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Comparison of FRF measurements and mode shapes determined using optically image based, laser, and accelerometer measurements

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ABSTRACT

Today, accelerometers and laser Doppler vibrometers are widely accepted as valid measurement tools for structural dynamic measurements. However, limitations of these transducers prevent the accurate measurement of some phenomena. For example, accelerometers typically measure motion at a limited number of discrete points and can mass load a structure. Scanning laser vibrometers have a very wide frequency range and can measure many points without mass-loading, but are sensitive to large displacements and can have lengthy acquisition times due to sequential measurements. Image-based stereo-photogrammetry techniques provide additional measurement capabilities that compliment the current array of measurement systems by providing an alternative that favors high-displacement and low-frequency vibrations typically difficult to measure with accelerometers and laser vibrometers. Within this paper, digital image correlation, three-dimensional (3D) point-tracking, 3D laser vibrometry, and accelerometer measurements are all used to measure the dynamics of a structure to compare each of the techniques. Each approach has its benefits and drawbacks, so comparative measurements are made using these approaches to show some of the strengths and weaknesses of each technique. Additionally, the displacements determined using 3D point-tracking are used to calculate frequency response functions, from which mode shapes are extracted. The image-based frequency response functions (FRFs) are compared to those obtained by collocated accelerometers. Extracted mode shapes are then compared to those of a previously validated finite element model (FEM) of the test structure and are shown to have excellent agreement between the FEM and the conventional measurement approaches when compared using the Modal Assurance Criterion (MAC) and Pseudo-Orthogonality Check (POC).

1. Introduction and motivation

Modal testing can be performed using a variety of different experimental techniques. Accelerometer, laser vibrometer, and stereo-photogrammetry measurement systems all have advantages and drawbacks, so each must be implemented where they will be most effectively employed. Accelerometers are by far the most traditional and widely used sensors employed in modal testing. Their ease of use allows for quick, broadband measurements to be made, however the effects of mass-loading (especially at higher frequency ranges or for lightweight structures) can corrupt a measurement and a large channel count can be challenging due to cost and bookkeeping. Laser Doppler vibrometers provide a non-contacting,

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broadband alternative to accelerometers, but large displacements and rigid body motion can dramatically contaminate the data and measurements over an area need to be scanned sequentially. Conversely, three-dimensional (3D) digital image correlation (DIC) and 3D point-tracking (3DPT) (or dynamic photogrammetry) are both displacement based approaches that analyze stereo image pairs to measure the 3D motion of surface patterns or specific points, respectively. Stereophotogrammetry has been used for many years in the field of solid mechanics to measure full field displacement and strain, but only very recently has the technique been exploited for dynamic applications to measure vibration [1–6]. As with laser vibrometry, a line of sight for both cameras must be maintained with the measurement points of interest. Furthermore, surface preparation is required for both techniques; a speckle pattern is applied to a test object prior to imaging for DIC while 3D point-tracking tracks high-contrast, circular targets. Three-dimensional point-tracking monitors the response at these discrete targets, while DIC is capable of providing a relatively continuous measurement on the order of tens of thousands of points, throughout a continuously patterned surface. More details and an overview of DIC measurement can be found in Ref. [6].

The primary motivation for exploring DIC as a measurement approach for structural dynamics is the fact that this non-contacting full-field technique can take shape measurements at thousands of points on the surface of an object in a single snapshot. With this abundant wealth of information now available from test, the ability to perform meaningful correlation with large scale finite element models is greatly improved as well as to monitor the full-field transient response of a structure in a single test.

Likewise, with the advent of digital cameras, optical point-tracking is becoming a more common method to track the motion of optical targets that are attached to a rigid or flexible body. To date, 3DPT has not been validated within the field of structural dynamics as a non-contacting vibration measurement tool. When evaluating the performance of any new system or technique, it is critical to compare the new approach to existing measurement methods or to analytical solutions. To accomplish this end, a well documented and understood test article were chosen to compare the image-based approaches to established measurement techniques. A structure known as the "Base-Upright" (BU) was chosen for its well-known dynamic characteristics to compare these four measurement approaches (DIC, 3DPT, laser vibrometry, and accelerometers). Test setups and measurement considerations for each case are addressed. Each test is correlated to a well known and highly accurate finite element model and to the other test cases using the Modal Assurance Criterion (MAC) or Pseudo-Orthogonality Check (POC).

To obtain accurate mode shapes from accelerometer and vibrometer FRF measurements, modal parameter estimation must be performed. With both optical based systems studied in this paper, the mode shapes are measured directly using low-speed cameras and forced normal mode testing (FNMT). A summary of past work using accelerometers, laser Doppler vibrometers, and low-speed cameras is presented, followed by a thorough discussion of the setup and results of tests run with high-speed cameras. Finally, conclusions are drawn to highlight the strengths and weaknesses of 3D point-tracking using high-speed cameras relative to the other measurement techniques.

The use of digital image correlation for vibration measurement is currently in its infancy. To the authors' knowledge, this paper represents the first attempt to obtain frequency response function measurements for a vibrating structure using 3DPT while simultaneously validating the shape of the two optically based measurements to the two other traditional vibration measurements as well as to a finite element model. Some of the advantages of the technique are discussed along with limitations that must be considered.

2. Description of the test article and finite element model

The BU was designed to be a time-invariant mechanical structure with well-spaced, directional modes that could be identified easily. Fig. 1a shows the BU with the primary dimensions labeled. The base plate is 24×24 in (0.6096×0.6096 m^2) in dimension and rigidly bolted to the concrete laboratory floor at four locations, while the upright

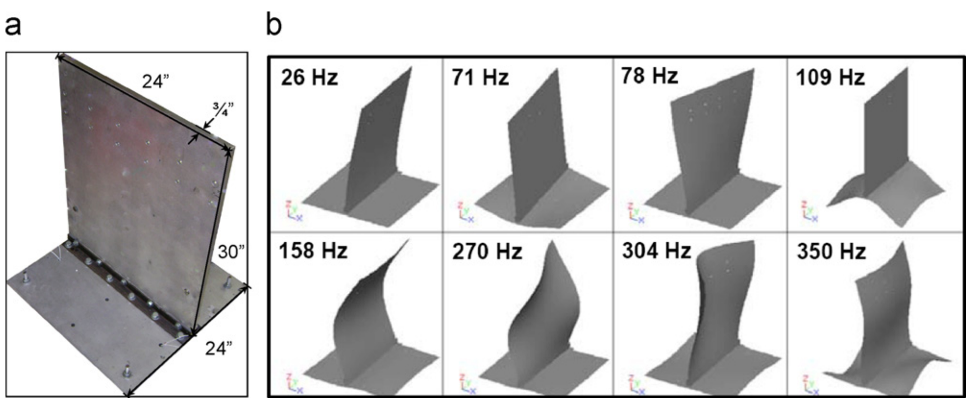

Fig. 1. (a) Photo of the base-upright (BU) with dimensions and (b) first 8 analytical frequencies and mode shapes of the BU.