COMPARATION OF TWO DAMAGE IDENTIFICATION METHODS APPLIED TO BEAM STRUCTURES

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ABSTRACT
This paper aims to present and compare the damage identification results of two methods proposed by the authors for beam-like structures. Both methods use the same numerical and regression models as well as the experimentally obtained values of the beam bending frequencies. The difference between these methods lies in the final stage of their usage. The first method relies on finding three closest intersection points of frequency curves and the second method is based on finding a minimum value of the proposed frequency related functional. The results of damage identification for 28 damage scenarios using the proposed methods are presented and compared in this paper. The comparison showed that the accuracy of both methods is almost the same and depends mostly on the input data quality.

Key words: damage identification, FEA, nonlinear regression, frequency

1. INTRODUCTION

Any change in structure physical parameters causes a change in its modal parameters (natural frequencies, mode shapes and modal damping). Damage in a structure causes change in its mass, damping and stiffness so this makes a well founded base for vibration based non-destructive structural health monitoring methods. Over the past few decades, great attention has been put to develop more efficient and accurate damage identification methods. Many of them are mentioned in literature, for instance in [1].

The aim of the present paper is to evaluate the performance of two similar damage identification methods that use numerical, regression and experimental data of beam bending frequencies.

2. DAMAGE IDENTIFICATION TECHNIQUES

Both of the considered damage identification methods are based on the same numerical and regression analysis of the real beam structure. Also, the performed experiments were the same so the same values of shifts in bending frequencies are used.

The difference between the proposed methods refers to the determination of damage parameters i.e. damage location and depth. In that sense, the proposed methods are named by characteristic way followed to find damage parameters, and they are: Method No.1. Intersections of frequency curves and Method No.2. Minimization of the proposed functional.

A brief glance on the common characteristics of both methods are presented in the part 2.1, and the specific properties of methods are presented in the part 2.2.

2.1. Common analyses for both of the proposed damage identification methods

For both of identification techniques, it's necessary to perform numerical and regression analysis as well as experimental measurements of bending frequencies of the real beam.

2.1.1. Numerical analysis

After establishing the numerical model of the real beam structure, the values of frequencies of undamaged and damaged state should be calculated. For the free-free beam with the length of L_B=400 mm, height H=8,16 mm, width B=8.12 mm, modulus of elasticity E=2.068x10^{11} Pa, mass density ρ=7820 kg/m^3, and Poisson's coefficient ν=0.29, using the solid elements in the software I-DEAS Master Modeler 9 and Normal Mode Dynamics option, the values of f_i^{NU}, i=1,2,3,4, corresponding to the first four natural bending frequencies of the undamaged beam were obtained. The damage perpendicular to the beam axis and at location L_D was simulated as an open notch of width of 1 mm and depth d. Varying the relative location $L = L_D/L_B$ and the relative depth of the damage $D = d/H$, the first four bending frequencies f_i^{ND} of the damaged beam were calculated. The location L_D was measured from the left end of the beam and due to structural symmetry was varied from 10-200 mm in 10 mm increments. The depth d was varied from 1-4 mm in 1 mm increments.

2.1.2. Regression analysis

The numerical values of frequencies f_i^{NU} and f_i^{ND} are used as input data for the software STATISTICA 6.0 to find appropriate regression relations between the frequencies and parameters D and L. The best fit was chosen on the basis of the value of coefficient of correlation in the Nonlinear Estimation option (coefficients here ranged from 0.996 to 0.998). The regression relations for the beam under consideration are found in the general form:

$$f_{iR}(D,L) = f_i^{NU}\left[1 - a_i\, D^2 \sum_{j=0}^{k} b_{ij} L^j\right], \qquad \ldots(1)$$

where f_i^{NU}, i=1,2,3,4, are numerical frequencies of the undamaged beam and k=4,5,6,7 for i=1,2,3,4 respectivelly. The a_i and b_{ij} are the regression coefficients.

Unfortunatelly, these regression relations inherently suffers of the trend to smooth the data at extreme points. More on this topic is presented in [2].

2.1.3. Experimental measurements

The experimental measurements of natural frequencies were performed using the PC, frequency analyzer HP 3567A, interface HP82335A, accelerometers B&K 4394 and impact hammer B&K 8202 with load cell B&K 8200, Figure 1. Bending frequencies f_i^{EU} and f_i^{ED}, i=1,2,3,4, were measured on seven beam samples shown on Figure 2, which were hung by silicon ropes to simulate a free-free state.

