 kg/m3. The beam was damaged by a saw cut as shown in Fig. 23(b). The measured frequencies before and after damage are shown in Table 1 as reported by Yang *et al.* (1985).

The beam is modeled by 20 equal Euler-Bernoulli beam elements and first six natural frequencies are calculated by eigenvalue analysis and are listed in column 2 of Table 2. The damage is

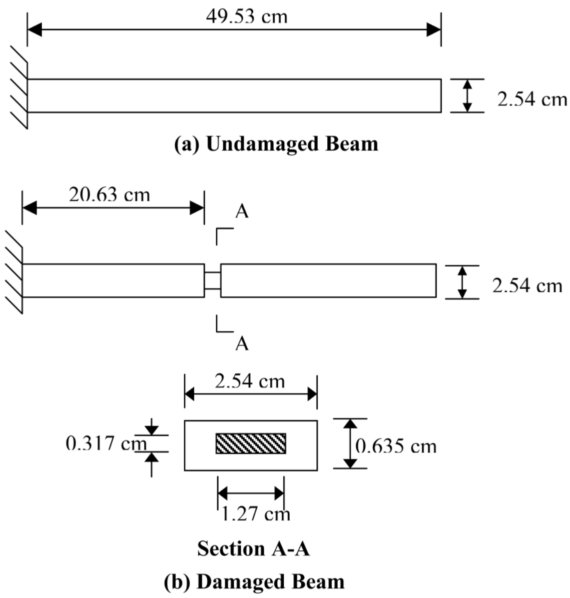


Fig. 23 Aluminum cantilever beam (Yang *et al.* 1985)

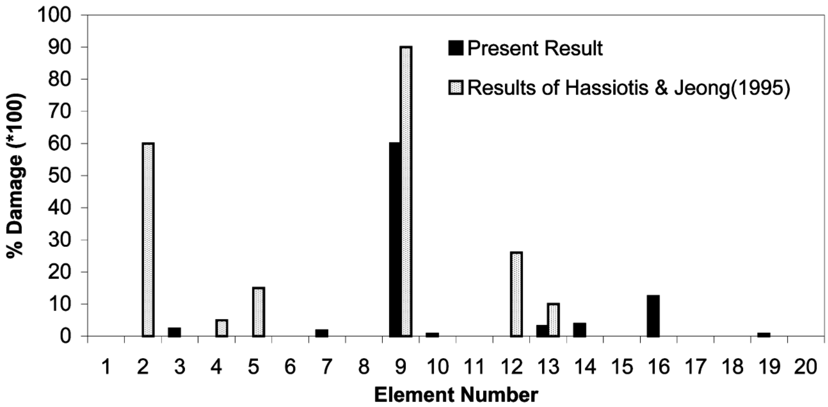
Table 1 Experimental frequencies of cantilever beam (Hz) (Yang *et al.* 1985)

Mode	Undamaged state	Damaged state	Change ratio (%)
1	19.53	19.00	–2.71
2	112.05	115.85	–5.08
3	339.26	332.36	–2.03
4	661.73	649.91	–2.24
5	1058.22	1037.46	–4.40
6	1594.59	1591.36	–0.77

introduced by reducing its stiffness in element number 9 in the FE model while calculating the eigenfrequencies in the damaged beam. The discrepancy found between the numerical and measured natural frequencies can be attributed to inherent uncertainties of the material and geometry, effects from the end support, or measurement error and noise. It can also be noted that the finite element discretization is too coarse to produce the accurate results as obtained by experiment in the undamaged beam. The FE refinement of the beam model has not been carried out to obtain the results closer to the measured one in this study. Instead, we have directly updated the FE model so that the frequency changes of damage and undamaged state match with the changes in frequencies obtained from experiment. It may be noted that the desired state of damage in column 4 of Table 2 is calculated directly using the same percentages of changes in frequencies as obtained in Table 1. With the application of GA, Eq. (1) is minimized and the updated frequencies are listed in column 5 of Table 2. It is observed that the changes are close to the frequency changes in the measurements. Fig. 24 shows the results obtained by the present method for the identification of the damage along with the results of Hassiotis and Jeong (1995) for a comparison. It is observed from the results that

