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High frequency mode shapes characterisation using Digital Image Correlation and phase-based motion magnification

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ABSTRACT

High speed video cameras provide valuable information in dynamic events. Mechanical characterisation has been improved by the interpretation of the behaviour in slow-motion visualisations. In modal analysis, videos contribute to the evaluation of mode shapes but, generally, the motion is too subtle to be interpreted. In latest years, image treatment algorithms have been developed to generate a magnified version of the motion that could be interpreted by naked eye. Nevertheless, optical techniques such as Digital Image Correlation (DIC) are able to provide quantitative information of the motion with higher sensitivity than naked eye. For vibration analysis, mode shapes characterisation is one of the most interesting DIC performances. Full-field measurements provide higher spatial density than classical instrumentations or Scanning Laser Doppler Vibrometry. However, the accurateness of DIC is reduced at high frequencies as a consequence of the low displacements and hence it is habitually employed in low frequency spectra. In the current work, the combination of DIC and motion magnification is explored in order to provide numerical information in magnified videos and perform DIC mode shapes characterisation at unprecedented high frequencies through increasing the amplitude of displacements.

1. Introduction

Digital Image Correlation (DIC) [1] has been presented in the last decade as an alternative to classical transducers in vibration analysis [2]. High speed cameras allow the use of DIC in dynamic events. Hence, DIC offers solutions to overcome typical drawbacks of accelerometer such as mass addition and improves spatial resolution through full-field displacement measurements. The possibility that DIC offers showing high-resolution contour plots is especially interesting when Operational Deflection Shapes (ODSs) are evaluated exciting with sine signal [3–8] or mode shapes are obtained during broadband excitation [9–14]. In all cases, relevant information of the behaviour of the whole structure is provided, and hence constituting a powerful tool to validate numerical models. As DIC is a displacement measuring technique, low level of displacements related to high frequency excitation represents a challenging task. Cited work presented high quality results regarding ODSs and mode shapes covering a spectrum of hundreds of Hertzs and just few of them obtained acceptable results up to 1500 Hz. High frequency characterisation is also conditioned by the resolution of high speed cameras. Due to current technical limitations of the cameras in the managing of the data memory, the image resolution has to be reduced when higher frame

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ratios are required. The relation of pixel-millimetre, on which DIC bases its accuracy [1], is compromised. Thus, DIC has been better positioned for low frequency events.

A new tool has been explored recently in the interpretation of subtle periodic motion in digital videos. It consists in phase-based motion magnification using image decomposition through complex steerable pyramid filters [15]. Motion magnification has multiple applications in revealing invisible periodic phenomena in the real world such as changes due to blood flow or even as a visual microphone extracting sounds from objects motion [16]. In particular, in this study the interest is focused on structural vibration analysis. Chen et al. [17] applied for first time phase-based motion magnification to visualise ODSs of different structures. The video of the specimen undergoing broadband excitation was magnified by identifying natural frequencies and magnifying the vicinity of the peak. Then, magnified reconstruction of the image shows clearer motion of the corresponding ODS. Yang et al. [18] proposed an autonomous phased-based methodology for complete modal analysis with practically no need for supervision. This methodology is proposed by the authors to monitor structures using just a video-camera with neither surface preparation, as is for DIC and laser vibrometry, nor a laborious, inefficient instrumentation. Although magnified motion visualisation is invaluable for the interpretation of the mode shape, there are cases in which magnification is not enough for a satisfactory visualisation and too much magnification blurs the images, so the perception of the shape of the motion is affected. More difficulties are found in higher order modes as a result of the increasing complexity of the shape.

With an adequate magnification, DIC technique is able to quantify motion that is not perceived by the naked eye, providing contour plots that offer a straightforward interpretation of the shape. Hence, DIC is a helpful complement in the search of a reliable tool to visualise and assimilate vibration shapes. Furthermore, the presentation of the results in form of displacement fields is suitable to compare with numerical models unlike simple visualisations. Additionally, full-field displacements provide more detailed information for model updating [4,19,20]. Thus, the combination of phase-based motion magnification and Digital Image Correlation would represent an interesting advance which allows the measurement of high quality displacements maps of periodic events even when low displacements (i.e. high order modes) occurs on the studied element.

In this work, a combination of DIC and phase-based motion magnification is explored in order to analyse mode shapes at unprecedented frequencies with DIC. The benefits of contour plots together with visualisation of magnified motion in the interpretation of video mode shapes are also presented. Special attention is paid to frequencies of the order of thousands of Hertz. To evaluate the procedure, a cantilever beam was analysed considering its separated and well-defined modes. Identification of natural frequency was firstly performed and compared with FEM model results. Subsequently, mode shapes were studied by acquiring images of the lateral edge of the beam while resonances are individually forced. Two extreme levels of excitation at each frequency, low and high, were studied to evaluate limitations in the measuring process, in the excitation hardware and in motion magnification. Limitation of resolution in high speed cameras to register high frequency mode shapes was worked out using strobe effect. Maximum resolution was thus available. Phase-based motion magnification method proposed in [15] was employed to evaluate improvements in contour plot video using different magnification factors. Mode shape of the FEM model was considered as reference to study the evolution of the error in the shape versus the magnification factor and analyse if this magnification procedure introduces some aberration in the image. A selection of tests is also presented in video format as online resources in the electronic version to enable the visualisation and interpretation of the motion in conjunction with DIC measurement and evaluate the capabilities of this combination.

2. Materials and methods

The proposed combination of DIC and phase-based magnification was performed in this study on a stepped bar of 2024 aluminium, shown in Fig. 1 which was designed for optical system calibration [21]. The behaviour of the thinner part corresponds to a cantilever beam and it is easy to predict by theoretical analysis or numerical models. The dimension of the thinner part was 160 mm in length, 40 mm in width and 4 mm in thickness.

The experimental procedure consisted in two stages of modal characterisation of the beam: natural frequencies identification and mode shapes characterisation. Excitation was performed by an electrodynamic shaker (Data Physics GW-V55/PA300E) in both cases. A clamping system fixed the beam from the thicker part to the shaker's armature, as seen in Fig. 2.

2.1. Natural frequencies identification

Natural frequencies were determined by inspecting the frequency response. As seen in Fig. 2(b), two accelerometers were employed, monitoring the excitation in the clamping device and the response signal at a point located 27 mm from the

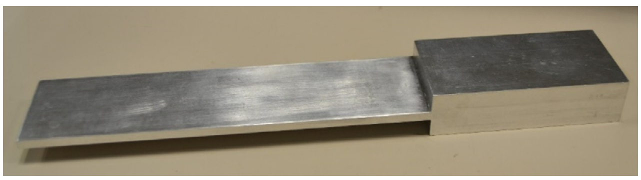

Fig. 1. Specimen of analysis: stepped cantilever bar.