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FREQUENCY-BASED DAMAGE DETECTION IN BEAMS USING AN ADDITIONAL ROVING MASS

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Abstract. *This paper applied the frequency-based damage detection using an additional mass to detect damage in free-free and simply supported beams by Timoshenko theory. This technique based on frequency-shift consists of the application of an additional mass along the length of the damaged structure. The natural frequency is monitored as an addictive mass is placed along the structure. The magnitude of the additional roving mass (m_r) applied is 2% of the total mass of the beam. The natural frequencies are obtained using FEM. Damage identification and location are investigated using Discrete Wavelet Transform (DWT). In the results, the frequency-shifts response of damage structure using additional mass are a promising alternative to damage identification and location.*

Keywords: *Timoshenko beam, damage detection, free vibration, additional mass, non-destructive technique.*

1. INTRODUCTION

Previous damage detection in structures, like beams, is extremally important to safe and satisfactory maintenance. Commonly, visual inspections are realized to investigate the presence of cracks but in some cases, this technique is unsuccessful, for instance, when the damage is in a place that is too hard to see.

Thusly, many non-destructive methods have been applied to the identification and localization of damages that prejudice the health of the structure. Generally, these techniques compare the intact and damaged response of the structures, which requires the identification of both beforehand. In most of the time, the intact response is impossibly obtained. Hence, researchers have been testing some techniques using damaged response, as Parloo *et al.* (2004), Duan *et al.* (2005), Zhong. S. and K. (2008).

In last decades, studies of identification of damage in structures using an auxiliary mass have been done (Mermertas and Erol (2001), Bilello and Bergman (2004), Zhong and Oyadiji (2008), Papatheou *et al.* (2010), Palechor *et al.* (2018) e Palechor (2018)). This technique consists of the application of an additional mass along the length of structure to magnify the effect of the discontinuities.

In this paper, we present the fundamental natural frequencies variation of free-free and simply-supported beams of aluminum due to the application of an additional mass along the length of the damaged structure with different magnitudes of damage, proposed by Zhong. S. and K. (2008). First of all, a numerical model on Timoshenko FE 2-nodes beam by Finite Element Method (FEM) is implemented. Wavelet Transform is applied to locate the damage, as Silva *et al.* (2019). Finally, some experimental tests are realized to compare numerical prediction.

2. TIMOSHENKO BEAM WITH ADDITIONAL MASS

Unlike the Euler-Bernoulli beam model, the Timoshenko beam model considers the transverse shear deformation and rotational inertia of the beam. Hence, this theory is much accurate than Euler-Bernoulli one. The formulation enables the modeling of thin or thick beams.

Lee and Park (2013) written the dynamic equilibrium equation based on the principle of virtual work in cases of free vibration of Timoshenko beam:

$$\int_0^L EI\frac{\partial\theta}{\partial x}\delta\left(\frac{\partial\theta}{\partial x}\right)dx+\int_0^L K_sGA\left(\frac{\partial w}{\partial x}-\theta\right)\delta\left(\frac{\partial w}{\partial x}-\theta\right)dx=\int_0^L\delta w\rho A\ddot{w}dx+\int_0^L\delta\theta\rho I\ddot{\theta}dx \tag{1}$$

where w and θ are displacement and rotation, Young's modulus E, second moment of area I, k_S is a shear correction factor ($k_S = 5/6$, for rectangular section), shear modulus G, beam cross-section area A, $\ddot{w}$ and $\ddot{\theta}$ are the acceleration, ρ is the density of material, L is the length of the beam and δ denotes that the terms are virtual. The equation of motion in matrix form is presented:

$$\left|K-\omega^2 M\right|\phi=0 \tag{2}$$

where ϕ is a set of displacement-type amplitude at the control points, ω is the natural frequencies and **K** and **M** are global stiffness and mass matrices.

