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Vibration based damage detection in a uniform strength beam using genetic algorithm

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Abstract Cantilever steel beams of uniform strength are having various industrial applications. In particular when it is used as leaf spring it undergoes very large deflection in comparison to beam of uniform cross section. The damage occurs in these beams mainly due to fatigue loading. Early detection of damage in such type of beams is very essential to avoid a major failure or accident. In this paper, firstly formulation of an objective function for the genetic search optimization procedure along with the residual force method are presented for the identification of macroscopic structural damage in an uniform strength beam. Two cases have been investigated here. In the first case the width is varied keeping the strength of beam uniform throughout and in the second case both width and depth are varied to represent a special case of uniform strength beam. The developed model require experimentally determined data as input and detect the location and extent of the damage in the beam. Here, experimental data are simulated numerically by using finite element models of structures with inclusion of random noise on the vibration characteristics. It has been shown that the damage may be identified for the said problems with a good accuracy.

Keywords Damage · Genetic algorithm (GA) · Residual force · Eigen value · Uniform strength beam

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1 Introduction

Following the introduction of advanced and costly materials in structural engineering applications, it becomes important for the development of non-destructive means for testing of structural integrity. A number of vibration based methods have been developed and applied to detect structural damage in the civil, mechanical and aerospace engineering communities [1, 2]. These methods are based on the fact that the vibration characteristics of structures (namely frequencies, mode shapes, and modal damping) are functions of the structural physical parameters such as mass, stiffness and damping. Structural damage usually causes a decrease in structural stiffness, which produces changes in the vibration characteristics of the structure. Abderrazek et al. [3] has used wavelet analysis method to detect defects in rolling bearing. Gawronski and Sawicki [4] employed modal norms to determine damage locations. The residual force concept has received wide attention for application to damage detection and assessment. Residual force provides an objective function to be minimized for achieving the dynamic balance. Another approach taken by Stubbs and Osegueda [5] was to utilize the frequency changes with the aid of sensitivity analysis of the modal parameters of the structure obtained both from analytical models and via experimental tests. Yang and Liu [6] have studied three different types of damage identification techniques. The first is the algebraic solution of the residual force equation, the second is the minimum rank elemental update (MERU) technique and the third is the natural frequency sensitivity method.

Identifying the structural damage with the measured vibration data is an inverse approach in mathematics. The usual damage detection methods minimise an objective function, which is defined in terms of the discrepancies between the vibration data identified by modal testing and those computed from the analytical model [7–9]. However, these conventional optimization methods are gradient based and usually lead to a local minimum only. A global optimization technique is needed to derive a more accurate and reliable solution. Among the non classical methods, genetic algorithm happens to be a powerful choice for solving non-trivial problems.

In the last two decades, since first introduced by Goldberg [10], genetic algorithm (GA) has been widely applied to various optimization problems. Many authors have recently taken up this optimization problem using neural networks [11–13], genetic algorithm [14, 15] and neural network with GA [16] by studying the variation of localized damage as a function of modal test data and machine learning. In [14] the authors have used GA for damage assessment for truss structure and uniform cantilever beam using roulette wheel selection method for reproduction purpose. Perera and Torres [15] have also used roulette wheel selection method in GA for damage identification of uniform simply supported beam. Fault classification has been done for cylindrical shells with autoassociative neural network along with GA in reference [16]. As compared with the traditional optimization and search algorithms, GA search from a population of points in the region of the whole solution space, rather than a single point, and can obtain the global optimum. Other advantage of using GA are that it is a self start method with no special requirement on the initial value of unknown parameters, other than defining a search range, and also it does not need information such as gradients or derivatives of the function to be minimised. Moreover, GA has the advantage of easy computer implementation. These properties make GA successful and powerful in the field of structural optimization [17].

All the investigations of damage identification mentioned above is done for structures with uniform thickness. Tapered structural members and uniform strength beams are very important from application point of view. It is found that a lot of work has been done on vibration analysis of beams and plates with variable thickness [18–20]. Similarly studies have been done on uniform strength beams for design and deflection calculation [21, 22]. But to the best of our knowledge method for damage identification in uniform strength beam is scarce. It is due to the fact that the inclusion of the slope function made the governing equation complex and thereby the damage detection also becomes complicated by traditional methods. Accordingly Genetic Algorithm (GA) has been established which may be used intelligently to identify and quantify the damage in a uniform strength beam. Rao et al. [23] and Ratnam and Rao [24] have used this procedure for uniform cantilever beam, truss structures and portal frames. Panigrahi et al. [25] addressed the problem of damage identification in a cantilever beam with uniform thickness only by changing the selection methods in GA. Here GA along with residual force vector method has been used for damage identification of a uniform strength beam with variation of depth along its length and another case with both width and depth varying.

In the present paper, first the concept of residual force vector is introduced to specify an objective function for an optimization procedure, which is then solved by using Genetic Algorithm. 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 minimum or null value is obtained when evaluated with true parameters of the structure. Here the parameters used are the damage factors which are nothing but the reduction in stiffness factor. GA is employed to determine the values of these parameters by following an iteration process. In this study a method known as steady-state selection is selected for reproduction purpose in GA which requires less number of iterations [26]. The main idea of the selection is that bigger part of the chromosome should survive to next generation. When the objective function is optimized, values of the parameters indicate the state of the structure. Two cases have been investigated in this study. In the first case, a uniform strength beam with inclusion of slope function in width has been discussed. The second case demonstrates this method with inclusion of slope functions for both the depth and width of the beam. For simulating the experimental measurement, the vibration characteristics viz. natural frequencies and the mode shapes were perturbed randomly. A computer program using MatLab is employed to find out the location and extent of the damage.

