DGKS

DRUŠTVO GRAĐEVINSKIH KONSTRUKTERA SRBIJE

14. KONGRES

NOVI SAD
24-26. SEPTEMBAR

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U SARADNJI SA:

GRAĐEVINSKIM FAKULTETOM UNIVERZITETA U BEOGRADU

MINISTARSTVOM PROSVETE, NAUKE I TEHNOLOŠKOG RAZVOJA REPUBLIKE SRBIJE

INŽENJERSKOM KOMOROM SRBIJE

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DGKS **DRUŠTVO GRAĐEVINSKIH KONSTRUKTERA SRBIJE**

14. KONGRES **NOVI SAD 24-26. SEPTEMBAR** **2014.**

Saad Al-Wazni[1], Ahmed Alalikhan [2], Zoran Mišković[3], Ratko Salatić[4]

NUMERIČKI EKSPERIMENT DETEKCIJE OŠTEĆENJA PRIMENOM *SIMULATED ANNEALING* METODE

Rezime:

U radu se prikazuje procedura detekcije oštećenja modela čelične slobodno oslonjene grede. *Simulated Annealing* metoda optimizacije primenjena je za određivanje elementa sa oštećenjem kao i nivoa oštećenja. Metoda detekcije oštećenja bazira se na promeni dinamičkih karakteristika konstrukcije uključivanjem karakteristika prvih pet modova za formirnje funkcije cilja. Procedura je sprovedena programa za proračun konstrukcija primenom konačnih elemenata ANSYS, sa glavnom optimizacionom rutinom razvijenom u *MATLAB* softveru. Dobijeni rezultati ukazuju na robusnost predloženog metoda.

Ključne reči: detekcija oštećenja, dinamičke karakteristike, simulirano kaljenje

NUMERICAL TEST OF DAMAGE DETECTION USING *SIMULATED ANNEALING* METHOD

Abstract:

In the paper, procedure of structural damage detection with application to a simple supported steel beam model, is presented. *Simulated Annealing* optimization technique is used to determine damaged element by numerical simulation of different scenarios of damage location and severity. The method of damage detection based on changing of dynamics properties of first five natural modes by formulating new objective function. The procedure is done using ANSYS Finite Element Analysis Software, with main optimization routine developed in *MATLAB* software. The results indicated that the performance of proposed procedure is robust.

Key words: Damage detection, Dynamic properties, Simulated annealing

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1 INTRODUCTION

In recent decades structural damage detection has attracted attention to estimate the reliability of structural systems during their service life. The changes of dynamic characteristics used in most of damage detection methods. Many researchers indicate that modal parameters, natural frequencies and mode shapes, of structure are very sensitive on structural stiffness properties, [1]. Therefore, multiple modes need to be considered for better estimation of severity and location of damage since each natural frequency and corresponding mode shape are affected by different extents depending on location of the damage and severity. *Simulated annealing* (SA) optimization method is applied for damage detection through minimization of objective function. *Simulated annealing* is a stochastic optimization method proposed by Kirkpatrick et al. (1983) to find the global minimum of a cost function [2]. The simulated annealing method has been widely used in different fields of engineering as a robust and promising technique, particularly for hard non-linear optimization problems.

2 DAMAGE DETECTION PROCEDURE

The adopted vibration based damage detection procedure consists of three main parts: (1) numerical analysis using Finite Element (FE) model of the structure; (2) scenarios of simulation of damage element position and severity; and (3) application of the designed SA algorithm for determination of damage severity and location. Numerical analysis implemented for extraction and selection of features from normal mode dynamic analysis, and it is performed by FEM of simple support steel beam model.

Different damage scenarios simulated by reduction of stiffness of selected elements, elements on different locations with different extents. The outputs from FE analysis are natural frequencies and corresponding normalized displacement mode shapes of first five modes of vibration. After performing optimization process, extracted modal properties and computed sum absolute differences between modal frequencies for particular scenario of damage and simulated damage during optimization, the natural frequencies are different respect to damaged scenario of structure respect to extents of damage. In addition, the sum of absolute difference between modal shapes of the particular scenario and the simulated damaged of structure are selected as input features.