$$\mathbf{K}=\mathbf{K}_{ab}=\int_0^L\begin{bmatrix}0 & -\frac{\partial N_{a,p}}{\partial x}\\ \frac{\partial N_{a,p}}{\partial x} & N_{a,p}\end{bmatrix}^T\begin{bmatrix}EI & 0\\ 0 & k_sGA\end{bmatrix}\begin{bmatrix}0 & -\frac{\partial N_{b,p}}{\partial x}\\ \frac{\partial N_{b,p}}{\partial x} & N_{b,p}\end{bmatrix}dx \tag{3}$$

$$\mathbf{M}=\mathbf{M}_{ab}=\int_0^L N_{a,p}\rho AN_{a,p}dx+\int_0^L N_{a,p}\rho IN_{a,p}dx \tag{4}$$

where $\mathbf{K}_{ab}$ and $\mathbf{M}_{ab}$ is matrices of stiffness and mass to control linking points a and b and N_ab_p is B-spline basis functions.

The integrals were computed by Gauss-Legendre quadrature. The bending stiffness is computed by 2 gauss points and shear stiffness is computed with 1 gauss point. This selective quadrature was found to be one possible solution for shear locking in thin beams (Ferreira, 2008).

3. EXPERIMENTAL PROCEDURE METHODOLOGY

The study cases are presented in this section. It shows the properties of the structure to be investigated and the methodology, including the instrumentation and procedure of the experimental tests.

3.1 Properties of the beam

The study was performed for an aluminum square-section beam with cross-section area $A = 19 \times 19mm^2$ and length L = 395 mm. The Young's modulus E = 66.662 GPa was obtained indirectly by experimental tests of axial vibration. Holman (1969) measured aluminum with Poisson's ratio ν = 0.33. Lastly, material density $\rho = 2702.3kg/m^3$ was estimated experimentally by mass ($m_b = 38.5g$) and volume ($v = 142595mm^3$) determination of intact beam, obtained by vernier caliper and precision balance, respectively. The dynamic tests were developed in the Laboratory of Vibration, at the Department of Mechanical Engineering, University of Brasilia (UnB-FT/EnM/GDS).

The additional roving mass (m_r) that is used in this work has 7.7 g, approximately 2% of beam total mass as recommended by Palechor (2018). The element beam was divided into 100 elements and the additional mass is placed on each node along the structure.

3.2 Instrumentation and Procedure

The numerical study was realized using the same parameters presented in the last topic. The Timoshenko beam with an additional mass was modeled by FEM on MATLAB software. The modeling of the damage consists of a concentrated mass (m_d) on some node of the beam. Different magnitudes of damage were applied (1 to 5% of the total beam mass). The results will be present in the next section.

The equipment to be used in dynamic experimental essays was: (a) accelerometer PCB 353B03, (b) impact hammer PCB 086C01, (c) VibSoft 2-channels data acquisition, and (d) laptop computer with VibSoft software to data acquisition. The additional mass will be placed along the beam every node. Once the mass is positioned, the modal hammer tests are performed to obtain the Frequencies Response Function (FRF). The fundamental frequency for each position of the additional mass will be identified.

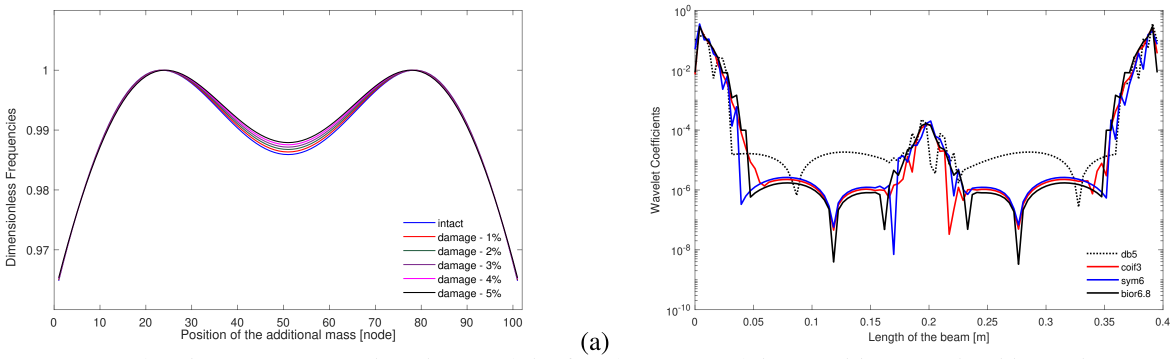
4. RESULTS

In the numerical study, the fundamental frequency of the beam with an additional roving mass was investigated. The material properties and geometry of the aluminum beam were presented in section 3.1 The m_r was placed on each node along the length of the damaged beam.

