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Photogrammetry and optical methods in structural dynamics – A review

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ABSTRACT

In the last few decades, there has been a surge of research in the area of non-contact measurement techniques. Photogrammetry has received considerable attention due to its ability to achieve full-field measurement and its robustness to work in testing environments and on testing articles in which using other measurement techniques may not be practical. More recently, researchers have used this technique to study transient phenomena and to perform measurements on vibrating structures. The current paper reviews the most current trends in the photogrammetry technique (point tracking, digital image correlation, and target-less approaches) and compares the applications of photogrammetry to other measurement techniques used in structural dynamics (e.g. laser Doppler vibrometry and interferometry techniques). The paper does not present the theoretical background of the optical techniques, but instead presents the general principles of each approach and highlights the novel structural dynamic measurement concepts and applications that are enhanced by utilizing optical techniques.

1. Introduction

Recently, there has been a growing interest in testing tools that can provide global information about the dynamics of structures. This information is used for understanding fundamental physics of structures and monitoring their dynamics as well as validating and updating analytical models. The computer simulation approaches such as the finite element (FE) method can provide full-field results over an entire structure. On the other hand, the conventional measurement techniques (e.g. accelerometers or strain gages) for all practical purposes can only provide measurements at a few discrete locations. Thus, there is a severe mismatch between the few measurement degrees of freedom for the empirical data compared to the potentially millions of degrees of freedom in the FE model that prevents a meaningful and effective correlation. Some reduction/expansion techniques have been used to correlate the measurement results with analytical models. However, because these techniques are usually extracted using analytical models, they may not be able to accurately represent the actual properties of the structure. Furthermore, the conventional sensors may induce mass loading and generally need wiring for data or power transmission. Therefore, for quite some time there has been a significant need for a non-contact measurement approach that has distributed sensing capability while not adding mass or stiffness to the structure or affecting the true dynamic motion through the addition of externally mounted sensors.

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The optical technology as a non-contacting measurement technique has seen many advances in the last few decades that have manifested itself because of the exceptional advances in computer power, memory storage, and camera sensors. Generally, the optical measurement techniques can be categorized in two groups: (1) the approaches that use laser beams and (2) the approaches that use white light. Laser Doppler vibrometry, electronic speckle pattern interferometry (ESPI), and digital speckle shearography (DSS) all use laser beams to monitor the dynamics of structures. The second class of optical techniques works by using white light and is called image based systems. Photogrammetry falls into the second category and leverages rays of light that are reflected from a structure.

Photogrammetry is a measurement technique that is used to extract the geometry, displacement, and deformation of a structure using photographs or digital images. The concept of photogrammetry is related to perspective concept and goes back to Leonardo da Vinci [1]. In its early days, photogrammetry was used for aerial and terrestrial applications largely motivated by military reconnaissance. With the advances in digital cameras and the ability to buy inexpensive, high resolution cameras, the applications expanded and included other branches of science such as civil and mechanical engineering. Researchers have used terms such as close range photogrammetry, videogrammetry, dynamic photogrammetry, computer vision, machine vision, and robot vision to refer to this measurement technique [2]. Two-dimensional (2D) photogrammetry uses a single fixed camera and is limited to in-plane deformation measurements of the planar object surfaces. If the test object is curved, or three-dimensional (3D) deformations occur after loading, the 2D photogrammetry will generally no longer be able to provide accurate results. The analytical aspects of the stereovision concept for 3D measurement were studied by Pulfrich and Fourcade in the 1900s [1]. The early applications of the photogrammetry were limited to extracting rigid body displacements of objects or discrete points on objects rather than collecting full-field information.

The idea of using photogrammetry to measure mechanical stress/strain during deformations in structures was first introduced by Peters and Ranson in 1980s [3]. Using a numerical model of a plate in uniform tension, they introduced the concept of subset in an image and combined digital imaging with an experimental boundary integral method to extract stress in structures. Sutton, Chu, and colleagues [4,5] expanded this approach and used it to perform a two-dimensional digital image correlation (2D DIC) on a specimen. This optical measurement technique includes image processing and numerical computation for measuring deformations of structures. The surface geometry is usually determined by observing a speckled pattern (typically black and white) and monitoring how the pattern deforms when multiple images from a sensor pair are captured in time. The three-dimensional point tracking was also developed based on using multiple cameras and the principles of photogrammetry [6]. Nowadays, stereovision and multiple-camera measurements are widely used to measure deformations and geometries of structures.

Photogrammetry and digital image correlation have matured over the last three decades and have been applied to the field of experimental solid mechanics [7], aerospace industry [8], 3D shape measurement [9], civil engineering and bridge inspection [10]. By improving camera technologies and production of new high-speed cameras, more recently researchers have begun to exploit the optically based approaches for measuring vibrations. Stereophotogrammetry, point tracking, and target-less vision have recently enabled new opportunities for measuring the dynamics of structures. The current paper is an effort to review the research papers published in this area. The paper begins by presenting a brief overview of the fundamentals of the photogrammetry technique and follows by comparing photogrammetry to other measurement techniques.

2. Fundamentals of photogrammetry

Digital photogrammetry is a non-contacting measurement approach that uses a series of images recorded with imaging sensors such as charge-coupled devices (CCD), complementary metal-oxide semiconductor (CMOS), and infrared cameras to identify coordinates of points, patterns, and features in the images or to detect the boundaries of objects. A single camera can be used to measure displacement of objects in a planar motion. However, 3D measurement must be performed using stereo cameras whose relative position is fixed in place during a test while images (or photos) are simultaneously recorded. The optical targets or features are found in the images and tracked to identify deformations. For 3D measurements, a triangulation technique using a ray-tracing process is used to determine the coordinates of features in test structures (see Fig. 1). Similar to many other measurement tools, a calibration process for the photogrammetric cameras needs to be performed before the test. The objective of the calibration process in photogrammetry is to identify lens distortions, camera pair's relative position (for 3D measurement), bundle adjustment, and scale of the units. A common approach for calibrating a photogrammetry system is to calibrate single cameras and then the stereovision system [11]. For the calibration process, a series of photos are recorded from a pattern that is fixed during calibration. This pattern can include coded targets, uncoded targets, or a combination of both. Usually, a minimum of two scale bars (measurements between two points in the calibration pattern) is needed to finalize the calibration.

In broad terms, the photogrammetry technique can be categorized based on the type of targets used into point-tracking (PT), digital image correlation (DIC), or target-less approaches. These three techniques are reviewed herein.

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