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A GLANCE TO A MODE SHAPE BASED DAMAGE DETECTION TECHNIQUE

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ABSTRACT
Damage in a structure is a local perturbation of its physical characteristics, i.e. its stiffness, mass and/or damping. Consequently, damage alters dynamic characteristics of the structure such as natural frequencies, damping value and mode shapes associated with each natural frequency. This is the base of vibration based structural health monitoring techniques. In this paper characteristics of mode shapes are investigated for identifying the location of damage in a beam structure. Cantilevered beam model is investigated numerically by use of finite element method. Slope and curvature of displacement mode shapes differences (between intact and damaged structure) were calculated using a central difference approximation. The results have shown that changes in the mode shape characteristics are good indicator of damage location and severity, and hence can be used to detect damage in a structure.
Key words: damage detection, mode shape characteristics

1. INTRODUCTION
The problem of detecting structural damage in different engineering structures using vibration data has gained a lot of attention over the past few decades. The presence of damage causes a change in physical parameters of the structure and, consequently, in modal parameters of the structure, i.e. natural frequencies, mode shapes and modal damping.
The problem of damage diagnostic can be approached at four levels, [1]:

Level 1-Detection. Indicating the occurrence of a damage in the structure,
Level 2-Localization. Level 1 and locating the damage,
Level 3-Assessment. Level 2 and estimating the magnitude of damage,
Level 4-Prediction. Level 3 and predicting the remaining life of the structure.

The majority of vibration based damage detection methods analyze changes in natural frequencies. As natural frequencies are global characteristics of the whole structure, many authors propose mode shape analysis to detect damage as being more sensitive to local changes in structure. The use of modal or spatial information in damage detection was introduced in 1984 using the MAC (Modal Assurance Criterion), which compares the mode shapes of damaged and intact structures, [2]. The use of mode shape curvature as a parameter more sensitive to damage than mode shape itself was suggested by Pandey at al., [3]. Their method was explored in many articles, such as: [4], [5], [6]. Comparison of damage detection methods based on changes in mode shapes such as: mode shape curvature (MSC), modal assurance criterion (MAC), strain energy (SE), modified Laplacian operator (MLO), generalized fractal dimension (GFD) and Wavelet Transform (WT) was presented in [7].

The aim of the present paper is to evaluate the performance of mode-shape based technique through computer simulation of a clamped beam and to show how damage alters mode shapes of the structure and its characteristics (slope and curvature).

2. THEORETICAL BACKGROUND

Mode shapes of a vibrating structure are the eigenvectors of the eigenvalue problem

$$[C]\{\psi_i\} = \omega_i^2 [M]\{\psi_i\},\ i=1,2,\ldots,N, \qquad \ldots (1)$$

arising from the matrix differential equation for undamped structure with N degrees of freedom

$$[M]\{\ddot{q}\} + [K]\{q\} = 0, \qquad \ldots (2)$$

where are: ω_i^2 and $\{\psi_i\}$ - eigenvalues and eigenvectors of the problem (i.e. natural frequencies squared and mode shapes of vibrating structure), $[M]$ and $[K]$ - mass and stiffness matrices of the structure, $\{\ddot{q}\}$ and $\{q\}$ - vector-columns of the generalized accelerations and displacements.

3. NUMERICAL MODEL AND DAMAGE CASES

To show how damage alters mode shape characteristics of the structure, the axial structure presented in Figure 1 is modeled in I-DEAS Master Series 11 using 500 Timoshenko beam elements, Figure 2. Beam dimensions: L=500mm, H=B=10mm. Material characteristics: E=2.068 $\cdot 10^{11}$Pa, ρ=7820 kg/m^3, G=8.0155 $\cdot 10^8$ Pa. Damage is simulated as a reduction of height H to h, from both sides in y direction to preserve the neutral axis.

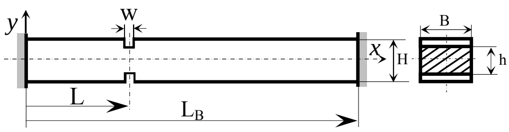

Figure 1. Beam geometry

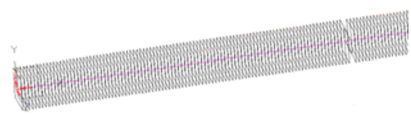

Figure 2. Finite element model of the beam with crack

The density of material in a damaged element is artificially increased to simulate the case of a crack that affects only the structural integrity (stiffness) without material loss. Several damage scenarios with different crack depths, widths and locations are analyzed as shown in Table 1.