Figure 1. Impact hammer and accelerometers

Figure 2. Seven beam samples

The damage was simulated by cutting the beam sample by a thin saw. The initial depth was 1 mm, and then varied from 1- 4 mm in 1 mm increments.
The values of frequencies obtained numerically and experimentally differ less or more due to modeling and measurement errors that are inevitable in reality. Also, it was impossible to cut accurately the nominal depth of the notches using the ordinary saw cut.

2.2. Specific characteristics of the proposed identification methods

2.2.1. Method No.1 (Intersections of frequency curves)

The regression relations given by Eq.(1), can be written in the relative form:

$$F_i = f_{iR}(D,L)/\ f_i^{NU} = 1 - a_i\ D^2 \sum_{j=0}^{k} b_{ij} L^j\ . \qquad \ldots(2)$$

These relative frequency changes F_i, i=1,2,3,4, represent the 3D surfaces in the (D, L, F_i) space. If these surfaces are cut by planes that correspond to the specific value of frequency change F_i, the intersection curves can be obtained and plotted in D-L plane, Figure 3. A particular intersection curve contains all points (D, L) that correspond to the same specific frequency change F_i.
For four values of F_i, there are four intersection curves that should theoretically intersect in one point (D_{est}, L_{est}), which represents the estimation of damage parameters. However, in practice, it would be very hard to obtain the same intersection point for all four frequency curves as the numerical values of intersection point coordinates can differ more or less, Figure 4.

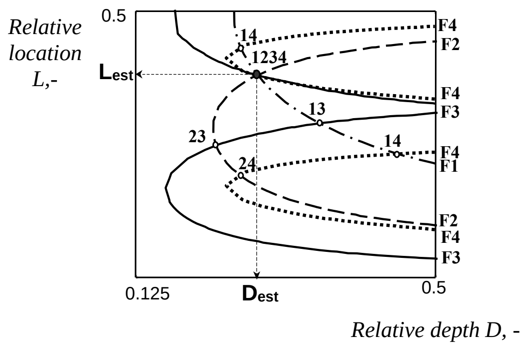

Figure 3. Finding the intersection points of frequency curves in D-L plane (ideal case)

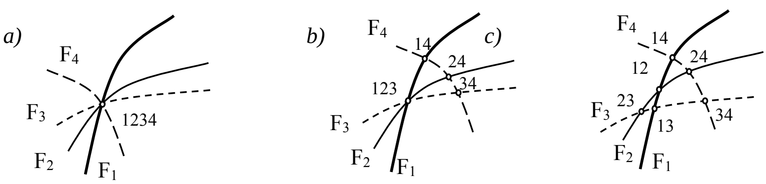

Figure 4. Characteristic cases of intersections: a) ideal case; b) special case; c) general case (note: the intersection point of F_1 and F_2 is marked as 12, etc.)

As can be seen from Figure 3, changes in only two first frequencies should be sufficient to find the characteristic intersection point. However, due to inevitable modeling and measurement errors, one should not rely solely on only two measured frequencies to find the estimation (D_{est}, L_{est}). It is much safer and reliable to locate this point using more frequency changes, which also contribute to the robustness of the technique.
Using an appropriate mathematical method to solve the system of regression relations, one can found a finite set of intersection points. The technique proposed in [2] suggests finding the three closest intersection points in the established set of intersection points. These three

points should give a minimal sum of their distances from their mean value. The mean value of these three points can be adopted to represent the estimation of damage parameters. The obtained estimation (D_{est}, L_{est}) of damage parameters should not be much beyond the numerically established ranges for L and D. In such a case, a next combination of three closest intersection points should be the appropriate estimation.

A finite set of intersection points (D,L) is obtained in the following way. The pair of regression relations in form of Eq.(2) can be written as:

$$F_i=1- a_i D^2 g_i(L) \quad \text{and} \quad F_j=1- a_j D^2 g_j(L) . \qquad \ldots(3)$$

Combining the equations (3) for all pairs i,j =1,2,3,4, $i \neq j$, it follows:

$$D^2 = \frac{1-F_i}{a_i g_i(L)} = \frac{1-F_j}{a_j g_j(L)} . \qquad \ldots(4)$$

For the measured frequency changes F_i and F_j, one can find all values of the relative location L that satisfy the second equality in Eq.(4). After that, the corresponding values of the relative depths D can be found also from Eq.(4). Of course, the proposed method that uses Eq.(4) is valid only for regression relations in the form of Eq.(2). For other types of best-fit regression relations, a feasible way to solve a set of generally nonlinear equations should be found.