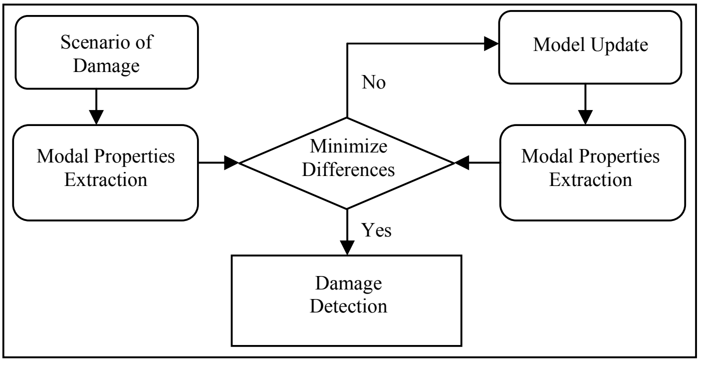

Figure 1 – General procedure of structural damage detection

Structural damage is typically related to change in the structural physical parameters. In damage detection, damage is usually represented by an elemental stiffness reduction factor (SRF) in order to preserve the structural connectivity and reduce the unknown variables [3]. The SRF is defined as the ratio of the elemental stiffness reduction respect to the initial stiffness. It ranges from 0 to 1, where 0 signifies no damage in the element and 1 means that the element loses its stiffness completely.

To represent damage severities, cross section second moment of inertia is reduced. In SA based damage detection techniques, structural damage is estimated from model update process using damage-induced changes in model properties. As shown figure 1, an FE model is continuously updated until the differences between modal fetures of the asumed scenario of damaged structure and simulated damaged structure during optimisation process, is minimized. This process is defined as the minimization problem and objective function have to be formulated for that purpose.

3 OPTIMIZATION USING *SIMULATED ANNEALING* METHOD

3.1 BASICS OF *SIMULATED ANNEALING* OPTIMIZATION PROCEDURE

Simulated annealing (SA) is the simulation of annealing of a physical many particle system to find the global optimum solutions of a large combinatorial optimization problem [2]. It uses a temperature parameter that controls the search. At each step the temperature is slowly lowered, system is "cooled", and a new point is generated using an annealing function. At each step, distance of the new points from the current point is proportional to the temperature. If the energy (cost) of this new point is lower than that of the old point, the new point is accepted. If the new energy is higher, the point is accepted probabilistically, with probability dependent on a "temperature" parameter. This unintuitive step sometime helps identify a new search region in hope of finding a better minimum.

In this paper, annealing function that takes random steps with size proportional to temperature and generates a point based on the current point and the current temperature is used. Also, the Boltzmann acceptance probability is used which is based on the chances of obtaining a new state E_{K+1}, relative to a previous state E_K, as shown in equation (1):

$$p = \begin{cases} 1 \;\ldots case\ \Delta E \le 0 \ldots E - energy \\ e^{\frac{-\Delta E}{T}} \ldots case\ \Delta E > 0 \ldots E - energy \end{cases} \tag{1}$$

Acceptance probability depends on internal energy level change $\Delta E = E_{K+1} - E_K$. Thus, if E_{K+1} results $\Delta E \le 0$, it will be always accepted, whereas if E_{K+1} results in $\Delta E > 0$, its acceptance depends on acceptance probability defined by equation (2):

$$p = e^{\frac{-\Delta E}{T}} \tag{2}$$

at particular annealing temperature T. Hence, if P larger than random value of r assumed to be from (0-1), then the E_{K+1} will be accepted, otherwise will be rejected. According to acceptance probability, there is a high probability that the change of variable(s) will be accepted, while the annealing temperature T is high, and vice versa. Thus, SA algorithm accepts changes of variable(s) in the case that it increases objective function value, which is helpful to avoid that solution become trapped in local minima. In the case that E_{K+1} is accepted, E_{K+1} becomes E_K in a new trail, and annealing temperature T reduces, which decreases the acceptance probability p. Important issue of SA algorithm is an initial temperature T_o, from which the algorithm starts and decrement of temperature during optimization procedure. Number of authors, suggested different approaches for determination of initial temperature and so-called cooling-schedule (decreasing of temperature). The SA optimization procedure terminates when variables/uncertain parameters a certain level of convergence achieve or after a certain run-time limit reached.

In this study, the cooling-schedule is given:

$$T = \alpha . T_o \tag{3}$$

where are:

T_o ….initial temp

α ….temperature reduction factor.

The Simulated annealing optimization algorithm stops when any of following situations occur: the number of itrations or evaluations of objective function reaches the max value; alteration in the improvement of objective function is less than the function tolerance. For this purpose, routine in *MATLAB*, was written to perform constrained minimization [4].

The SA used in the analysis are selected from the numerical work performed on simple supported steel beam model. This SA implemented by using numerically generated input data from FEM of the intact and damaged steel beams FE model solution. Assuming scenarios to obtain input data are introduced to the selected SA for severity and location prediction to simulate damage case. In SA based damage assessment, the accuracy of damage detection depends on the feasibility of modal features and a baseline analytical model that are selected for the test structure [3]. Also, the time consumed for damage detection process would be reduced by using optimization techniques.

