About the Effectiveness of Damage Detection Methods Based on Vibration Measurements

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Abstract: - Researches concerning structure's safety improvement have increased significantly in the past decades, structural health monitoring becoming an important support in taking decision regarding the need of these structures' remediation. Various techniques, from visual inspection to nondestructive evaluation or vibration-based damage detection are used. The last ones use information regarding changes of natural frequencies, damping ratios, flexibility or mode shapes. Even if numerous results have been achieved in this field, several problems still have to be solved for specific applications before their implementation in practice.
Our study approaches the method's viability of damage detection in simple structures using only one accelerometer by analytical method, finite element method and experimental test. The obtained results by all three methods showed that this approach can be used only in high damage rates cases. Finally, are pointed some issues which have to be further worked out.

Key-Words: - structural health monitoring, damage detection, vibration, simulation, structures

1 Introduction

Non-destructive testing, including monitoring and diagnostics, is nowadays widely practiced in mechanical and civil engineering. It influences our approach of designing of new structures and monitoring and maintenance of existing ones. From the series of now available non-destructive testing methods, the dynamic ones grow in importance comparing with conventional diagnostic methods, like the once based on visual inspection or ultrasonic analysis. This is motivated by the global perspective offered by dynamic techniques (tests developed over time are able to indicate the appearance of possible damages in the structure), comparing with the local nature of conventional methods (which require good preliminary knowledge about the position of the area where the damage is located). Another advantage of the dynamic methods is linked to the fact that these techniques do not requested access to the damaged area, while conventional methods require direct accessibility to the area to be inspected. However, the two methods can be used complementary; they do not exclude each other [1].

Numerous researches have been performed in order to develop and prove the viability of dynamic methods. In this context, important progresses made on the technological field have generated accurate and reliable experimental methods, while the interpretation of measurement results remains a bit behind. In literature, [2] and [3], are presented a series of vibration based damage detection techniques, for structures and simple elements, based on: natural frequency shifts, damping, change of mode shapes and flexibility of structures. There are a series of authors who focused their researches on simple elements, like cantilever beams [4], [5], [6] or on simple supported beams [7], while other authors developed methods to detect damages [8], [9], [10], [11], [12]. It has to be mentioned that all methods base on processing data of change of natural frequency and shape modes. Similar researches have been done by the authors [13] in order to show that it is possible to detect damages in cantilever beams, without concentrating on the localization or characterization of the damage.

2 Theoretical Investigations

The researches developed last time, presented in this paper, had the intention to determine how relevant the information obtained by vibration measurements is, for locating and characterizing of damages in various types of structures. In this sense we determined the natural frequencies for a beam, supported in different ways, both in undamaged and damaged state. The comparison of results has shown how relevant the shift in frequency is and if it provides enough information to identify and locate damages in real time.