For the modeling of the damage was applied the technique presented by Papatheou *et al.* (2010) that consists of the application of an additional mass in one point of the structure. Surely, the damage is defined by the alteration on mass/stiffness of the structure, in this case, the mass on the system was increased. In the next topics, we present 2 cases that were studied.

4.1 Case 1 - Free-free beam

Firstly, the aluminum beam is on a free-free boundary condition. Five different concentrated masses (1 to 5% of the beam total mass) are positioned in the half of the beam span to simulate the damage. Fig. 1 (a) presents the fundamental frequency as a function of the additional roving mass position used to identify the presence of damage in the length of the beams. The figure also presents the results obtained with the application of the Discrete Wavelet Transform (DWT) to locate the damage. Four mother wavelet function was tested to detect the damage (db5, coif, sym6, and bior6.8).

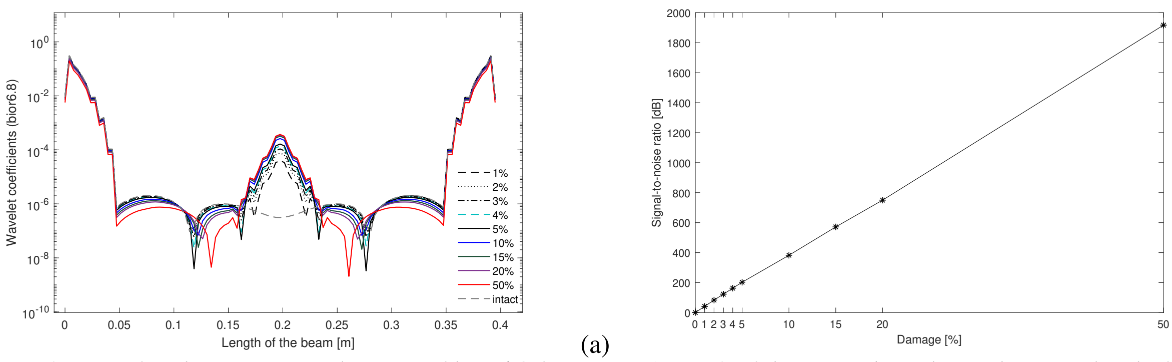


(a) (b)

Figure 1: *Free-free beam: (a) Spatial evolution of the first frequency of damaged beam with additional mass; (b) DWT application for the case of 5% of damage.*

After, the signal-to-noise (S/N) ratio was investigated. The S/N of the dB5 function is equal to 12 dB, coif3 143 dB, sym6 163 dB and bior6.8 203 dB. This way, the chosen function was the bior6.8 because the noise effect is shorter.

Then, five levels of damage were analyzed using the wavelet function chosen and the S/N is observed, like present Fig. 2.



(a) (b)

Figure 2: *Free-free beam: (a) Application of bior6.8 function - 1 to 5% of damage; (b) Relation between level of damage and the S/N.*

It is noted the presence of the damage at the middle of the span of the beam. Next, the Fig. 2 (b) shown that the behavior of the damage is linear for this case.

4.2 Case 2 - Simply-supported beam

Secondly, we investigated the beam in a simply-supported boundary condition. The damage is positioned in the same node of the last case. Fig. 3 presents the graphic of the frequency in function of the position of the additional mass and the result of the application of the DWT for this case.

