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# Damage identification in beams using speckle shearography and an optimal spatial sampling

M. Mininni [a], S. Gabriele [a], H. Lopes [b], J.V. Araújo dos Santos [c,*]

[a] LaMS – Modelling and Simulation Lab, Department of Architecture, "Roma Tre" University, Italy
[b] DEM, ISEP, Instituto Politécnico do Porto, Portugal
[c] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Portugal

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ABSTRACT

Over the years, the derivatives of modal displacement and rotation fields have been used to localize damage in beams. Usually, the derivatives are computed by applying finite differences. The finite differences propagate and amplify the errors that exist in real measurements, and thus, it is necessary to minimize this problem in order to get reliable damage localizations. A way to decrease the propagation and amplification of the errors is to select an optimal spatial sampling. This paper presents a technique where an optimal spatial sampling of modal rotation fields is computed and used to obtain the modal curvatures. Experimental measurements of modal rotation fields of a beam with single and multiple damages are obtained with shearography, which is an optical technique allowing the measurement of full-fields. These measurements are used to test the validity of the optimal sampling technique for the improvement of damage localization in real structures. An investigation on the ability of a model updating technique to quantify the damage is also reported. The model updating technique is defined by the variations of measured natural frequencies and measured modal rotations and aims at calibrating the values of the second moment of area in the damaged areas, which were previously localized.



## 1. Introduction

Over the last two decades, the structural damage identification problem has been object of an increase in interest by researchers and designers, which are attracted to the economic and safety advantages of its solution. The problem is felt mainly in three engineering areas: civil engineering, where structures, like bridges and buildings, are subjected to several types and different intensities of forces; mechanical engineering, where components of machines and engines are subjected to many cycles of stress during their useful life, and aeronautical engineering, where the constituent parts of the aircraft fuselages and wings are subjected to complex fluid–structure interactions. In all this type of structures there is a high probability that a more or less severe damage will eventually occur. Therefore, the possibility of its identification has high importance for one to be able to schedule a repair or to make a precise estimation of the bearing capacity and the remaining useful life of the structure. The damage identification problem can be faced from different perspectives, leading to a large number of methods. However, none of the methods seems able to give a complete and reliable answer to the problem of

* Corresponding author.
*E-mail address:* viriato@tecnico.ulisboa.pt (J.V. Araújo dos Santos).

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detecting, localizing and quantifying the damage [1]. Among these different methods, the ones based on the changes of the dynamic characteristics of the structure due to the damage development are very important. The basic ideas behind these methods are that, being the modal parameters function of the mechanical and geometric properties of the structure, any changes in these properties cause changes in modal properties. The experimental data most commonly used for the application of the mentioned methods are: the change in the values of the natural frequencies, the mode shapes variations and the differences of the modal rotations and curvatures between the initial or reference state and the damaged state. The most critical issue in the application of these methods is to figure out the sensitivity level of the modal parameters in case of small defects in the structure. In his PhD thesis, Rytter [2] proposed a classification of the ability of the different structural damage identification methods, which is nowadays commonly accepted as a standard classification. This classification is related with different levels of characterization of the damage. These levels can be defined by answering the following questions: (1) Is the structure damaged?, (2) Where is (are) the damage(s)?, (3) Is it possible to quantify the damage(s)?, and (4) What is the remaining service life of the structure?

Pandey et al. [3] proposed the use of the curvature mode shapes as a parameter for detecting and localizing damage in a structure. They show, by using numerical examples and by checking the behavior of the structure between undamaged and damaged states, how the absolute changes in the curvature of mode shapes are localized in the damage region. Therefore, they conclude that the curvature can be used to locate damage in a structure. Besides, it is also possible to see in their study that the changes in curvature mode shapes increase with the increase of the damage size. Pandey et al. also demonstrated that the natural frequencies are not a useful parameter to identify the damage. Since the natural frequencies are a global parameter, they can only be used to detect the damage presence. Furthermore, the same frequencies changes can be due to different damages configurations. Also by using some other parameters, like the modal assurance criteria (MAC) and the coordinate modal assurance criteria (COMAC), it is not possible to identify the damage, since their differences become averaged over all the measurements points or all the mode shapes, not giving any information at local level. Finally, it is also shown that the changes in displacement mode shapes are not restricted to the damaged zones. To demonstrate the usefulness of the curvature mode shapes, the authors applied the finite element method to two different structures in order to obtain the displacement mode shapes. Afterwards, the curvature mode shapes, for which thin structures can be assumed equal to the second derivatives of the displacement mode shapes, are computed numerically by using a second order central difference approximation. Wahab and Roeck [4] introduced a new parameter based on the averaged difference in curvature mode shapes over all available modes. Besides the study using simulated data for a simple and a continuous beam, the authors also applied the technique to really measured data on a prestressed concrete bridge, Z24, which lies crosses the highway A1 between Bern and Zurich. Although the authors say that the application of the method of curvature mode shapes to detect damage in civil engineering structures is very promising, they also state that the quality of the measured mode shapes should be improved using proper techniques.

In order to improve the accuracy of the second order central difference approximation for the computation of the curvature mode shapes, Sazonov and Klinkhachorn [5] presented an optimal sampling interval for discretization of the displacement mode shapes of beams. They also considered the formulas for the computation of the strain energy. This work was motivated because experimental observations show that both undersampling and oversampling of the displacement mode shapes seem to have adverse effects on the quality of damage detection. Guan and Karbhari [6] also presented an improvement to the computation of curvatures using sparse measurements. The method is based on the use of a polynomial depending on vertical displacements and rotations of beams, and the curvature is obtained by differentiating twice this polynomial. Thus, the method does not rely on numerical differentiation. A different approach to the improvement of the damage localization in beams is proposed by Chandrashekhar and Ganguli [7]. According to the authors, the geometric and measurement uncertainty can be alleviated by using a fuzzy logic-based approach. The damage indicator applied is based on curvatures. The changes in the damage indicator, due to uncertainty in the geometric properties of the beam, are studied with Monte Carlo simulations. The fuzzy logic system is developed and tested by studying the variations of the damage indicator due to randomness in structural parameter. Since the damage is numerically simulated, these structural parameters are further contaminated with measurement noise. The results show that the method identifies single and multiple damages in a tapered cantilever beam. The average sum of the mode shape curvature squares for all modes of interest is proposed by Rucevskis and Wesolowski [8] as a way to reduce the influence of the measurement noise present in experimentally measured mode shapes. The proposed indicator is applied to the damage localization in two aluminum beams with different size mill-cut damage at different locations. Tomaszewska [9] proposed a stochastic analysis, instead of the determinist approach, and a damage indicator that distinguish the false results from the true ones in the damage detection procedure. The damage indicator proposed is the difference between the indicators calculated stochastically and deterministically. A simple supported beam and a real building structure are presented as case studies. Improvements on the effectiveness of most damage detection methods can also come from digital signal processing, as proposed by Radzienski et al. [10]. The improvements are greater for wavelet transform, which is more noise independent and versatile. Solis et al. [11] also used wavelet transform for crack detection in beams. Their method includes a curve fitting approach, which also works as a smoothing process, to reduce the effect of experimental noise in the mode shapes. The Teager energy operator together with wavelet transform is used by Cao et al. [12] to deal with the susceptibility to the measurement noise present in the displacement mode shape. This approach is applied to analytical cases of cracked pinned–pinned, clamped-free and clamped–clamped beams. It is also validated by using a scanning laser vibrometer to acquire mode shapes of a cracked aluminum beam. Xu et al. [13] proposed a modification of the second order central finite difference by taking into