High Spatial Density Vibrational Measurements via 3D-Particle Tracking Velocimetry

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ABSTRACT: Within a structural health monitoring (SHM) framework, the performance of a monitoring system is considerably influenced by the number of deployed sensors, their positions and orientations as well as their performance characteristics. With the recent advancements in low-cost sensor technologies, high spatial density sensor networks have become affordable. However, there are still difficulties to overcome, i.e., the inability of measuring a multi-scale and 3-dimensional phenomenon using a single sensor, deployment constraints, heavy cabling and the available number of channels for a reasonable cost. Wireless sensors, despite the recent progress, are still lacking of self-sustaining energy management solutions. Capitalizing on recent advances in low-cost video recording devices we propose a new approach for dynamic measurements based on three dimensional particle tracking velocimetry (3D-PTV).
In order to assess the performance and accuracy of the proposed method, a 4-story shear frame was excited on a uniaxial shake table with different input signals and its response was recorded with a high-speed camera equipped with an image splitter that mimics a stereoscopic 4-camera arrangement. A spatially dense pattern of markers was painted on the frame and subsequently tracked by the 3D-PTV algorithm to extract displacement and velocity information. Phase-Based Motion Magnification (PBMM) was used to amplify the small amplitude motions within certain frequency bands. For validation, accelerometers and a 3D infrared light tracking system was used. Results demonstrate a good agreement between 3D-PTV and conventional tethered measurement systems, validating the performance of this method for moderate to high range motions, and methods to tackle very small motions are discussed.

1 INTRODUCTION

With the increasing interest in identification and continuous monitoring of engineering structures, substantial effort is put into the development of affordable-yet-sensitive sensor technologies, efficient data acquisition, as well as powerful feature extraction and discrimination methodologies (Sohn, et al., 2003). In order to obtain an adequate knowledge about the behavior of a structure, a fairly high number of sensors are required, whether it be for global or local structural response (Zhang & Xu, 2006). With recent advancements in low-cost sensor technologies, SHM has become an accessible tool to implement for civil structures. However, room for improvement still remains, particularly for the development of measurement techniques offering high-spatial density information without the need for heavy cabling, deployment constraints as well as providing a reasonable cost per channel availability. Optimal sensor placement methodologies are a current focus of research, which aim to maximize the amount of information from the least amount of sensors (Papadimitriou, 2004) by precisely calculated arrangements. A potentially different way to tackle this problem is to couple optical acquisition devices (video cameras) with appropriate image processing techniques. Optical measurement techniques allow non-intrusive (non-contact) and high spatial density information within its field of view. The limitation of using optical sensors for civil engineering structures lies in the reality of structures typically experiencing very low amplitude displacements during operational conditions. Even with today's high resolution imaging technology, the movements of such structures are barely perceivable, which hinders their use for SHM. A recent development in computer vision, namely the Phase-Based Motion Magnification (PBMM) by Wadhwa et al. (2013), opens up new possibilities in the implementation of optical measurement techniques in SHM. PBMM allows for motion amplification in selected temporal frequency bands of a recorded video by making use of its local phase variations. The feasibility of this method for SHM was investigated by Chen et al. (2015) on simple structures, employing optical flow to measure displacements. Real-time magnification up to 35 frames per second (fps) (Chen et al. (2015b)), and long-range measurements in outdoor settings (Chen, et al., 2016) were explored by the same authors. Terán et al. (2016) conducted a similar study, yet using digital image correlation techniques for displacement measurements. Yang et al. (2017a, b) used blind source separation techniques and spatiotemporal pixel information together with PBMM for modal analysis. Lastly, Zimmermann et al. (2016) have employed a PTV approach to obtain displacements and velocities from original and motion magnified high speed videos.

A common trait of all works mentioned above is that the captured videos are in two dimensions (2D) only, since only one camera is used. In many cases placement of the camera in an ideal setting, i.e., perpendicular to the structure may not be feasible, which leads to inaccurate estimates of displacement. Additionally, considering the fact that many civil engineering structures do contain out-of-plane motion (torsional mode shapes), a 3D setup would greatly enhance SHM based on video recordings. This work proposes a novel SHM framework, which relies on the use of a non-invasive optical measurement technique, 3D-PTV (Maas et al. (1993), Virant and Dracos (1997), Willneff and Gruen (2002)) by employing a high-speed camera equipped with an image splitter that mimics a stereoscopic camera arrangement. A 4-story shear frame was excited on a uniaxial shake table and its structural response was measured with accelerometers, a commercial optical system (NDI - Northern Digital Incorporated) and the aforementioned stereoscopic camera arrangement. The markers placed on the structure are then tracked to obtain the displacements and compared to accelerometers and the NDI system for its accuracy within time and frequency domains. The comparison in frequency domain was conducted employing the 3D-PTV algorithm after magnifying recorded videos in frequency bands where the resonant frequencies were expected to be.