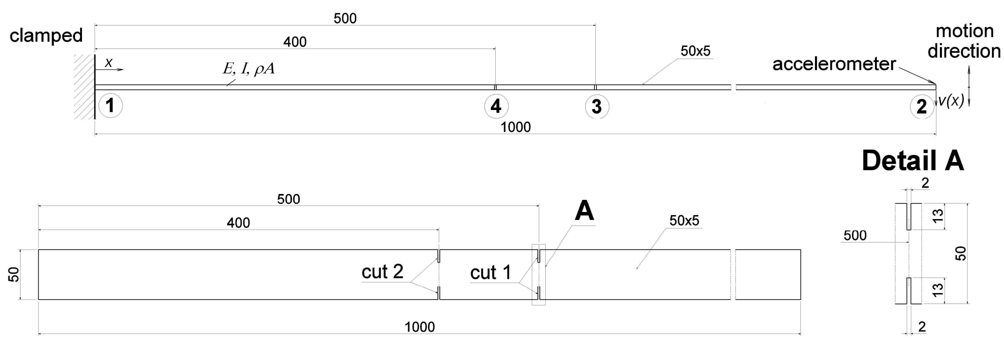


Fig. 1

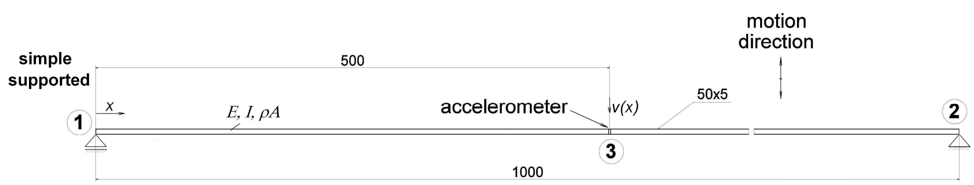


Fig. 2

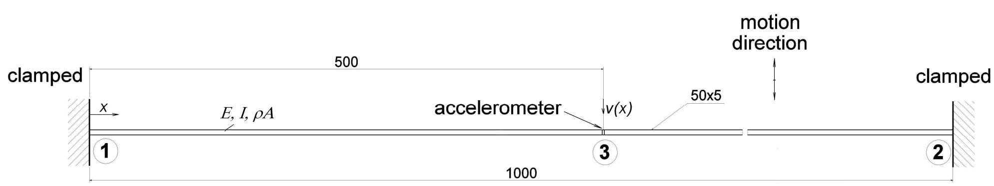


Fig. 3

We used theoretical investigations (analytic study and numerical methods) and experiments. At first a steel cantilever beam, clamped on one end (point ① - as shown in figure 1) and free on the other (point ② in figure 1), is considered as testing structure. The beam has length $l = 1000$ mm, wide $b = 50$ mm, height $h = 5$ mm and consequently a cross-section $A = 250 \cdot 10^{-6}\,\text{m}^2$ and a moment of inertia $I = 520.833 \cdot 10^{-12}\,\text{m}^4$ respectively.

The producer indicates following material parameters: mass density $\rho = 7850$ kg/m^3, Young's modulus $E = 2.0 \cdot 10^{11}\,\text{N/m}^2$ and the Poisson's ratio $\mu = 0.3$.

Afterwards similar beams, simple supported and clamped on both ends (points ① and ②) respectively, are considered, like it is presented in figures 2 and 3. The accelerometer was mounted in both this cases close at the middle of the beam.

2.1 Analytical Method

To find out the analytical calculated natural frequencies for the undamaged cantilever beam, we started from the beam equations [14]:

$$\frac{\partial^4 v}{\partial x^4} + \frac{\rho A}{EI} \cdot \frac{\partial^2 v}{\partial t^2} = 0 \qquad (1)$$

where v is the vertical displacement of the beam at distance x measured from the free end. Considering that v depends on distance x and time t, and the evolution in time is harmonically, v can be written:

$$v = X(x) \cdot T(t) = X \cdot \sin \omega t \qquad (2)$$

After derivation and substitution in relation (1), one obtains:

$$X^{IV} - \frac{\rho A \omega^2}{EI} X = 0 \qquad (3)$$

with the solution:

$$X = A \sin \alpha x + B \cos \alpha x + C \sinh \alpha x + D \cosh \alpha x \qquad (4)$$

where we noted

$$\frac{\rho A \omega^2}{EI} = \alpha^4 . \qquad (5)$$

After three derivations of the solution (4) results the system (6), presented below:

$$\begin{cases} X = A \sin \alpha x + B \cos \alpha x + C \sinh \alpha x + D \cosh \alpha x \\ X' = \alpha (A \cos \alpha x - B \sin \alpha x + C \cosh \alpha x + D \sinh \alpha x) \\ X'' = \alpha^2 (-A \sin \alpha x - B \cos \alpha x + C \sinh \alpha x + D \cosh \alpha x) \\ X''' = \alpha^3 (-A \cos \alpha x + B \sin \alpha x + C \cosh \alpha x + D \sinh \alpha x \end{cases}$$

Putting the boundary conditions for the clamped cantilever beam $X(0) = X'(0) = 0$, and $X''(l) = X'''(l) = 0$, one obtains the equation

$$1 + \cos \lambda \cdot \cosh \lambda = 0 , \qquad (7)$$

with $\lambda = \alpha l$, which permits to calculate the λ_i values for i vibrations modes. Multiplying relation (5) with l^4 and substituting the values of λ_i, results the analytic calculated angular frequencies ω_i, and consequently the natural frequencies of the undamaged cantilever beam:

$$f_i = \frac{\lambda_i^2}{2\pi} \sqrt{\frac{EI}{\rho A l^4}} , \qquad (8)$$

the first six being presented in table 1.