Table 2 Frequencies of cantilever beam (Hz) from FE model

Mode	Initial state (Undamaged)	Reduction (%) (As in Table 1)	Desired state (Damaged)	Updated state using GA	Change ratio (%)
1	23.70	–2.71	23.06	23.22	–2.02532
2	148.55	–5.08	141.0	142.5	–4.0727
3	416.05	–2.03	407.6	407.9	–1.9589
4	815.04	–2.24	796.78	792.05	–2.82072
5	1347.8	–4.40	1288.56	1291.05	–4.21057
6	2027.4	–0.77	2011.76	2012.1	–0.75466



(Damage in element 9)

Fig. 24 Comparison of results on damage identification of a cantilever beam

the actual damage is detected successfully by the present method where as the method presented by Hassiotis and Jeong (1995) incorrectly detect damage in element 2 in addition to element 9. It is interesting to note that a small amount of false damages are also present using GA in element 16. This is may be due to the presence of noise in the measurements of frequencies and nonlinearity caused by the damage of element 9.

7. Conclusions

A simple but robust methodology is presented to determine the location and amount of damages in structures using genetic algorithms. A laboratory tested cantilever beam has been used to validate the proposed technique, which shows the accuracy and efficiency of the present algorithm. Two different kind of structures, i.e., plane stress and plane frame problem, are considered in the present study. The most significant advantages of this method over the traditional search methods used for inverse problems are avoiding local optima. Also, the number of calculations needed for damage detection is much less than those required for classical search algorithms. As a result, the requisite computational time becomes less. The outcomes are promising not only in case of single element damage, but also in multi-element damage. The results show that the accuracy increases with the increase in the number of measured natural frequencies. However, it is observed that the first three natural frequencies are sufficient enough to locate and estimate the amount of damage with satisfactory precision.

References

Au, F.T.K. (2003), "Structural damage detection based on a micro-genetic algorithm using incomplete and noisy modal test data", *J. Sound Vib.*, **259**, 1081-1094.

Barai, S.V. and Pandey, P.C. (1995), "Multilayer perceptron in damage detection of bridge structures", *Comput. Struct.*, **54**, 597-608.

Cerri, M.N. and Vestroni, F. (2000), "Detection of damage in beams subjected to diffused cracking", *J. Sound Vib.*, **234**(2), 259-276.

Chondros, T.G. and Dimarogonas, A.D. (1989), "Influence of cracks on the dynamic characteristics of structures", *J. Vibration, Acoustics, Stress and Reliability in Design*, **111**, 251-256.

Chondros, T.G., Dimarogonas, A.D. and Yao, J. (1998), "A continuous cracked beam vibration theory", *J. Sound Vib.*, **215**(1), 17-34.

Chondros, T.G. and Dimarogonas, A.D. (1998), "Vibration of a cracked cantilever beam", *J. Vibration, Acoustics, Stress and Reliability in Design*, **120**, 742-746.

Chou, J.H. and Ghaboussi, J. (2001), "Genetic algorithm in structural damage detection", *Comput. Struct.*, **79**, 1335-1353.

Elkordy, M.F., Chang, K.C. and Lee, G.C. (1993), "Neural network trained by analytically simulated damage states", *J. Computing in Civil Eng.*, ASCE, **120**, 251-265.

Feng, M.Q. and Bahng, E.Y. (1999), "Damage assessment of jacketed RC columns using vibration tests", *J. Struct. Eng.*, **125**, 265-271.

Frishwell, M.I., Penny, J.E.T. and Garvey, S.D. (1998), "A combined genetic and eigensensitivity algorithm for the location of damage in structures", *Comput. Struct.*, **69**, 547-556.

Gounaris, G., Papadopoulos, C. and Dimarogonas, A.D. (1996), "Crack identification in beams by coupled response measurements", *J. Comput. Struct.*, **58**(2), 299-305.