2 EXPERIMENTAL INVESTIGATION AND METHODOLOGY

2.1 Experimental Investigation

A 4-story shear frame (floor: 500 × 470 mm, story height: 550 mm) was fixed on a uniaxial shake table and excited using several ground excitations. Two types of conventional sensors were used to compare and validate the optical measurements. A set of biaxial MEMS accelerometers were attached to the floors to obtain accelerations and the commercial NDI system (Optotrack Certus) was used to obtain 3D-displacements. An overview of the experimental setup can be seen in Figure 1.

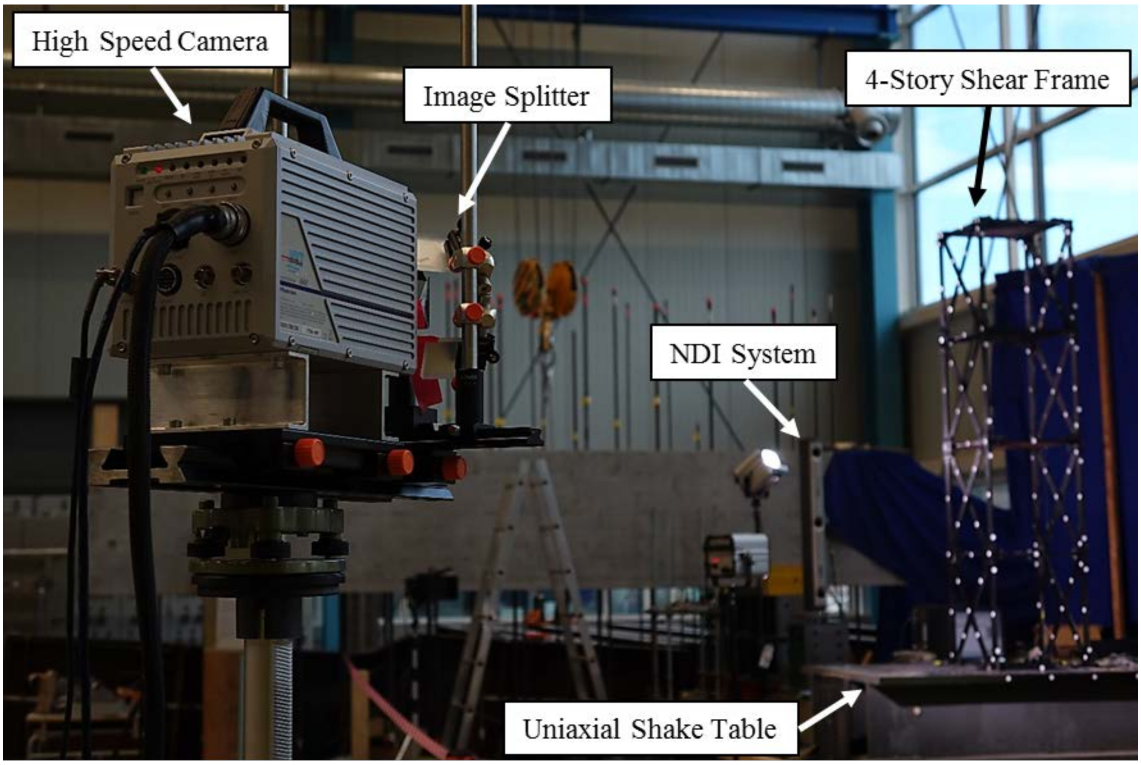

Figure 1: Overview of experimental setup (3D-PTV system including high speed camera and image splitter, NDI System, Uniaxial shake table and shear frame)

2.2 Measurement systems

2.2.1 3D-PTV System

3D-PTV is a non-intrusive image-based Lagrangian flow measurement technique, which has been in use for decades in fluid mechanics research to measure particle displacement, velocity, acceleration, and turbulence related parameters such as turbulent kinetic energy and energy dissipation in different complex flows (Lüthi et al. (2005), Holzner et al. (2008), Gülan et al. (2012)). Recently PTV has been used to assess the structural health monitoring for the first time (Zimmermann et al. (2016)). The technique has been applied to a 3-DOF cantilever structure for measuring the displacement in 2D in the scope of structural healthy monitoring via video recording. The results obtained via PTV were validated using the data from accelerometers which reveals that the technique allows assessing the modal characteristics of structural systems.