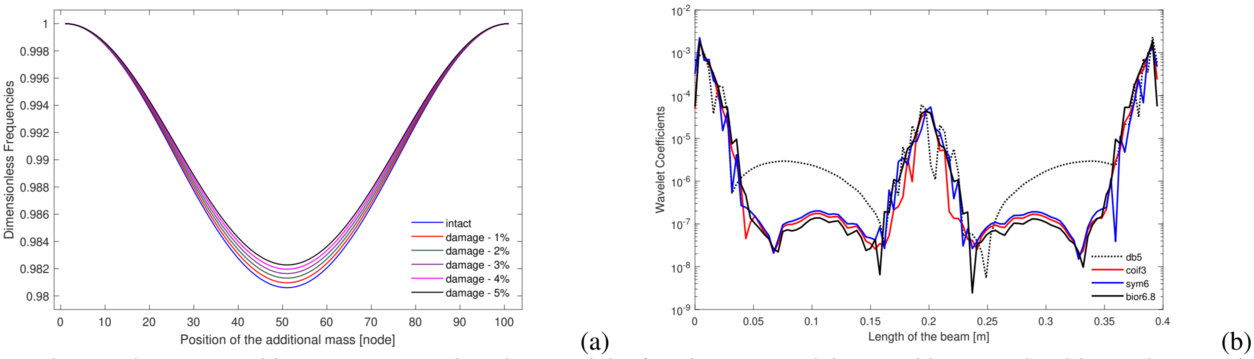


Figure 3: *Simply-supported beam: (a) Spatial evolution of the first frequency of damaged beam with additional mass; (b) DWT application for the case of 5% of damage.*

It is observed that the application of wavelet functions to detect signal damage presents the same behavior. Next, Fig. 4 presents the signal/noise ratio when applying the bior6.8 function.

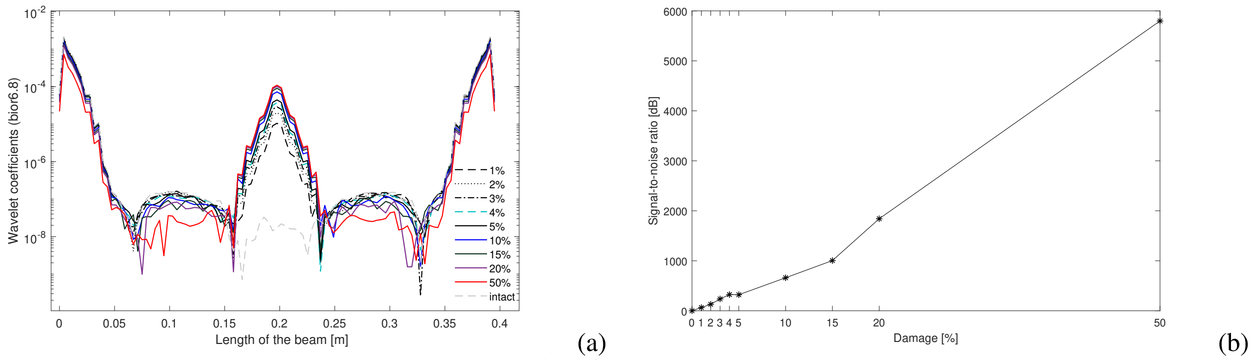


Figure 4: *Simply-supported beam: (a) Application of bior6.8 function - 1 to 5% of damage; (b) Relation between level of damage and the S/N.*

For both cases, the results obtained were consistent. Different levels of damage can be detected from the proposed technique which does not require the previous response to structure damage.

5. CONCLUSIONS

This paper contributes to studies of damage detection in beams, exploring non-destructive methods. The technique based on the frequencies shift using an additional roving mass presented coherent results for the two cases that were investigated (free-free and simply-supported beam). It was possible to conclude the presence of the damage causes the variation in the natural frequencies of the beam. Also, it is possible to observe that the bigger the damage, the bigger this variation.

Different mother wavelet functions (db5, coif3, sym6, and bior6.8) were analyzed and the one that presented the best results was the last, that is, obtained a better signal to noise ratio.

Furthermore, with presented results, it can be concluded that the DWT was able to generate perturbations in the response signals induced by the presence of damage.

Finally, the proposed methodology has shown promise as it only needs to analyze the dynamic data of the damaged structure to successfully localize the damage , unlike other techniques that require the intact and damaged response.

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