Similar, by putting the corresponding boundary conditions for the undamaged simple supported and double clamped beam respectively, one obtains the natural frequencies presented also in table 1.

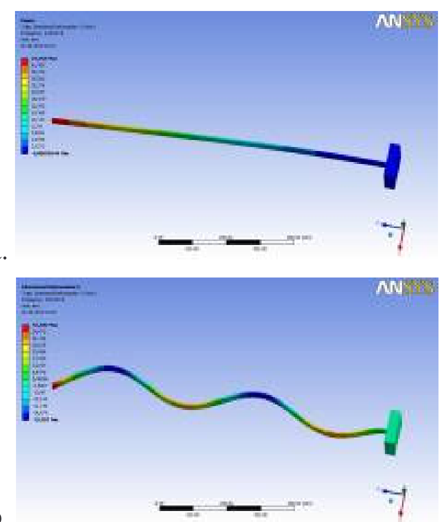
Table 1

Mode	Natural frequency f_i [Hz]		
	Cantilever	Simple supp.	Double clamped
1	4.077	11.444	26.021
2	25.549	45.776	71.727
3	71.539	102.996	140.614
4	140.189	183.105	232.441
5	231.742	286.101	347.227
6	346.182	411.985	484.970

2.2 Finite Element Method

The FEM computation was made on 3D model beams, whit a 5 mm element size; the weight of the accelerometer was neglected.

The first and fifth mode shapes for the undamaged beams (cantilever, simple supported and double clamped) are presented in figures 4-6, while their first six natural frequencies in vertical direction for the intact and damaged state are presented in tables 2-4. Following notations are used: U for the undamaged beam, D1 for the beam with damage at point ③ - figure 1 and D2 for the beam with two damages, at point ③ and point ④ - figure 1.



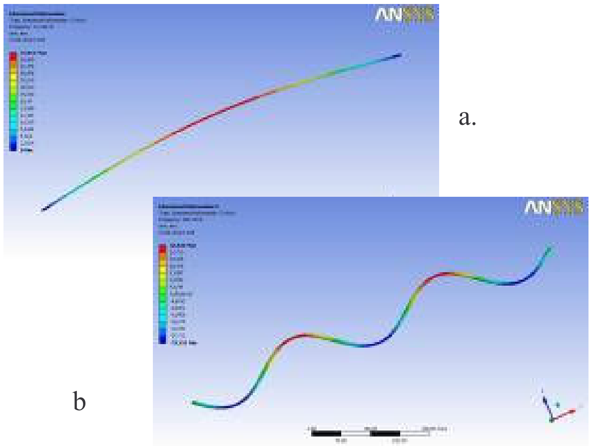
a.

b.

Fig. 4

Table 2

Mode	Cantilever beam				
	Natural frequency f_i [Hz]			Change [%]	
	U	D1	D2	U-D1	U-D2
1	4.091	4.079	4.0548	-0,293	-0,880
2	25.634	25.302	25.100	-1,295	-2,083
3	71.780	71.767	71.360	-0,018	-0,585
4	140.69	138.94	138.62	-1,244	-1,471
5	232.65	232.53	229.72	-0,052	-1,259
6	347.69	343.44	343.07	-1,222	-1,329

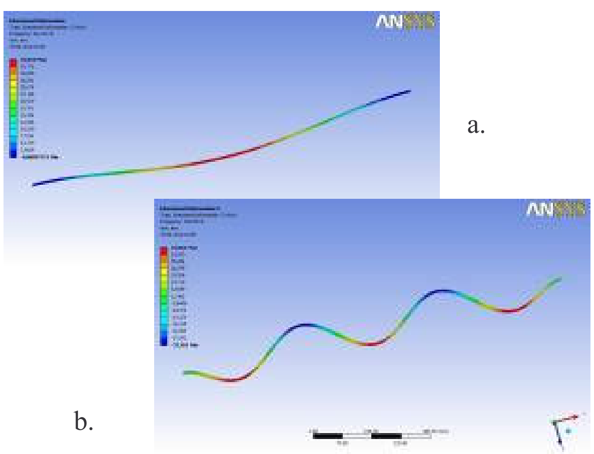

a.

b

Fig. 5

Table 3

Mode	Simple supported beam		
	Natural frequency f_i [Hz]		Change [%]
	U	D1	U-D1
1	11.444	11.289	-1,354
2	45.779	45.775	-0,009
3	103.010	101.650	-1,320
4	183.140	183.070	-0,038
5	286.150	282.450	-1,293
6	411.960	411.640	-0,078


a.

b.