Table 1. Damage scenarios

	Damage location (Node N°)	Damage width		Damage depth from both sizes (mm)	Reduced height h (mm)	Density of damaged elements (kg/m^3)
		Element N°	w (mm)			
CASE 1	from N°100 to N°101	100	1	1	8	9775
CASE 2	from N°100 to N°101	100	1	2	6	13033
CASE 3	from N°100 to N°101	100	1	3	4	19550
CASE 4	from N°199 to N°102	99,100,101	3	3	4	19550
CASE 5	from N° 98 to N° 103	98,99,100,101,102	5	3	4	19550
CASE 6	from N° 98 to N° 103	98,99,100,101,102	5	2	4	19550
	from N°272 to N°273	272	1	2	8	9775

4. NUMERICAL RESULTS

First mode shapes of undeformed y_{und} and damaged structures y_{dam} obtained in software I-DEAS are exported to Microsoft Excel. The central difference approximation for the first and second order derivatives of order O(h^2)

$$z_i' = \frac{z_{i+1} - z_{i-1}}{2h}, \qquad z_i'' = \frac{z_{i+1} - 2z_i + z_{i-1}}{h^2}, \quad h=1 \qquad \ldots (3)$$

are applied on mode shape difference z = y_{und} - y_{dam}. The first order derivative of z represents the slope of mode shapes difference z, and the second order derivative represents the curvature of z.

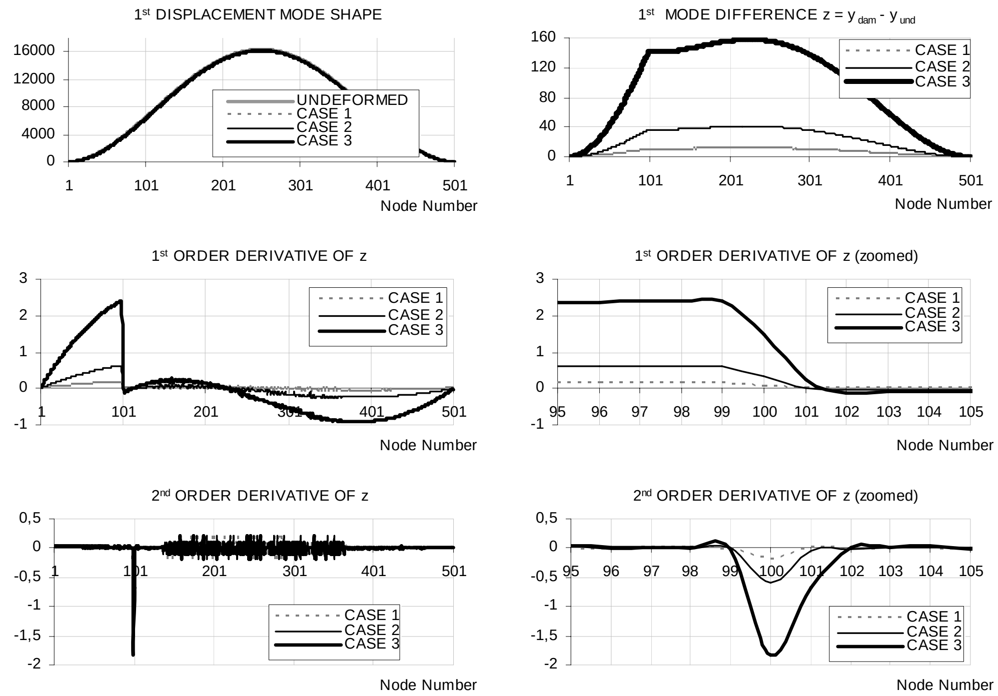

Figure 3. Characteristics of the first mode shape difference along the beam with variable crack depth