2 Formulation of objective function

This section describes the construction of objective function. The governing equation of motion of the dynamics of a multi degree freedom system is given by

$$[M]\{\ddot{X}(t)\} + [K]\{X(t)\} = F(t) \tag{1}$$

where $[M]$ and $[K]$ are $(n \times n)$ system mass and stiffness matrices and $X(t)$ and $F(t)$ are $(n \times 1)$ physical displacement and applied force vectors.

The jth eigen value equation for ambient vibration associated with (1) is

$$[K]\{\phi_j\} - \lambda_j[M]\{\phi_j\} = 0 \tag{2}$$

where λ_j and ϕ_j are the jth eigen value and corresponding eigen vector.

In the finite element model of the structure, the global stiffness can be represented as a sum of the expanded element stiffness matrices

$$[K] = \sum_{i=1}^{m} [k]_i \tag{3}$$

where k_i represents the expanded stiffness matrix of the ith element and m is the total number of elements.

When damage occurs in a structure, the stiffness matrix of the damaged structure $[K_d]$ can be expressed as a sum of element stiffness matrices multiplied by damage factors associated with each of the 'm' elements α_i $(i = 1, 2, \dots, m)$, resulting from the damage.

Then, stiffness matrix of damaged structure may be given by

$$[K_d] = \sum_{i=1}^{m} \alpha_i.[k]_i \tag{4}$$

where

$$\alpha_i = [0, 1] \quad \text{and} \quad m = \text{Number of elements.}$$

The values of the parameters fall in the range 0 to 1. The value $\alpha_i = 1$ indicates that the element is undamaged and $\alpha_i = 0$ or less than 1 implies completely or partially damaged element respectively.

If it is assumed that the experimental natural frequencies and mode shapes of the damaged structure continue to satisfy the eigen value equation (2), the jth mode of the damaged structure can be written as

$$[K_d]\{\phi_{jd}\} - \lambda_{jd}[M]\{\phi_{jd}\} = 0 \tag{5}$$

where λ_{jd} is the experimentally determined eigen value corresponding to the jth mode shape of the damaged structure. Furthermore, the stiffness matrix is directly affected by the damage and the mass matrix M is assumed to be unaltered.

By substituting on (4) in (5), an expression for residual force vector for jth mode in terms of α_i can be written approximately as:

$$R_j = -\lambda_{jd}[M]\{\phi_{jd}\} + \sum_{i=1}^{m} \alpha_i.[k]_i\{\phi_{jd}\}, \tag{6}$$

R_j will be zero, only if a correct set of α_i are introduced under available damaged modal information λ_{jd} and ϕ_{jd} for a particular mode j.

From (6), it is found that the residual force vector is a $(n \times n)$ matrix where n is number of modes. If $[K_d]$ and $[M]$ are real symmetric matrices, it can be shown that the diagonal terms of matrix $[R]$ are zero, when a correct set of λ_d and ϕ_d are introduced.

Hence the function of damage factors chosen in the present situation is as follows:

$$f(\alpha_1, \alpha_2, \dots \alpha_m) = \sqrt{R_{11}^2 + R_{22}^2 + \dots + R_{nn}^2} \tag{7}$$

where m is the number of elements and n is the number of degrees of freedom.

Here our problem is to find out the minimum residual forces. Then the objective function (fitness function) V in the present task is an inverse function defined as follows;

$$V = \frac{C_1}{\{C_2 + f(\alpha_{1,}\alpha_{2,\dots}\alpha_m)\}} \tag{8}$$

where C_1 and C_2 are constants.

The genetic search procedure requires a proper selection of crossover and mutation operators.

After some trials, the GA was set up with population size as 20, crossover probability as 0.55 and mutation probability as 0.01. The procedure for damage identification of the present problem is illustrated by flow chart in Fig. 1 which is repeated until a new generation ceases to improve the objective function.

