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Experimental detection by magnetoelastic sensors and computational analysis with finite elements, of the bending modes of a cantilever beam with minor damage

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ABSTRACT

This work introduces for first time the use of the magnetoelastic sensors as vibration probes for damage detection in mechanical structures such as cantilever beams. The purpose is to show some of the advantages of these materials as vibration detectors, as well as the accuracy of them in detecting the natural frequencies of mechanical structures. The sensor used is a ribbon which is composed of an amorphous metallic alloy known as "Metglas 2826MB3". Various long aluminum alloy beams of the same dimensions but with a single transverse crack at different positions and depths were tested, fixed at one end by using a hydraulic press so as to have consistent boundary conditions. The beams were excited by a single short and intense mechanical contact pulse and then left free to vibrate. The vibrations were forcing the magnetoelastic sensors to change their magnetic state dynamically and thus produce a voltage signal at a close-by external coil. The Fourier analysis reveals seven dominant peaks which lay very close (most of the error values are between 0.5–1.5 %) to the first seven bending mode peaks predicted by the finite-element-method (FEM) commercial software "ANSYS". Thus the current work is a proof-of-principle that the magnetoelastic sensors can be used for damage detection of mechanical structures.

1. Introduction

The term cantilever beam refers to any rigid structural limb projecting horizontally from a vertical support, especially one in which the projected dimension (length) is much greater than the other two dimensions (width and depth). In the field of engineering many structures can be treated as cantilever beams such as, projected parts of bridges and buildings, airplane wings, rotating blades of turbines, etc. These structures are subjected to various adverse conditions during their lifetime which cause damages and increase the risk of failure. When a structure suffers from damages its dynamic properties change and its natural frequencies shift, and by exploiting this information using suitable sensors, damage detection is possible. It is therefore important to develop techniques that can monitor the mechanical state of such structures and be able to determine their health at all times.

Over the years many researchers have tried to develop efficient methods that could detect changes in the dynamic behavior of a structure through the modal parameters such as mode shapes and natural frequencies. Pandey et al. [1] have investigated two different configurations, a cantilever and a simply supported beam, and have shown that changes in the curvature mode shapes (second derivative of mode shape) are localized in the region of damage, and increase with increasing the size of damage. Abdo and Hori [2] examined the rotation of the mode shapes of a steel plate model versus damage detection. They found that changes in the derivative (rotation or slope) of the mode shapes are more sensitive than the changes in the displacement mode shapes and that the rotation of a mode is localized in the region of the damage. Wahab and Roeck [3] investigated the change in modal curvatures towards damage in a prestressed concrete bridge. They introduced a damage indicator called "curvature damage factor" (CDF) in which the difference in curvature mode shape for all modes can be summarized in one number for each measured point. Yazdanpanah et al. [4] proposed a damage detection method by introducing a new mode shape data base indicator (MSDBI) which includes the mode shape, the mode shape slope and the mode shape curvature of a uncracked and cracked beam. Shi et al. [5] developed a sensitive statistical method to localize structural damage by direct use of incomplete mode shapes. Their damage detection strategy was to localize the damage sites first by using incomplete measured mode shapes, and then to detect the damage site and extent again by using

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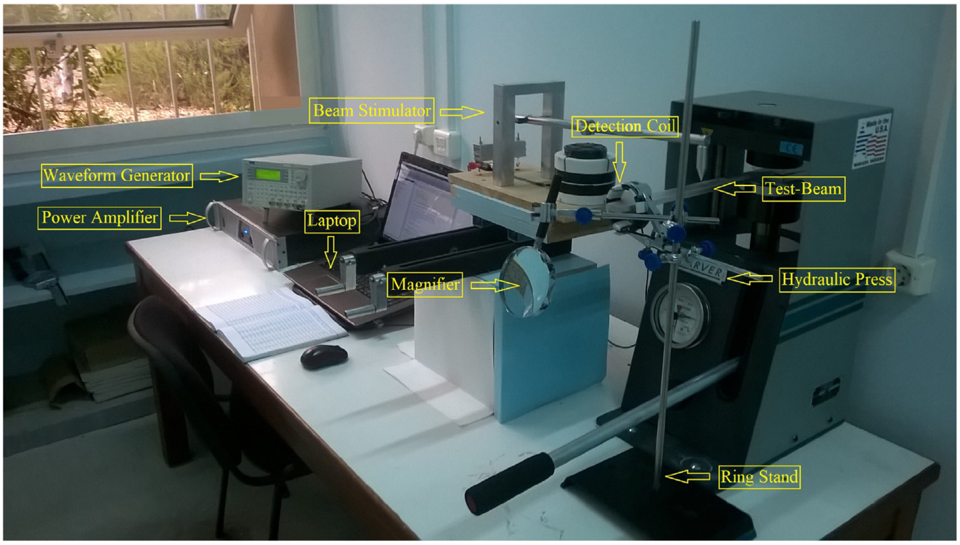