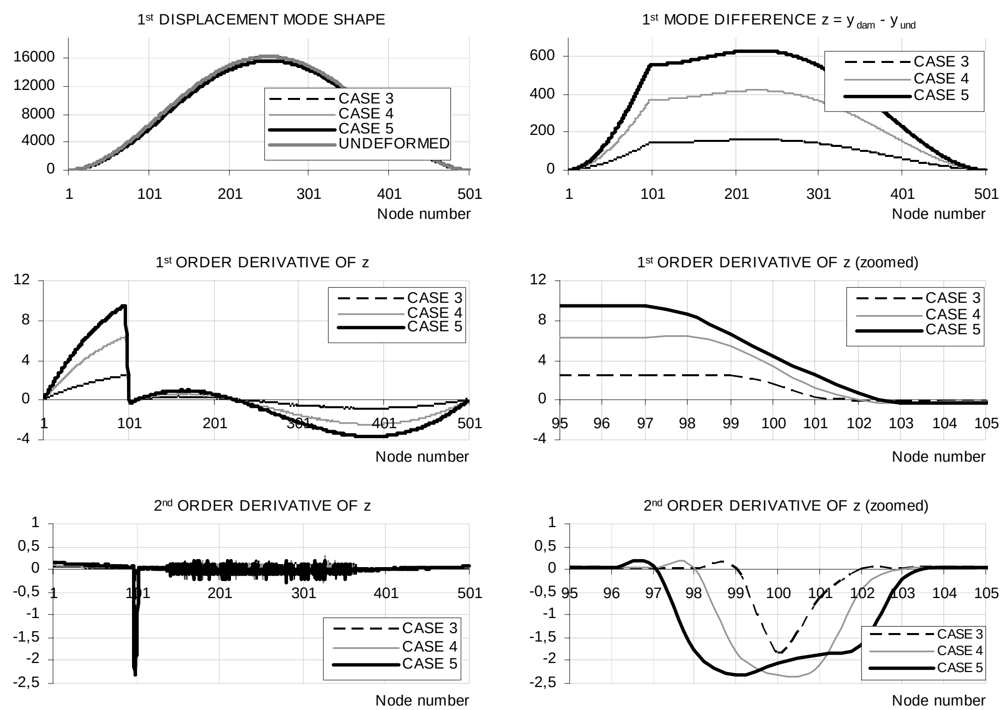

Figure 4. Characteristics of the first mode shape difference along the beam with variable crack width

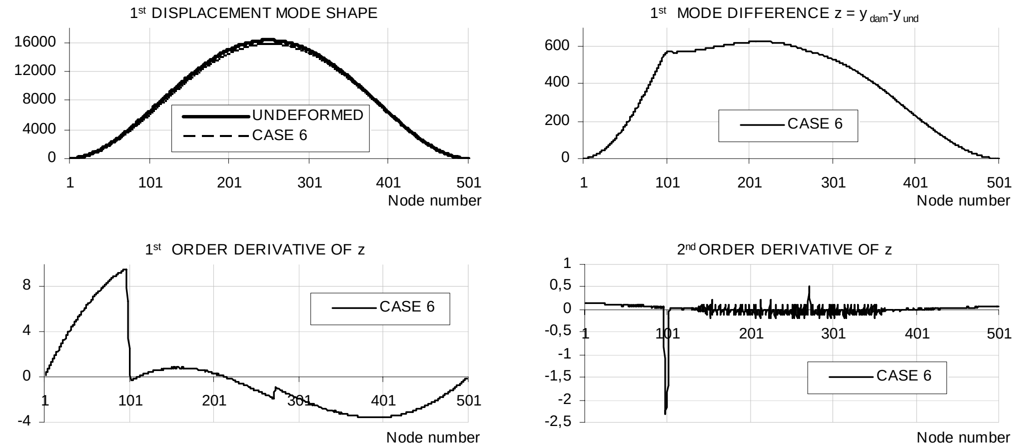

Figure 5. Characteristics of the first mode shapes difference along the beam with two cracks

The results are shown for different depth of crack (CASE 1, CASE 2, CASE 3) in Figure 3, different width (CASE 3, CASE 4, CASE 5) in Figure 4, and for the case of two different cracks (CASE 6) in Figure 5. The results are presented for the difference of the first mode shapes but similar results can be obtained for higher flexural modes.

5. CONCLUSIONS

Using only the displacement mode shapes of a damaged structure, it´s very hard to notice any perturbation due to damage. The difference between mode shapes of damaged and intact structures loses smoothness at damaged location. The slope of the mode shape difference, as well as the slope of the mode shape of damaged structure alone, has an abrupt change in the area of damage. The second order derivative, i.e. the curvature is the best indicator of damage location as possessing the peak value at damaged location (Figure 3) or two peaks at the ends of a wider damage (Figure 4). The height of the peak is proportional to the magnitude of damage, as can be seen in Figure 3. The method is also successful in detecting multiple damages, as shown in Figure 5.

The major drawback of this method is that experimentally identified modes lack the necessary measurement accuracy demanded for this procedure and a lot of sensors is required for mode shape measurements. This problem, however, can be overcome by use of modern Laser Scanning Vibrometer. Also, a lot of efforts has to be put on distinguishing perturbations due to small damages from the measurement noise.

6. REFERENCES

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