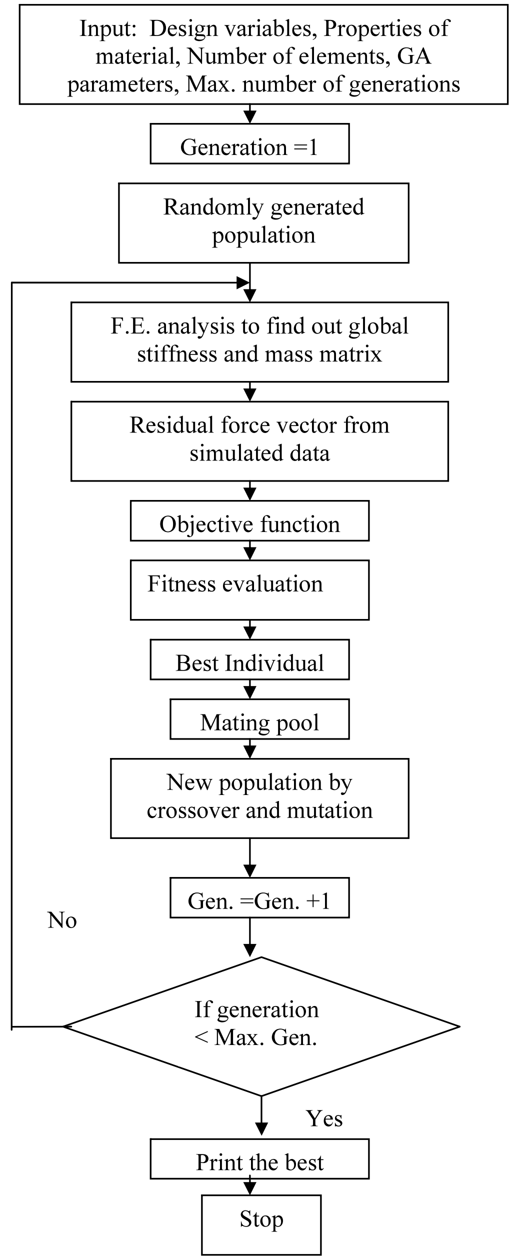

Fig. 1 Flow chart for identification of structural damage

3 Uniform strength beam

Beam having uniform strength along its length is known as uniform strength beam. Design of this type of beam is based upon linear classical theory which is explained below.

The maximum stress and the curvature remain constant along the beam of the uniform strength. So, the section modulus and moment of inertia of such beam increases as x increases in the same proportion as the bending moment, and so one can write

$$\frac{M}{Z} = \frac{6PL}{b_0 d_0^2} = \frac{6P(L-x)}{bd^2} \tag{9}$$

where $M =$ bending moment, $Z =$ section modulus, $P =$ point load at the free end, $x =$ distance from the fixed end, $L =$ total length of the beam, b_0 and $b =$ width at fixed end and at distance x from fixed end, d_0 and $d =$ depth at fixed end and at distance x from fixed end.

4 Illustrative examples for uniform strength beam

A uniform strength beam is considered for the damage detection and extent of the damage using residual force vector method along with genetic algorithm. The beam is simulated numerically with a finite element model taking eight elements. Each element is having both translation and rotational degrees of freedom at each nodal point to give a total of eighteen degrees of freedom (dof). Because the fixed point degrees of freedom has zero rotational and translation movements, the total degrees of freedom here turns out to be sixteen. The properties of the beam chosen are as follows: modulus of elasticity, $E = 70.3$ GPa; density, $\rho = 2685$ kg/m^3 and the total length of the beam, $L = 0.8$ m and length of each element $l_e = 0.1$ m.

In this section, two cases of a uniform strength beam are considered. In the first case, an uniform strength beam with variation in width and constant depth is considered. A cantilever beam with variation both in width and depth has been undertaken as special case of uniform strength beam in the second case.

4.1 Case I—uniform strength beam with variation in width

Here, a triangular plate is considered as shown in Fig. 2. The depth 'd' remains constant along the length. But, the width 'b' varies from zero to b_0. In case of a real leaf spring, this triangular plate is cut into strips of uniform width and placed one below the other. The beam that is made by piling separate leaves is just strong as the beam with leaves beside each other as in triangular plate. For the case of a leaf spring, the analysis is carried out for a triangular plate with uniform depth and slope parameter as below.

From (9), it may be found that the width,

$$b = \frac{b_0(L-x)}{L}, \quad \text{so the slope,} \quad r = \frac{b_0}{2.L}. \tag{10}$$

Then area and moment of inertia are given respectively as follows

area, $\quad A_e = 2r(L-x)d$

and the *moment* of inertia, $I = \frac{r(L-x)d^3}{6}$.

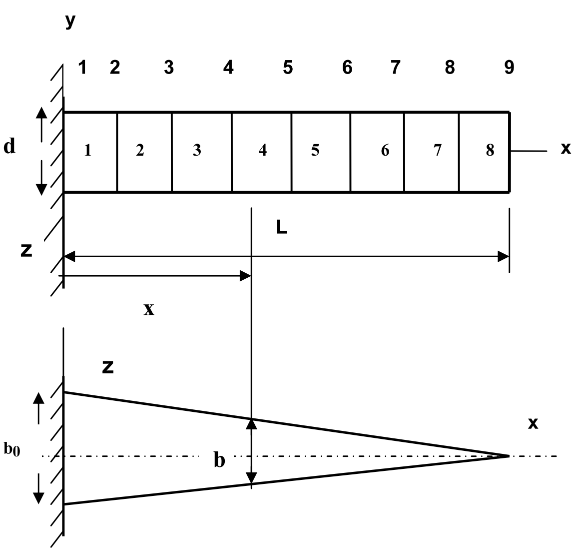

Fig. 2 Shape of uniform strength beam with variation in width

Properties of the beam are as follows: width at the fixed end, $b_0 = 0.08$ m; the height, $d = 0.01$ m, and other parameters are same as above for uniform strength beam.

As mentioned above, the beam is divided into eight number of elements. Figure 3 shows the second element of the beam. Q_3 and Q_5 are the transverse displacement and Q_4 and Q_6 are the rotational vectors. There are a total of four degrees of freedoms in the element. For the element as shown, has a length $l_e = 0.1$ m and other parameters remain same as of the full beam.

