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A new procedure of modal parameter estimation for high-speed digital image correlation

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ABSTRACT

The paper deals with the use of 3D digital image correlation in determining modal parameters of mechanical systems. It is a non-contact optical method, which for the measurement of full-field spatial displacements and strains of bodies uses precise digital cameras with high image resolution. Most often this method is utilized for testing of components or determination of material properties of various specimens. In the case of using high-speed cameras for measurement, the correlation system is capable of capturing various dynamic behaviors, including vibration. This enables the potential use of the mentioned method in experimental modal analysis. For that purpose, the authors proposed a measuring chain for the correlation system Q-450 and developed a software application called DICMAN 3D, which allows the direct use of this system in the area of modal testing. The created application provides the post-processing of measured data and the estimation of modal parameters. It has its own graphical user interface, in which several algorithms for the determination of natural frequencies, mode shapes and damping of particular modes of vibration are implemented. The paper describes the basic principle of the new estimation procedure which is crucial in the light of post-processing. Since the FRF matrix resulting from the measurement is usually relatively large, the estimation of modal parameters directly from the FRF matrix may be time-consuming and may occupy a large part of computer memory. The procedure implemented in DICMAN 3D provides a significant reduction in memory requirements and computational time while achieving a high accuracy of modal parameters. Its computational efficiency is particularly evident when the FRF matrix consists of thousands of measurement DOFs. The functionality of the created software application is presented on a practical example in which the modal parameters of a composite plate excited by an impact hammer were determined. For the verification of the obtained results a verification experiment was conducted during which the vibration responses were measured using conventional acceleration sensors. In both cases MIMO analysis was realized.

1. Introduction

Non-contact optical methods allowing full-field measurements belong to the current trends in experimental mechanics. Into this group scanning laser Doppler vibrometry (SLDV), electronic speckle pattern interferometry (ESPI), digital speckle

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shearography (DSI), and digital image correlation (DIC) can be incorporated [1,2]. In vibration analyses, laser vibrometry is preferred for practical reasons. To its main advantages belong high sensibility, frequency range, accuracy, flexibility, promptness and ability to measure over long distances. The biggest drawback is the relatively high price of measuring devices. Laser Doppler vibrometry has a wide range of uses in different areas of science and research, which is evident in the great deal of published contributions devoted to experimental modal analysis, operational modal analysis, analysis of operational deflection shapes and vibrodiagnostics. Šároši et al. [3] used LDV for complex analysis of disc vibration during its rotation. For that purpose, they performed experimental modal analysis of the disc in stationary condition, the measurement of operational deflection shapes at 5000 rpm and a run-up analysis, in which the aim was to assess the influence of rotational velocity to shifting natural frequencies of the disc. A scanning laser Doppler vibrometer and an optical derotator were used for the measurement. The excitation of the disc was provided by a volume velocity source (VVS) from LMS company. The paper [4] is an example of using the continual scanning technique (CSLDV). In this work Zucca et al. used SLDV technique for acquiring frequency response functions and operational responses of 24 turbine blades at a specific angular velocity. Stanbridge et al. [5] introduced an effective approach of scanning (sinusoidal area scan), which allows to obtain vibration mode shapes with a relatively small data set. Roozen et al. [6] used LDV technique for the measurement of radiated sound power of a building element in a transmission suite. Trebuňa et al. [7] applied a laser vibrometer to identify sources of excessive vibration of a gas compressor outlet pipe. The use of the laser vibrometer was necessary in regard to the level of vibration, when accelerometers could not be used. The application of laser Doppler vibrometry in operational modal analysis is described in the papers [8,9].

Digital image correlation is another method which has potential for use in vibration analysis [10], for this purpose it is necessary to use of high-speed cameras. Although the DIC method is mainly utilized for testing of components and determination of material properties [11–13,18], various contributions devoted to vibration analysis as well as modal analysis are published. There are well known papers dealing with motion analysis in a plane or a space [14,15].

The principle of DIC is known from the eighties of the last century [16,17], however its biggest development was denoted at the end of the nineties due to advances in the areas of computer technology and digital optics. The conception of the method allows observation of various phenomena during deformation and/or movement of an object, and the method is suitable for testing of a wide range of materials. The fundamental of digital image correlation is based on capturing of a stochastic speckle pattern created on an investigated object surface, e.g., by the spraying of black color on a white background. The use of preprinted vinyl foils is also convenient [18,20]. An observed region is divided into smaller subsets, so-called facets, in such a way that each of facets includes a characteristic part of speckle pattern with sufficient contrast in order to be ensured its uniqueness. The relative displacements are determined by correlation of corresponding facets in a state before and after deformation of the object, or with regard to a reference step. As the system tracks a wide range of points on the object surface via two cameras, the obtained results are in the form of displacement component fields in directions x, y and z [2]. The principle of DIC is graphically expressed in Fig. 1 and explained in detail in the book [19].

As DIC method measures responses in the form of displacements, frequency response functions (FRFs) are in the form of receptance. The sensibility of the measuring system depends on the resolution of CMOS sensor and size of measured surface. The frequency range is limited by the sampling frequency of cameras, i.e. the reciprocal value of a minimal shutter time. Currently there are high-speed cameras with sampling frequencies from several thousand up to several hundred thousand fps at full resolution of a sensor. If the sensor region of interest is decreased, then the maximal frame rate is increased. Measurements at high frame rates require using of an additional source of illumination for ensuring of optimal light conditions. For that purpose, high-power reflectors with specified achromatic light are commonly used. The major advantage of DIC is an ability to capture the responses of all points on the object surface in the same time and under the same conditions as an excitation. When compared to conventional techniques it means a significant time savings in terms of measurement because it is not necessary to relocate the sensors and repeat the measurement several times. However, it is necessary to note that the correlation is relatively time consuming. The density of measuring points (mesh points) and also accuracy of the measurement is dependent on the facet size. Authors [20] investigated the influence of the facet size on modal parameters estimated from DIC measurement. They found that the facet size has no impact on natural frequencies, however, in the case where the facets are too small, an increase in correlation errors which introduce inaccuracies to frequency response func-

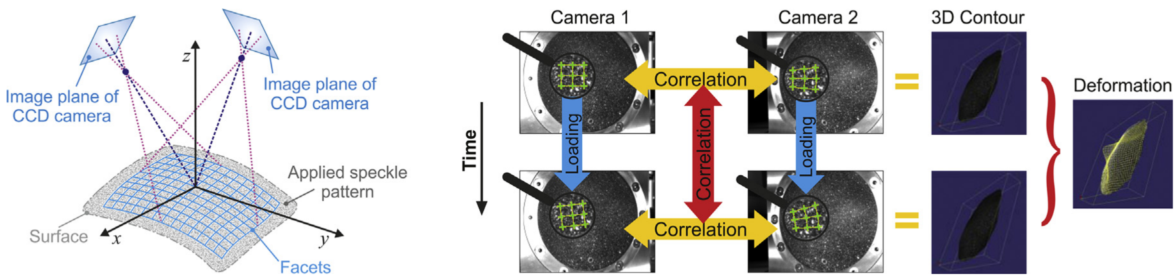

Fig. 1. Basic principle of 3D digital image correlation.