Fig. 6

Table 4

Mode	Double clamped beam		
	Natural frequency f_i [Hz]		Change [%]
	U	D1	U-D1
1	26.241	25.990	-0,957
2	72.317	72.036	-0,389
3	141.770	139.850	-1,354
4	234.380	234.260	-0,051
5	350.220	345.660	-1,302
6	489.330	488.840	-0,100

3 Experimental Research

The experimental tests performed an analysis of the steel beam's dynamic behavior for two situations: undamaged and with damage on its middle (point ③ in figure 7). The cantilever beam described in chapter 2 was mounted in a rigid support. The measurement system (figure 7), composed by a Toshiba laptop, a NI cDAQ-9172 compact chassis with NI 9234 four-channel dynamic signal acquisition modules and a Kistler 8772 accelerometer has been used for signal acquisition.

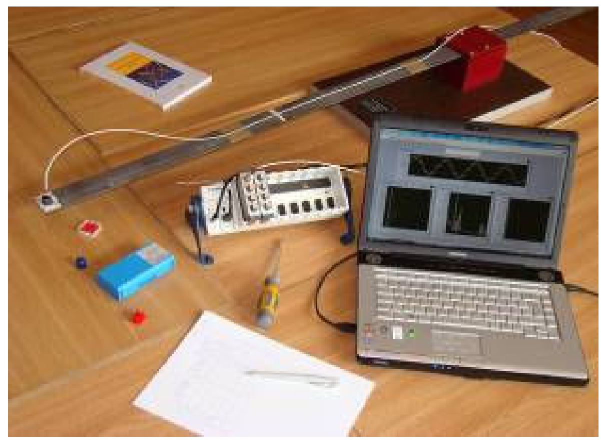


Fig. 7

As programming environment LabVIEW was used to develop the virtual instrument which acquire the time history of acceleration and realize the spectral analysis. A window presenting the acquired and processed signal is shown in figure 8.

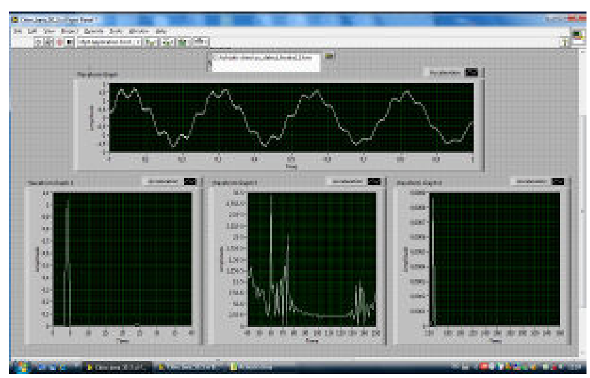


Fig. 8

To measure the accelerations on vertical direction for the free end of the beam (point ② in figure 7) a vertical force was applied to bring the mechanical system out of its equilibrium position. Suppressing the force, the beam started to vibrate. We recorded and stored the acceleration values using the acquisition system, for the undamaged beam; repeating the process for nine times.

Afterwards damages on the middle (point ③ in figure 7) of the beam were produced by saw cuts, like those presented in detail A in figure 1, and a new series of measurement realized.

All signals were processed in order to obtain their frequency spectrum. Using the pick detector we extracted the natural frequencies of the undamaged and damaged steel cantilever beam respectively. The mean values for the first six natural frequencies are presented in table 5.

Table 5

Mode	Cantilever beam		
	Natural frequency f_i [Hz]		Change [%]
	U	D1	U-D1
1	4.000	3.975	-0,625
2	24.000	24.000	0,000
3	70.000	69.000	-1,429
4	134.000	131.000	-2,239
5	226.000	222.000	-1,770
6	335.000	329.000	-1,791

4 Influence of the Cross-Section on the Damage Detection Sensitivity

In the analysis above presented, just a beam with the width much larger than the height was considered. It is also interesting to find out the behavior of beams with other types of cross-sections and how effective damages detection methods are for this kind of beams. Therefore, we considered a beam with three types of cross sections:

- type A, with low stiffness
- type B, with medium stiffness
- type C, with high stiffness.

