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Crack localization on a statically deflected beam by high-resolution photos

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Abstract. In a context where the complexity of systems and their interconnection is increasing exponentially, the possibility of being able to monitor the structural integrity of crucial parts of structures is of considerable importance. In addition, the availability of modern and advanced tools opens the door to the advent of new diagnostic techniques. In this regard, the authors here deeply investigate and test a modern technique that allows to analyze a structure starting from a photo in order to identify and locate damage present in the structure in a rapid and non-destructive way. This allows to obtain an accurate location of the damage and consequently a quick evaluation of its state of integrity. Moreover, a further advantage lies in the possibility of carrying out the analysis in a non-invasive way without any physical interaction with the analyzed structure. The suitability of the technique is tested on a statically deformed beam in epoxy glass laminate. It has a notch, which represents the defect, and the goal is to determine the notch position, which is not visible in the photo. The basis of the proposed method is the correlation between the curvature that the beam presents under load conditions and its flexural stiffness. The damage on the beam, in fact, leads to a punctual alteration of its flexibility which is identified by sudden changes in the second derivative of the transversal deflection. The proposed methodology consists in taking a photo of the inflected beam; subsequently, the acquired photo is manipulated with specifically designed image processing tools, first to segment the beam shape and then to extract its axis. Finally, the second derivative is extracted using two different numerical differentiator filters (Lanczos filters and Gaussian wavelets) along with suitable processing to reduce the border distortions. The tests conducted demonstrate that it is possible to accurately detect the position of the notch. Although the authors realize that the technique can generally need sensibly large displacements, the results seem promising. Such a need is probably due to the resolution of the camera, which can sometimes represent a technological limit. It is believed that higher resolution would allow damage to be detected even for smaller displacements. A fundamental advantage is the speed of the methodology illustrated since it takes just a few moments from taking the photo to evaluating the results. This is accompanied by the ease of acquiring the measurement, which involves the use of the camera and its support without additional equipment.

Introduction

Structural health monitoring (SHM) is a crucial aspect of ensuring the safety and reliability of various engineering mechanical structures such as buildings, bridges etc. The ability to detect, assess, and manage structural degradation or damage is essential for preventing catastrophic failures and minimizing risks. SHM techniques generally consist in collecting data related to structure behavior, load distribution, vibrations, and material properties to analyze using sophisticated algorithms and models to detect any abnormalities or signs of deterioration [1].

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Advantages of computer vision for SHM are several [2,3]: they are generally inexpensive, contactless, non-destructive and allow for the assessment of structural integrity without the installation of sensors directly on the structure, unlike traditional techniques that rely on data collection through accelerometers or strain gauges. Given the advantages, it is not surprising that vision-based SHM techniques are not limited to civil engineering structures but can also be extended to mechanical components (such as beam-type structures) characterized by operational conditions significantly different from those in civil engineering, such as small displacements and high vibration frequencies.

A computer-vision technique is adopted in [4–6] where a computer vision method for measuring the in-plane displacement field of cantilever beams is presented. The purpose of these articles is to carry out a structural health analysis starting from the deformed shape of the beam (acquired by the vision-based algorithm) by exploiting different damage detection techniques: second derivative algorithm, line segment algorithm and voting algorithm in [4], fractal dimension, wavelet transform and roughness methods in [5,6].

The authors' intent in this study is to develop and evaluate the potential of a vision-based method for SHM and damage detection. To achieve this goal, an algorithm was first developed to extract the deformation axis of a deflected beam starting from a photo of it. Then the acquired information is used as input for the damage detection procedure. Its basis is the correlation between the curvature that the beam exhibits under load conditions, and its flexural stiffness (e.g. [7,8]). The damage on the beam results in a localized change in its flexibility, manifesting as abrupt variations in the second derivative of the transverse deflection. Therefore, the proposed methodology can be summarized in two parts: first the acquisition and processing of the photo to extract the axis of the deformed beam, and second, the damage detection using the second derivative method. To conclude, the effectiveness of the proposed method was tested in the laboratory on a beam of which the structural integrity had already been evaluated in a previous study [9]. Furthermore, this allowed for a comparison between a traditional data acquisition methodology (PSD-triangular laser sensor) and a vision-based data acquisition technique.

Materials and Methods

The proposed methodology was tested on an epoxy glass laminate beam with dimensions equal to 500 x 10 x 25 mm; a notch, 2 x 5 x 25 mm, is made at 265 mm from the beam clamped end to simulate the damage.

With the purpose of evaluating suitability of the vision-based data acquisition methodology compared to a classical one (results are available in [9]), the beam was statically deformed to emulate its second mode shape.

The experimental setup (Fig. 1a) was composed by a frame, in which the beam was clamped at one end, two operating screws to impose the deflection shape, and a consumer-grade camera (Canon EOS 1200D) fixed on a tripod. Black cardboard was used as the background to make the beam more visible and to improve the segmentation processing.

The beam was deformed by setting its maximum displacements equal to those measured in [9]; subsequently, such an initial deflection was amplified by 2, 4, 6 and 10 times to test the method sensitivity.

In order to take non-distorted photos, camera calibration was carried out by the Matlab Camera Calibrator Toolbox.