Accordingly, the element mass matrix for this element is

$$m^e = \frac{\rho A_e l_e}{420}\begin{bmatrix} 156 & 22l_e & 54 & -13l_e \\ & 4l_e^2 & 13l_e & -3l_e^2 \\ & & 156 & -22l_e \\ & & & 4l_e^2 \end{bmatrix} \tag{11}$$

and the element stiffness matrix is given by

$$k^e = \frac{EI}{l_e^3}\begin{bmatrix} 12 & 6l_e & -12 & 6l_e \\ & 4l_e^2 & -6l_e & 2l_e^2 \\ & & 12 & -6l_e \\ & & & 4l_e^2 \end{bmatrix}. \tag{12}$$

Substituting the values of A_e and I, in (11) and (12), the element mass and stiffness matrices m^e and k^e will both become the functions of the slope parameters. By putting the appropriate value of the slope parameter, the values of m^e and k^e may be obtained. Here A_e and I of an element has been assumed same as A_e and I values at the middle point of that element i.e. for the second element putting $x = (L/8) + (L/16)$, A_e and I may be obtained for the middle point of the second element which may approximately represents the value for the second element.

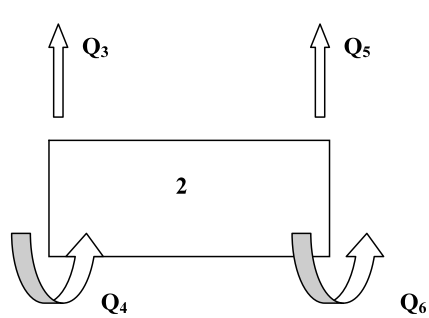

Fig. 3 One element force diagram

Four different problems for the present case are considered as (a) beam is in a state of undamaged, (b) the beam having element 3 and 5 damaged partially to an extent of 40% and 30% respectively (c) the beam having element 2, 5 and 8 damaged partially to an extent of 20%, 45% and 30% respectively and (d) only the element number 6 of the beam is having 35% damage. Next, each problem is investigated with inclusion of noise in natural frequency and mode shape. First the damage identification is considered with no noise in vibration characteristics. Next, random noise of 2% in natural frequency and 3% in mode shapes are considered. From (11) and (12), the global matrices for mass and stiffness were derived for undamaged

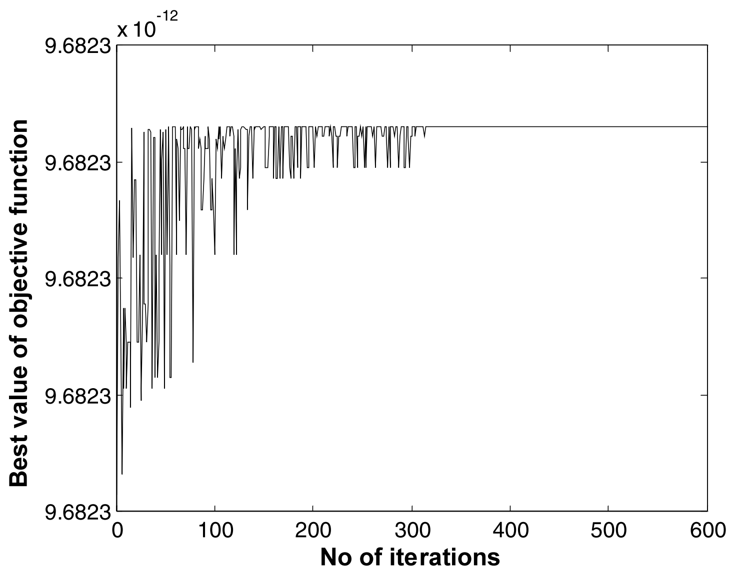

Fig. 4 Graph for maximum value of objective function verses number of iterations for problem (a) of undamaged uniform strength beam without noise

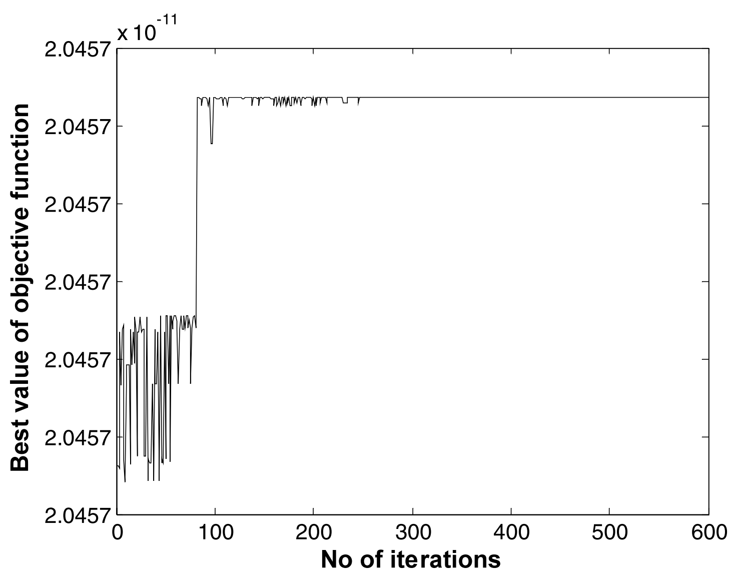

Fig. 5 Graph for maximum value of objective function verses number of iterations for problem (b) of damaged uniform strength beam without noise

beam. Then by reducing the stiffness of the third element by 40% and fifth element by 30%, the global stiffness and mass matrices were derived for the damaged structure for problem (b). Similarly in problems (c) and (d), global stiffness and mass matrices were written. Now Finite element analysis is performed to solve the eigen value problem of these four problems and are presented in Table 1. It is found as usual that the frequencies in damaged structure in all modes are lower than the undamaged one.