3.2 OBJECTIVE FUNCTION

The aim of any optimization method is to maximize or minimize the objective (fitness) function. In the case of damage detection task, an objective function represents the error between the measured/simulated and numerical modal data. Fundamental objective functions relate with the damage detection process usually correspond, as it is defined in [5], to the error of frequencies, modal vector differences, MAC (Modal Assurance Criterion) values, strain energy residuals, between real (measured or for particular scenario assumed) and simulated damage. Each research contains a part or all these fundamental objectives.

In this study adopted objective function was related to the error in frequencies and modal displacements. The new objective function, improved from Au et al. (2003), replacing $Norm - matrix$ with $Absolute - values$, according to equation (6):

$$Obj\_Func = W_f \times Freq + W_d \times Disp \tag{4}$$

where are :

$Freq$, $Disp$ ....error in frequencies and normalized displacements, respectivelly.

W_f , W_d ....weighting factors for frequencies and displacements, equal to 1000 and 0.001, respectivelly.

$$Freq = \sum_{i=1}^{n} \left(\frac{\mathrm{Freq}_{\mathrm{Exp}} - \mathrm{Freq}_{\mathrm{Num}}}{\mathrm{Freq}_{\mathrm{Exp}}} \right)^2 \tag{5}$$

where are:

$Freq_{Exp}$, $Freq_{Num}$ ...experemental/real and numerical/simulated natural frequencies, respectivelly.

n ....number of frequencies.

$$Disp = \sum_{i=1}^{m} \frac{\left| Disp_{Exp} - Disp_{Num} \right|}{\left| Disp_{Exp} \right|} \tag{6}$$

where are:

$Disp_{Exp}, Disp_{Num} = Disp_y + Disp_z$ ..experemental/real and numerical/simulated displacements, respectivelly.

$Disp_y, Disp_z$ ...normalized experemental and numerical displacment in y (vertical axis of structure) and z (transverse axis of structure) direction, respectivelly.

m ....number of nodes of structure.

Have to be recall that in our study, index Exp corresponds to assumed particular scenario of damage.

4 NUMERICAL TEST OF DAMAGE DETECTION AND RESULTS

In this section, efficiency and effectiveness of the proposed procedure are evaluated through some simulated damage identification tests using modal data. A simply supported steel beam is chosen with two different scenarios of damage. Finite Element model of the beam is developed using the program for FE structural analysis ANSYS-ver.11 [6].

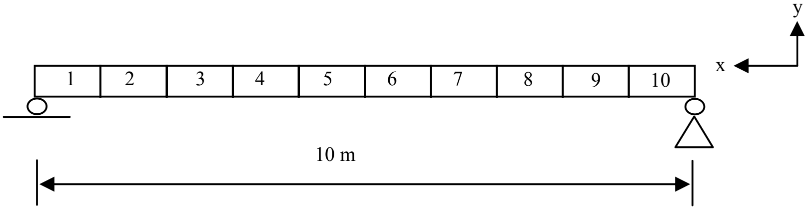

Figure 2 - The simple supported beam with finite element model

FE structural model is shown in figure 2, and it consists of 10 beam elements and 11 nodes, while the Beam4 finite element type used. For the considered steel beam of 10 m length, material properties include Young's modulus of E=200 GPa and mass density of ρ =7860 kg/m3.

Table 1 - Natural frequencies and mode shapes of the intact model

	Frequency	*Mode shape*
1	6.8595	1st bending
2	13.7038	1st Lateral
3	27.4077	2nd bending
4	54.5742	2nd Lateral
5	61.5538	3rd bending

Cross-sectional area and second moment of area of the beam are A=0.18 m^2 and I=0.0054 m^4, respectively. The natural frequencies and mode shapes of the first five computed modes for the intact FE model are shown in table 1.

Table 2 - Damage scenarios of the model

	Scenario 1	*Scenario 2*
Element	3	5
Damage (%)	30%	50%

In this case study, two damage scenarios are applied with damage location and severity, as defined in table 2. The severity of damage is repersented as percent of reduction of (second moment of area /or) moment of inertia of the model cross section of chosen damaged element. The percent of reduction is defined as ration crack length and height of cross section.