2.2.2. Method No.2 (Minimization of the proposed functional)

To identify damage location and depth, the functional $FUN(D,L)$ is proposed in the form:

$$FUN(D,L)=\sum_{i=1}^{4}\left[\frac{\left(f_i^{NU}\,\frac{f_i^{ED}}{f_i^{EU}}\right)^2-\left(f_{iR}(D,L)\right)^2}{\left(f_i^{NU}\,\frac{f_i^{ED}}{f_i^{EU}}\right)^2}\right]^2 , \qquad \ldots(5)$$

where are:

f_i^{NU}- i^{th} natural frequency of the undamaged beam numerically obtained,
f_i^{EU}- i^{th} natural frequency of the undamaged beam experimentally obtained,
f_i^{ED}- i^{th} natural frequency of the damaged beam experimentally obtained,
$f_{iR}(D,L)$ - i^{th} natural frequency of the damaged beam calculated by regression relation Eq.(1).

The proposed functional is similar to the functional given in [3] and is based on presumption that the ratio $f_i^{NU}/f_{iR}(D,L)$ is close to the f_i^{EU}/f_i^{ED}.

The estimation of damage parameters is made by minimization of the functional $FUN(D,L)$ inside the reasonable bounds 0-0.5 for both D and L, using the software Mathematica 5.1.

3. DAMAGE IDENTIFICATION RESULTS

The abovementioned procedures were repeated for 28 cases of damaged states (7 locations by 4 depths). Figure 5 shows the results of damage identification obtained by the presented methods. It can be concluded that the accuracy of both of the presented methods are higher for higher L and D parameters. The main reason for low accuracy for damages near the beam end (low L) and with a small depth (low D) can be found in smoothing trend of regression relations and low measurement accuracy (low frequency resolution) for small damage depths.

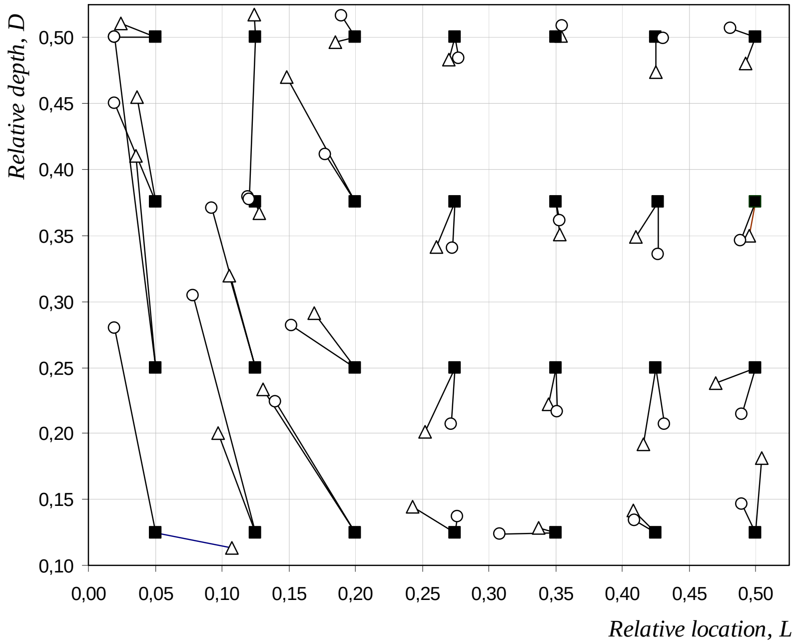

Figure 5. Results of damage identification: ■ - point indicating L_{real} & D_{real} ,
△ - estimation L_{est} & D_{est} by method No.1, ○ – estimation L_{est} & D_{est} by method No.2

4. CONCLUSION

The paper shows how damage parameters can be estimated using bending frequencies of a beam obtained in numerical, regression and experimental way.

The results of the both identification technique are quite satisfactory and very similar. This means that their accuracy mostly depends on the quality of numerical model and regression relationships, as well as the accuracy of frequency measurements. The numerical model of the beam was not updated to match all seven real beams so there were slight discrepancies in the dimensions and frequency values in undeformed beam states.

In reality, however, the efforts should be made to establish the numerical model that is the best representation of the real beam, so the better identification results would be obtained. Also, the identification results could be improved by more numerical damage scenarios to provide a sufficient number of points needed for establishment of regression relations. Also, more attention should be put on reducing the measurement errors since a certain level of noise always exists.

5. REFERENCES

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