The above modal data are employed as input to the developed model for finding out the values of damage factors from which the location and extent of damage may be identified. Figures 4, 5, 6 and 7 show the best

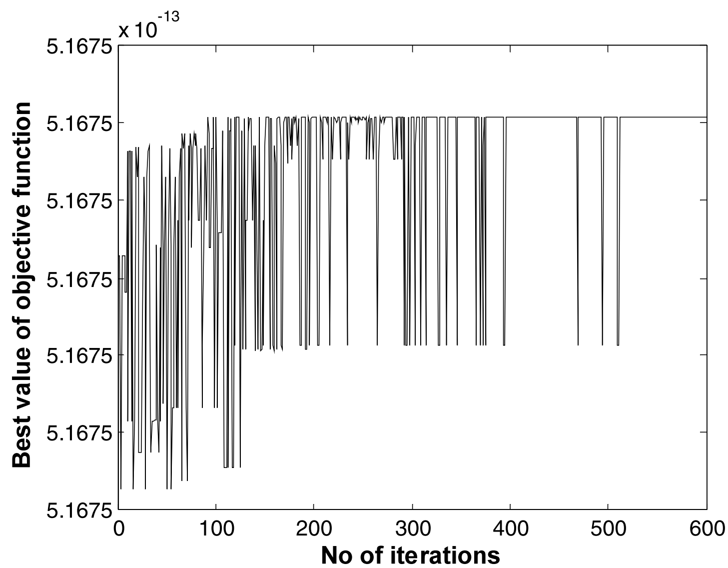

Fig. 6 Graph for maximum value of objective function verses number of iterations for problem (c) of damaged uniform strength beam without noise

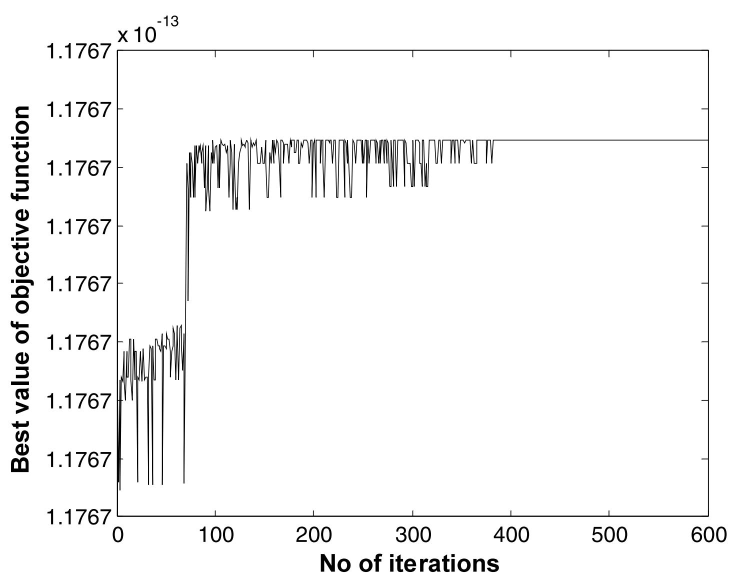

Fig. 7 Graph for maximum value of objective function verses number of iterations for problem (d) of damaged uniform strength beam without noise

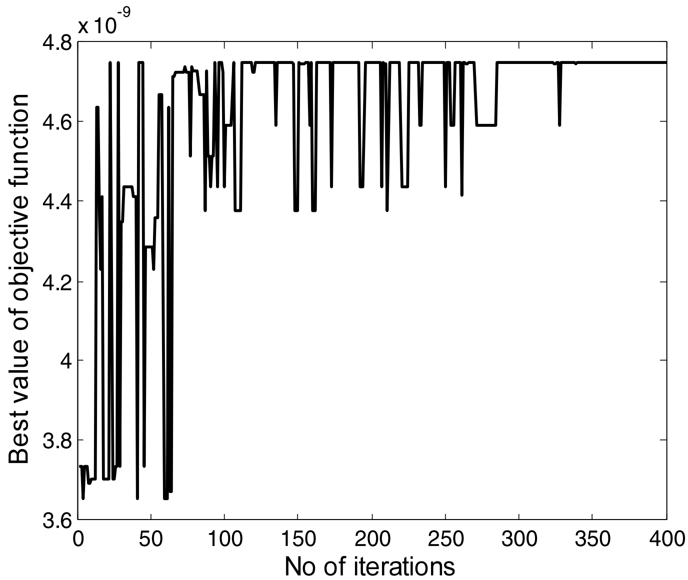

Fig. 8 Graph for maximum value of objective function verses number of iterations for problem (b) of undamaged uniform strength beam with noise

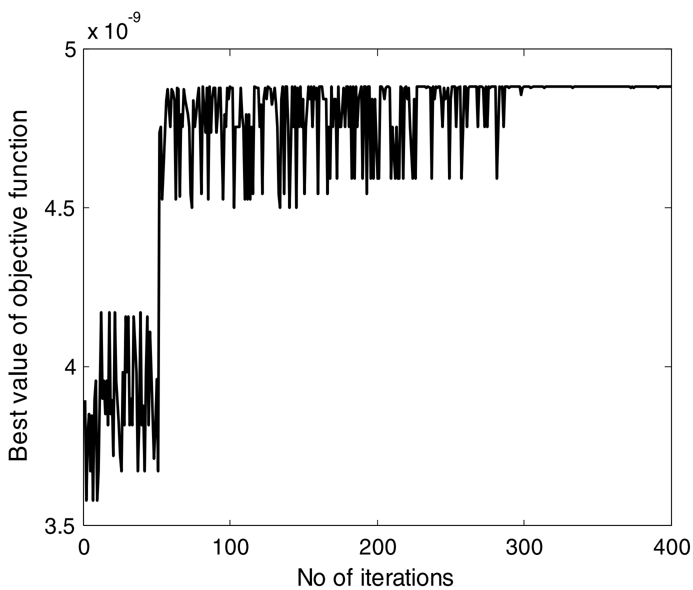

Fig. 9 Graph for maximum value of objective function verses number of iterations for problem (d) of damaged uniform strength beam with noise