Table 3 - Input parameter for SA method

Parameter	*Value*
Max iteration	500
Temp. update function	Linear temperature update
Initial temp. T_0	20
Reduction factor α	0.7

During the proposed damage detection procedure, using SA algorithm, assumed the paramteters summarized in table 3. Therefore, it has been tried to prevent divergence of the proposed algorithm by defining two weighting factors W_f and W_d that are suitable enough for the new proposed objective function. The selection of these parameters is based on trial and error and depend on the values of frequencies and modal displacement of the structure. So, the selected values of the weighting factors W_f and W_d are 1000 and 0.001, respectively.

As it is mentioned above, the objective function is based on first five modal frequencies and mode shapes. Decreasing the objective function, during the iterations for both tested cases, are illustrated in figure 3. It is clear, from figure 3, that SA method has quick convergence and has avoided local trapping during the iterations and fast running with short time and iterations, which are the most advantage features of the applied optimisation procedure.

Figure 4 shows the results of damage identification of the simply supported steel beam for two damage scenarios with application of the proposed objective function. The results indicate that the proposed procedure is a robust and effective in detecting and quantifying various damage scenarios.

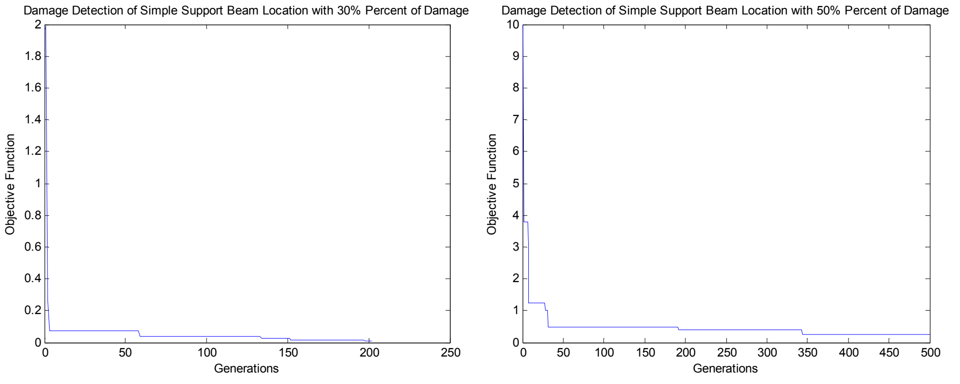

Figure 3 - Variations of the objective function for applied two scenarious of damage

As it is mentioned above, the objective function is based on first five modal frequencies and mode shapes. Lowering of the objective function, durring the iterations for both tested cases, are illustrated in figure 3. It is quite obvious from figures, that proposed procedure has got damaged element 3 and percent of damage equal to 31% for number of itrations is equal to 202, for first scenario. While for the second scenario, proposed procedure has got damaged element 5 and percent of damage equal to 52% for number of itrations is equal to 500.

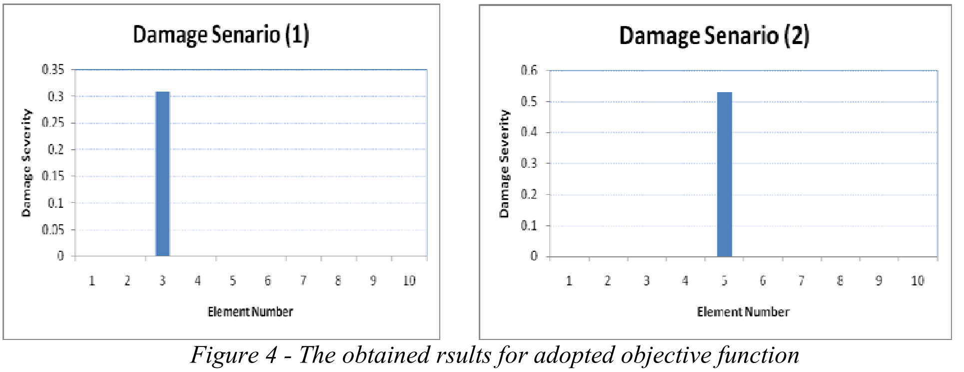

Figure 4 - The obtained rsults for adopted objective function

6 CONCLUSION

The presented study shows the possibililty of application structural damage detection method based vibration (or modal properties) with implemetation of simulated annealing algorithm using adopted new objective fuction for determination damage location and severity. High sensitivity is obvious, for structural modal properties, to presence of damage in structure. The proposed objective function includes composed of modal frequencies and modal displacement error. It exhibits an excellent performance to sense the decreasing objective function through the searching space. Numerical tests, performed on the simply supported beam model with two scenarios, show the efficiency and effectivness of the SA algorithm for damage detection in the structures by getting global without trapping local minimum value. The results indicate that the performance of proposed procedure shows strong capacity for damage identification, including location and severity of the damage, and could be applied and adopted for more complex structures.

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