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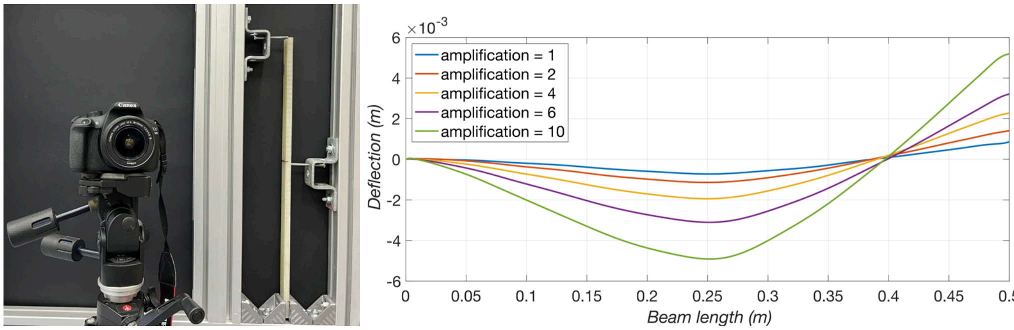

Figure 1: experimental setup (a) and extracted axis (b)

The segmentation algorithm was implemented in Matlab. Its output is a mask in which the beam is the foreground. The beam axis extraction algorithm is applied to this mask; such a procedure employs a $2\Delta_m$ x $2\Delta_n$ pixel window moving along the beam profile by one pixel per step. At every iteration the axis point coordinates (in pixels) are calculated by (1):

$$(x_P, y_P) = \left(\frac{m_{max}+m_{min}}{2}; \frac{\sum_{i=1}^{4\cdot\Delta m\cdot\Delta n} I_i . n_i}{\sum_{i=1}^{4\cdot\Delta m\cdot\Delta n} I_i} \right) \tag{1}$$

where m_{max} and m_{min} are the coordinates, along the beam axis direction, of the extreme pixels of the window, n_i is the coordinate of the i-th pixel in the transversal direction and I_i its intensity. Afterwards, a scale factor S [10] transformed pixel-coordinates into physical units [m]; in particular, photos having a resolution equal to 5184x3456 pixels produced $S \sim 0.1$ mm/pixels.

This procedure allowed the extraction of the bent beam axis $y(x)$ (Fig. 1) which was subsequently processed to estimate its second derivative (Fig. 2).

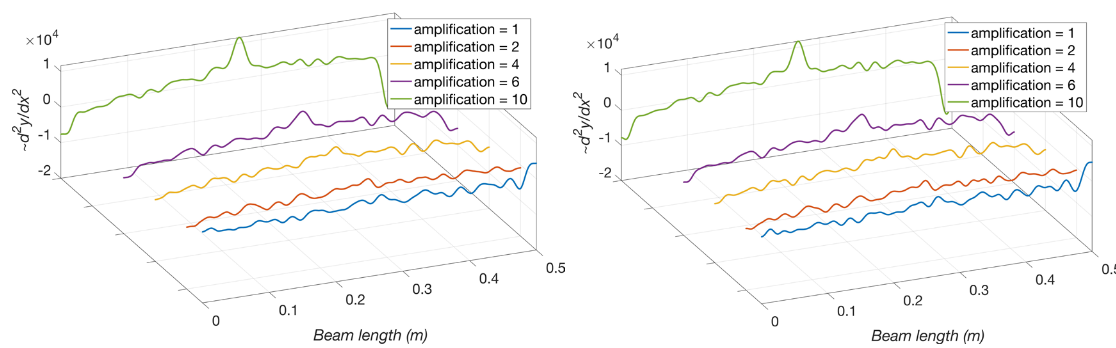

Figure 2: 2nd order derivative calculated by Lanczo's filter (a) and Continuous Wavelet Transform (b)

In particular, Figure 2 shows the second derivatives estimated with two different differentiator filters, i.e. Figure 2(a) represents the estimate through the Lanczos filter [11,12] while the estimate in Figure 2(b) is obtained by means of the continuous wavelet transform [12]. In both cases the second derivative was obtained by performing the numerical convolution (*) of the bent beam $y(x)$ twice through the respective filters of first derivative (h_1 in (2)). This to extend the physical signal through the *Rotation* option for each convolution step for reducing distortions at the edges [13]. Therefore, the following formula was applied for both filters.

$$\frac{d^2y}{dx^2} \cong h_1 * (h_1 * y_{ext})_{ext} \tag{2}$$

The length of the filters was calibrated through dilation parameters which provided similar performance to reject the experimental/numerical noise.

Results

It was observed that the displacements of the reference deformation [9] did not initially allow the damage to be identified with the proposed method. At least, this has been the case with the experimental setup herein used. Sensitivity analyses, based on different amplifications, suggested that a minimum deflection of 3 mm over a 500 mm long beam was needed to have a clear location of the damage.

Conclusions

The purpose of this work was to evaluate the suitability of a vision-based data acquisition method for damage detection compared to previous analyses. The results proved that the proposed vision-based method needs larger displacement than a PSD-triangular laser sensor to acquire valuable data. However, we found this technique is rather encouraging because it allowed to acquire a dense full-field displacement with a minimum effort in comparison to [9] which involved the acquisition of a large number of discrete points in a time consuming way.

Future research will be conducted by considering dynamic shapes of the beam excited by a shaker or, even, by environmental forces.

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