value of the objective function verses the number of iterations for problems (a), (b), (c) and (d) respectively without introducing noise and Figs. 8 and 9 depict the same with noise for problems (b) and (d). As discussed previously, it may be seen from Figs. 4 to 9 that the best value is achieved at 21, 87, 100, 75, 25 and 50 iteration numbers respectively. Again it is worth mentioning that there is no further development of the best value after these iterations. However, computations are carried out up to 600 number of iterations and the same are given in all the figures.

Table 1 First six natural frequencies for cases (a), (b), (c) and (d) (taking variation in width only)

Cases	Frequency parameter					
	First	Second	Third	Fourth	Fifth	Sixth
Case (a)	936.9	148519.6	1670328.7	7041764.3	20120420.8	46308310.5
Case (b)	896.7	123263.5	1443891.8	6629100.5	17534793.5	41128920.9
Case (c)	893.7	125463.7	1460904.5	6253038.7	17402017.8	41002897.3
Case(d)	935.85	140378.3	1455461.3	6703269.9	19392246.2	43210586.5

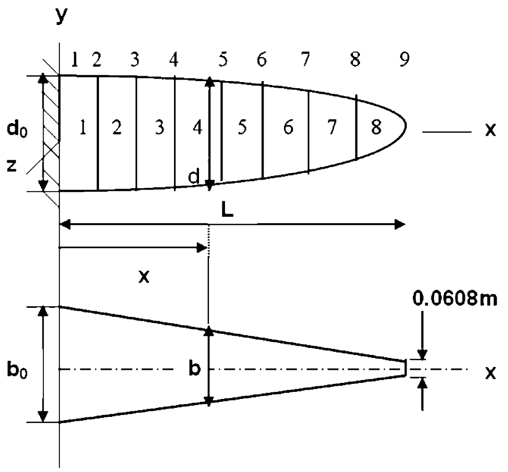

Fig. 10 Shape of the beam of uniform strength with variation in both width and depth

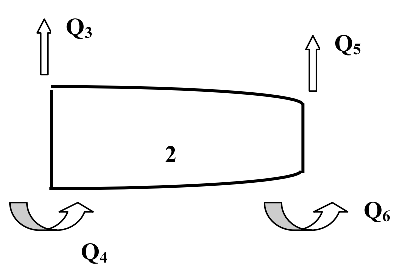

Fig. 11 One element force diagram

From Tables 2 and 3, it reveal that in both the damaged and undamaged situations with and without noise, the theoretical and GA identification results are in good agreement for the present problem.

4.2 Case II—uniform strength beam with a variation both in width and depth

Here a uniform strength beam with variation both in width and depth have been addressed as shown in Fig. 10. This is a special case of uniform strength beam. The properties of the beam are as follows: width and depth at the fixed end are $b_0 = 0.08$ m; $d_0 = 0.015$ m.

From (9) the relation between width and depth at a distance x from fixed end may now be written as

$$\frac{b}{b_0} = \frac{(L-x)}{L}\left(\frac{d_0}{d}\right)^2. \tag{13}$$

We define 'b' here as, $b = b_0(1 - sx)$ where s is a parameter controlling the width. Now from (13), 'd' is written as,

$$d = \sqrt{\frac{(L-x)}{L(1-s.x)}} X d_0. \tag{14}$$

It is to be noted that the (14) is satisfied only under the condition $s < (1/x)$.

Putting the values of b and d, the area A_e and moment of inertia I at distance x may again be found out. A number of studies have been done by putting different values of s. In this investigation, only a single value of $s = 0.3$ has been taken for illustration purpose.

Substituting the values of A_e and I, in (11) and (12), the element mass and stiffness matrices m^e and k^e will both become the functions of the slope parameter. By substituting the appropriate value of the slope parameter, the values of m^e and k^e may be obtained.

Here also, four different problems similar to case I with $r = 0.3$ are considered as (a) beam is in a state of undamaged, (b) the beam having element 3 and 5 damaged partially to an extent of 40% and 30% respectively (c) the beam having element 2, 5 and 8 are damaged partially to an extent of 20%, 45% and 30% respectively and (d) the beam element number 6 of the beam is having 35% damage. Each problem is considered with inclusion of noise in the vibration characteristics viz. natural frequency and mode shape. Computations are carried out first without noise in natural

Table 2 Results of identified damage factors (α_i) of uniform strength beam with variation in width only (no noise in natural frequencies and mode shapes)