Figure 9 presents the cross-section of the three types of beams, all of them having the same cross-section $A = 250 \cdot 10^{-6}\,\mathrm{m}^2$ in undamaged state. The section presents also the simulated damages.

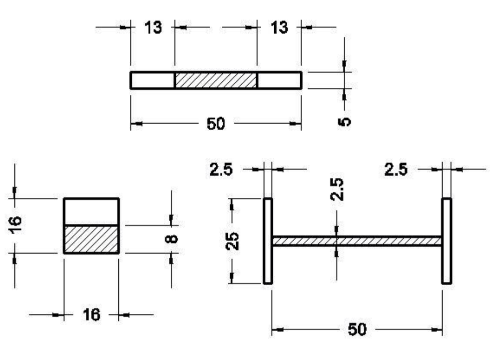


Fig. 9

The length of the cantilever beam is for all cases $l = 1000$ mm. The dimensions of the cross-sections for the three beams are:

- *b* = 50 mm, *h* = 5 mm;
- *b* = 16 mm, *h* = 16 mm;
- *b* = 25 mm, *h* = 54 mm, *d* = 2,5 mm.

The simulated damages affect in all cases 50 % of the cross-section, in form of cuts with a wide of 2 mm. By the FEM analysis, we obtained the natural frequencies, both for undamaged and damaged state, presented in tables 6-8.

Table 6

Mode	Cantilever beam – rectangular cross-section		
	Natural frequency f_i [Hz]		Change [%]
	U	D1	U-D1
1	4.091	4.079	-0,293
2	25.634	25.302	-1,295
3	71.780	71.767	-0,018
4	140.69	138.94	-1,244
5	232.65	232.53	-0,052
6	347.69	343.44	-1,222

Table 7

Mode	Cantilever beam – square cross-section		
	Natural frequency f_i [Hz]		Change [%]
	U	D1	U-D1
1	13.053	12.867	-1,425
2	81.707	77.061	-5,686
3	228.34	228.33	-0,004
4	446.23	423.54	-5,085
5	735.02	734.94	-0,011
6	1093.2	1038.1	-5,040

Table 8

Mode	Cantilever beam – I profile cross-section		
	Natural frequency f_i [Hz]		Change [%]
	U	D1	U-D1
1	14.499	11.015	-24,029
2	90.576	54.300	-40,050
3	252.31	251.93	-0,151
4	489.14	381.68	-21,969
5	792.85	790.51	-0,295
6	1146.0	989.52	-13,654

5 Conclusions

Previous studies present various methods to the structures integrity dynamic evaluation, without specifying the conditions for which the methods are recommended to be applied. This implies, by structures' dynamic analysis, a previous good experience for engineers in the field of structural health monitoring. Our research, partially presented

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in the actual paper, intend to bring novelty in this field, providing recommendations about the methods to be used for different cases in dynamical evaluation of structures.

Examining the results for the cantilever beam, presented in tables 1, 2 and 5, we remark a good concordance between the natural frequency values obtained by analytical calculus, deduced with the FEM and the experimental ones. This proves that correct theoretical algorithms and accurate measurement equipment and methodologies have been used.

On the other side the results presented in tables 2 to 5 show that the shifts in frequency for the analyzed structures, even for damages which reduce dramatically the moment of inertia, don't exceed 3%, being for the large majority of the cases lower than 1.5%. It is also to be mentioned that increased number of damages does not increase dramatically the shift in frequency. This makes damage detection methods based alone on the shift of frequency not suitable for elements of type A, implying the need of more information about the structure's behavior.

By analyzing tables 6 to 8 we can conclude that damage detection methods based just on shift of natural frequency are effective for elements with the mass placed far from the center of mass (type B and C), the shift in frequency increasing to 5% and even 25-40%. The method conducts alone to relevant information regarding the harm of the element.

As next researches the authors plan to extend the experiments on trusses as well as on plates too.

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