Hassiotis, S. and Jeong, G.D. (1995), "Identification of stiffness reductions using natural frequencies", *J. Eng. Mech.*, **121**(10), 1106-1113.

He, Y.Y., Guo, D. and Chu, F. (2001), "Using genetic algorithm and finite element methods to detect shaft crack for rotor-bearing system", *Mathematics and Computers in Simulation*, **57**, 95-108.

Krawczuk, M. (2002), "Application of spectral beam finite element with a crack and iterative search technique for damage detection", *Finite Elements in Analysis and Design*, **38**, 537-548.

Liu, G.R. and Chen, S.C. (2002), "A novel technique for inverse identification of distributed stiffness factor in structures", *J. Struct. Eng.*, **254**, 823-835.

Loland, O. and Dodds, C.J. (1976), "Experiencing in developing and operating integrity monitoring system in North Sea", *Proc. of the 8th Annual Offshore Technology, Conf. 2*, Paper No. 2551, 313-319.

Mares, C. and Surace, C. (1996), "An application of genetic algorithms to identify damage in elastic structures", *J. Sound Vib.*, **195**(2), 195-215.

Morassi, A. (2001), "Identification of a crack in a rod based on changes in a pair of natural frequencies", *J. Sound Vib.*, **242**(4), 577-596.

Nandwana, B.P. and Maiti, S.K. (1994), "Detection of the location and size of a crack in stepped cantilever beams based on measurements of natural frequencies", *J. Sound Vib.*, **203**(3), 435-446.

Narkis, Y. (1994), "Identification of crack location in vibrating simply supported beams", *J. Sound Vib.*, **172**(4), 549-558.

Nikolakopoulos, P., Katsareas, D. and Papadopoulos, C. (1997), "Crack identification in frame structures", *J. Comput. Struct.*, **64**(1), 389-406.

Ostachowicz, W.M. and Krawczuk, M. (1991), "Analysis of the effect of cracks on the natural frequencies of a cantilever beam", *J. Sound Vib.*, **150**(2), 191-201.

Pandey, A.K., Biswas, M. and Samman, M.M. (1991), "Damage detection from changes in curvature mode shapes", *J. Sound Vib.*, **145**(2), 321-332.

Pandey, A.K. and Biswas, M. (1994), "Damage detection in structures using changes in flexibility", *J. Sound Vib.*, **169**(1), 3-17.

Rumelhart, D.E., Hinton, G.E. and Williams, R.J. (1986), "Learning internal representations by error back-propagation", *Parallel Distributed Processing Exploration in the Microstructure of Cognition*, **1**, 318-362.

Ruotolo, R. and Surace, C. (1997), "Damage assessment of multiple cracked beams: Numerical results and experimental validation", *J. Sound Vib.*, **206**(4), 567-588.

Sanayei, M. and Onipede, O. (1991), "Damage assessment of structures using static test data", *AIAA J.*, **29**, 1174-1179.

Suh, M.W., Shim, M.B. and Kim, M.Y. (2000), "Crack identification using hybrid neuro-genetic technique", *J. Sound Vib.*, **238**(4), 617-635.

Szewczyk, Z.P. and Hajela, P. (1994), "Damage detection in structures based on feature sensitive neural networks", *J. Computing in Civil Eng.*, ASCE, **8**, 163-178.

Tsou, P. and Shen, M.H. (1994), "Structural damage detection and identification using neural networks", *AIAA J.*, **32**, 176-183.

Wahab, M.M.A. and Roeck, G.D. (1999), "Damage detection in bridges using modal curvatures: Application to a real damage scenario", *J. Sound Vib.*, **226**, 217-235.

Wu, X., Ghaboussi, J. and Garrett, J.H. (1992), "Use of neural networks in detection of structural damage", *Comput. Struct.*, **42**, 649-659.

Yang, J.C.S., Tsai, T., Pavlin, V., Chen, J. and Tsai, W.H. (1985), "Structural damage detection by the system identification technique", *Shock and Vibration Bulletin*, **55**, 57-66.