Element No.	Case (a)		Case (b)		Case (c)		Case (d)	
	Theo.	Identified	Theo.	Identified	Theo.	Identified	Theo.	Identified
1	1.0	0.95	1.0	0.93	1.0	0.97	1.0	0.94
2	1.0	0.96	1.0	0.97	0.8	0.76	1.0	0.96
3	1.0	0.94	0.6	0.57	1.0	0.93	1.0	0.93
4	1.0	0.97	1.0	0.98	1.0	0.96	1.0	0.97
5	1.0	0.96	0.7	0.66	0.55	0.51	1.0	0.95
6	1.0	0.94	1.0	0.93	1.0	0.98	0.65	0.62
7	1.0	0.97	1.0	0.97	1.0	0.93	1.0	0.98
8	1.0	0.95	1.0	0.94	0.7	0.67	1.0	0.95

Table 3 Results of identified damage factors (α_i) of uniform strength beam with variation in width only (with 2% noise in natural frequencies and 3% in mode shapes)

Element No.	Case (a)		Case (b)		Case (c)		Case (d)	
	Theo.	Identified	Theo.	Identified	Theo.	Identified	Theo.	Identified
1	1.0	0.92	1.0	0.94	1.0	0.96	1.0	0.95
2	1.0	0.93	1.0	0.93	0.8	0.74	1.0	0.93
3	1.0	0.95	0.6	0.53	1.0	0.96	1.0	0.94
4	1.0	0.92	1.0	0.95	1.0	0.93	1.0	0.96
5	1.0	0.92	0.7	0.64	0.55	0.52	1.0	0.94
6	1.0	0.95	1.0	0.94	1.0	0.96	0.65	0.60
7	1.0	0.96	1.0	0.97	1.0	0.94	1.0	0.95
8	1.0	0.93	1.0	0.94	0.7	0.65	1.0	0.96

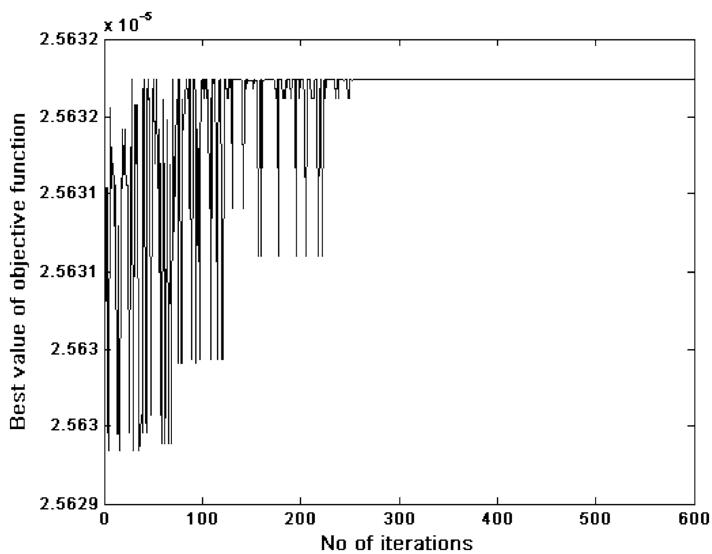

Fig. 12 Graph for maximum value of objective function verses number of iterations for problem (b) of damaged uniform strength beam without noise

frequency and in mode shape. Again random noise of 2% for natural frequency and 3% in mode shapes have been considered in the analysis as in previous case. From (11) and (12), the global matrices for mass and stiffness were derived for undamaged beam. Then by reducing the stiffness as in the previous section, the global stiffness and mass matrices were written for all cases. Now finite element analysis is performed to solve the eigen value problem of these four situations. Here also, it is found as usual that the frequencies in damaged structure in all modes are lower than the undamaged one.

The above modal data are employed as input to the present model for finding out the values of damage factors from which the location and extent of damage can be identified. Figures 12 and 13 show the best

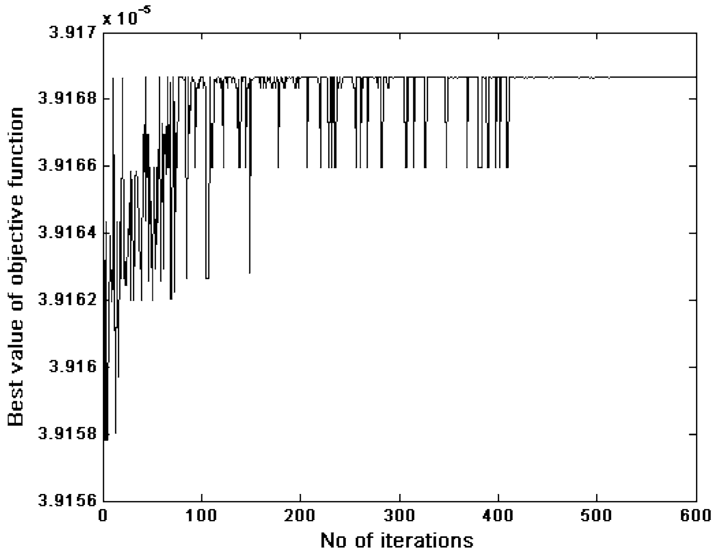

Fig. 13 Graph for maximum value of objective function verses number of iterations for problem (d) of damaged uniform strength beam without noise