Fig. 1. Experimental setup.

measured natural frequencies. Wang and McFadden [6] are among the first who tried to use wavelets transform for damage detection. They used orthogonal wavelet transform to detect abnormal transients generated by early damage from a gearbox casing vibration signal. Liew and Wang [7] examined the wavelet theory for crack identification of structures. The solved the simply supported cracked beam using both the eigentheory and the wavelet method of analysis, and showed that crack identification via wavelet analysis is accomplished easily whereas it can hardly be detected by the traditional eigenvalue analysis. Chang and Chen [8] presented a technique for structure damage detection based on spatial wavelet analysis. They used the technique to analyze the mode shape of a Timoshenko beam and observed that distributions of the wavelet coefficients can identify the crack position and that the position can be identified even when there are measurement errors. Authors in refs. [9–12] also used wavelet transform method for structure crack detection, through the decomposition of the mode shapes.

An important parameter in the experimental study of the dynamic behavior of a structure is the detection method of the eigenvalues characteristics, such as mode shapes and natural frequencies. Sriram et al. [13] applied a time-domain sorting algorithm to demonstrate the use of a scanning LDV (Laser Doppler Vibrometer) to simulate multiple discrete sensors distributed over the test structure. They illustrated the technique by measuring the second mode shape of a light-weight cantilever beam through the processing of the LDV output signal in the frequency domain. Okafor and Dutta [14] recorded and analyzed with wavelet transform, the first six mode shapes of a damaged and undamaged aluminum cantilever beam using scanning laser vibrometer. A finite-element model of the beams showed a close correlation to the corresponding experimental beam results. Seeley and Chattopadhyay [15] developed a multiobjective optimization technique which includes actuator locations, vibration reduction, power consumption, minimization of dissipated energy and maximization of the natural frequency as design objectives by using piezoelectric sensors. The technique was demonstrated through a cantilever beam problem and showed that performance control can be obtained with only a few optimally placed actuators. Wang and Wang [16] presented a theoretical analysis of the application of piezoceramic transducers to cantilever beam modal testing by considering four pairs of sensors and actuators including accelerometer-point force, accelerometer-PZT, PVDF-point force and PVDF-PZT. Results showed that any sensor-actuator pair can successfully determine natural frequencies and damping ratios. Abramovich and Pletner [17] proposed a piezo-laminated sandwich type structure for active control of sound radiated by harmonically excited thin walled structures. The numerical results are compared with experimental ones obtained during a test series on a cantilever sandwich beam equipped with piezoceramic sensors and actuators, and constructed according to the proposed concept. Sundaresan et al. [18] investigated the concept of a continuous sensor for detecting vibration and stress waves in bars. The sensing material used was PZT fibers patched inside an active fiber composite (AFC) which was bonded to the center of an aluminum panel. Strain, vibration, and wave propagation responses were simulated and results indicate that damage to the bar can be detected by recognizable changes in the sensor output as the wave propagates along the bar and passes over each sensor node.

In this paper an effort has been made to study the dynamic behavior of a cantilever beam using magnetostrictive-magnetoelastic sensors made of an amorphous magnetic alloy. Magnetostriction is the property of some ferromagnetic materials to deform continuously when they are subjected to an external applied magnetic field. The reverse effect, that is the change in the magnetic properties of a material caused by the application of mechanical stress, is known as the magnetoelastic effect. According to Hernado et al. [19] the parameter associated with the energy transfer between the elastic and magnetic subsystems is known as magnetoelastic coupling coefficient k ($0 < k < 1$). By far the best-known materials for mechanical stress sensing are metallic glasses. Authors in refs [20,21] investigated the magnetoelastic coefficient factor of some metallic glasses and found very high values of it ($0.70 < k < 0.97$). They compared the metallic glasses with a conventional strain gage on static stress measurements and calculated sensitivity three to five orders of magnitude. Ausanio et al. [22] examined the in influence of stress on the amplitude of the resonant mechanical waves inside a $Fe_{62.5}Co_6Ni_{7.5}Zr_6Cu_1Nb_2B_{15}$ ribbon for strain and/or 2 stress real-time monitoring in civil buildings. The results exhibited good reliability and stability as well as, better sensitivity [up to 200 times higher in proper conditions using resistive and vibrating wire strain gauges].

In the current work Metglas ribbons are used for the first time, at least to our knowledge, to detect the natural frequencies of a cantilever beam with a single traverse crack, and the results were found to have an excellent agreement by a corresponding FEM model made with ANSYS software. The advantage of this new sensing