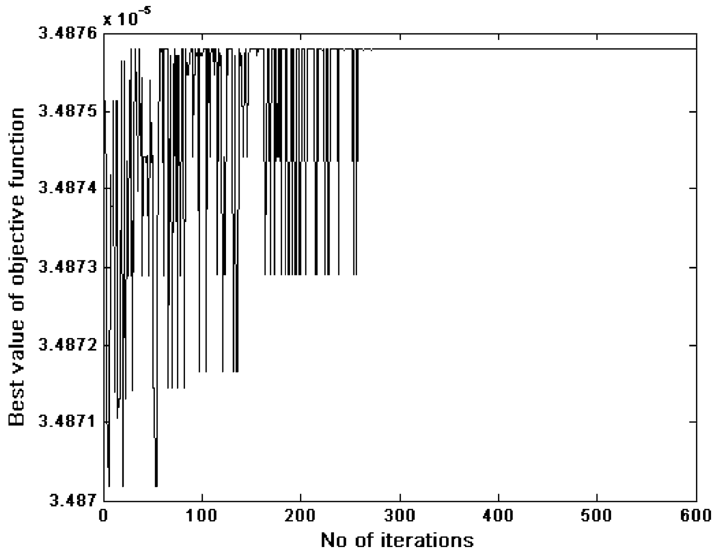

Fig. 14 Graph for maximum value of objective function verses number of iterations for problem (b) of damaged uniform strength beam with noise

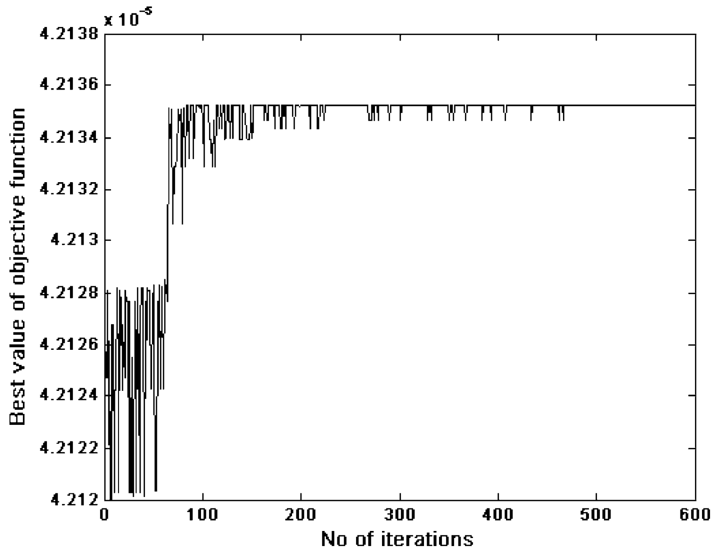

Fig. 15 Graph for maximum value of objective function verses number of iterations for problem (d) of damaged uniform strength beam with noise

Table 4 Results of identified damage factors (α_i) of uniform strength beam with variation both in width and depth (no noise in natural frequencies and mode shapes)

Element No.	Case (a)		Case (b)		Case (c)		Case (d)	
	Theo.	Identified	Theo.	Identified	Theo.	Identified	Theo.	Identified
1	1.0	0.96	1.0	0.95	1.0	0.98	1.0	0.93
2	1.0	0.93	1.0	0.95	0.8	0.75	1.0	0.97
3	1.0	0.96	0.6	0.56	1.0	0.95	1.0	0.95
4	1.0	0.94	1.0	0.96	1.0	0.97	1.0	0.95
5	1.0	0.97	0.7	0.67	0.55	0.53	1.0	0.93
6	1.0	0.93	1.0	0.98	1.0	0.97	0.65	0.63
7	1.0	0.93	1.0	0.94	1.0	0.95	1.0	0.96
8	1.0	0.97	1.0	0.95	0.7	0.66	1.0	0.97

value of the objective function verses the number of iterations without noise for problems (b) and (d) respectively. Figures 14 and 15 depict the best value of the objective function verses the number of iterations with noise for problems (b) and (d) respectively. It may again be seen from Figs. 12 to 15 that the best value is achieved at 26, 10, 27 and 56 iteration numbers respectively. It is to be noted here also that there is no further development of the best value after these iterations.

From Tables 4 and 5, it reveal that in both the damaged and undamaged situations with and without noise the theoretical and GA identification results are in good agreement.

5 Conclusion

Procedure has been presented for the simultaneous location and quantification of the damage in uniform strength beam with first case on variation of depth along its length and second case on both width and depth varying. Genetic algorithms with steady-state selection for reproduction purpose have been employed for which the optimization function has been formulated in term of modified residual force vectors. The damage factors identified for the said beam problems by using GA for optimization purpose show excellent agreement with that of the chosen values of the parameters for simulated experimental data of dam-

Table 5 Results of identified damage factors (α_i) of uniform strength beam with variation both in width and depth (with 2% noise in natural frequencies and 3% in mode shapes)

Element No.	Case (a)		Case (b)		Case (c)		Case (d)	
	Theo.	Identified	Theo.	Identified	Theo.	Identified	Theo.	Identified
1	1.0	0.94	1.0	0.96	1.0	0.95	1.0	0.94
2	1.0	0.95	1.0	0.94	0.8	0.73	1.0	0.96
3	1.0	0.94	0.6	0.54	1.0	0.97	1.0	0.96
4	1.0	0.93	1.0	0.98	1.0	0.93	1.0	0.94
5	1.0	0.96	0.7	0.65	0.55	0.50	1.0	0.94
6	1.0	0.94	1.0	0.95	1.0	0.95	0.65	0.61
7	1.0	0.95	1.0	0.95	1.0	0.96	1.0	0.95
8	1.0	0.96	1.0	0.92	0.7	0.64	1.0	0.95

aged structures. This shows the powerfulness and efficacy of the model for identifying the damage of a uniform strength beam.

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