The main principle of the 3D-PTV algorithm comprises four different steps, i.e. calibration, pre-processing, processing and post-processing. The calibration step determines the external and internal camera parameters, e.g. position, orientation, focal length (Gülan et al. (2012)). In this study the calibration is performed statically using the initial position of the markers obtained via the NDI system. In the pre-processing step the images are low-pass filtered to remove pixel noise. In the processing phase, the image coordinates of the markers are detected relying on grey value intensity and connectivity on the 2D image. Thereafter, the 3D positions of each marker are calculated using the four stereoscopic camera views. In the final part of the processing the 3D positions are tracked in time to establish Lagrangian trajectories. One of the advantages of the technique is that it allows extracting displacement, velocity and acceleration of the markers. An illustration of the processing steps, from a single view of the stereoscopic arrangement, is presented in Figure 2.

Videos were recorded with a frame rate of 500 fps, with a resolution of 1024x1024 pixels for the entire stereoscopic image containing 4 views of the frame. Two LED spotlights were used to ensure adequate illumination and increased contrast between the background and the markers. As markers white paper stickers with a diameter of 18 mm were used.

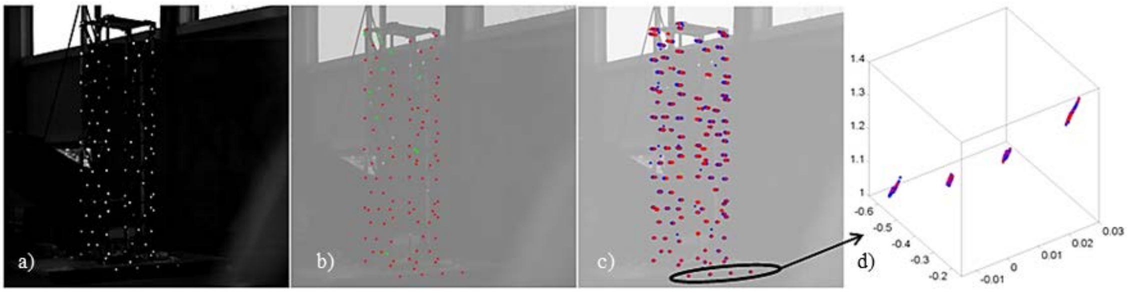

Figure 2: a) Raw image of the region of interest and the markers from one view of the camera, b) markers detected by the software (red corresponds to the ones seen by four cameras, green corresponds to the ones seen by three cameras), c) tracked markers and their paths for 0.1 seconds, d) a close-up view of the tracked marker trajectories on the shake table in 3D space.

2.2.2 NDI System

The Optotrack Certus system (NDI) is a commercial optical motion tracking device that can capture 3D motion in real time. It captures the position and orientation of special wired markers that emit a short light pulse within $20m^3$ measurement volume. An accuracy of 0.1mm and resolution of 0.01mm is provided by the producer. It should be noted, however that this optical system does not give any images as output, but only processed displacement-time results. A limitation of this system is a maximum measuring distance of ~6 m to the target and a sampling rate that depends on the amount of markers used, given by the relationship $F_s = 4600/(n+1.3)$, where n denotes the number of markers. Eight markers were used during this experimental investigation, resulting in a maximum available sampling frequency of Fs ~ 494 Hz. The sampling frequency of this system was thus selected to be 250 Hz.

2.2.3 Accelerometers

Eight biaxial MEMS accelerometers were used, where one accelerometer was installed on the shake table and the remaining 7 were installed in different configurations on the shear frame. Data acquisition was performed with a 16-channel DAQ (Q.series, Gantner), with a sampling frequency of 500 Hz.

3 RESULTS AND DISCUSSION

As an initial step, the time-domain response of 3D-PTV was compared to the NDI system for a marker on the shake table, which is excited by a sine wave of 3Hz period and 6 mm amplitude. Displacements obtained from 3D-PTV in the direction of the shake table movement, as seen in Figure 3 (middle), contains considerable noise corruption. In a static measurement, i.e., when the frame was not subjected to any excitation, the noise level of the camera setup was measured (Figure 3-top). By using this “sensor noise”, as a secondary measurement and the noise corrupted sinusoidal signal as the “desired signal”, an adaptive LMS filter (Hayes, 2009) was employed for noise cancellation. Subsequently, a Savitzky-Golay moving-average filter was used to smoothen the signal. Comparing the displacement-time signal of the filtered sine-wave to the NDI system (Figure 3-bottom), shows a fairly accurate correspondence, proving that the 3D tracking scheme works for such conditions.

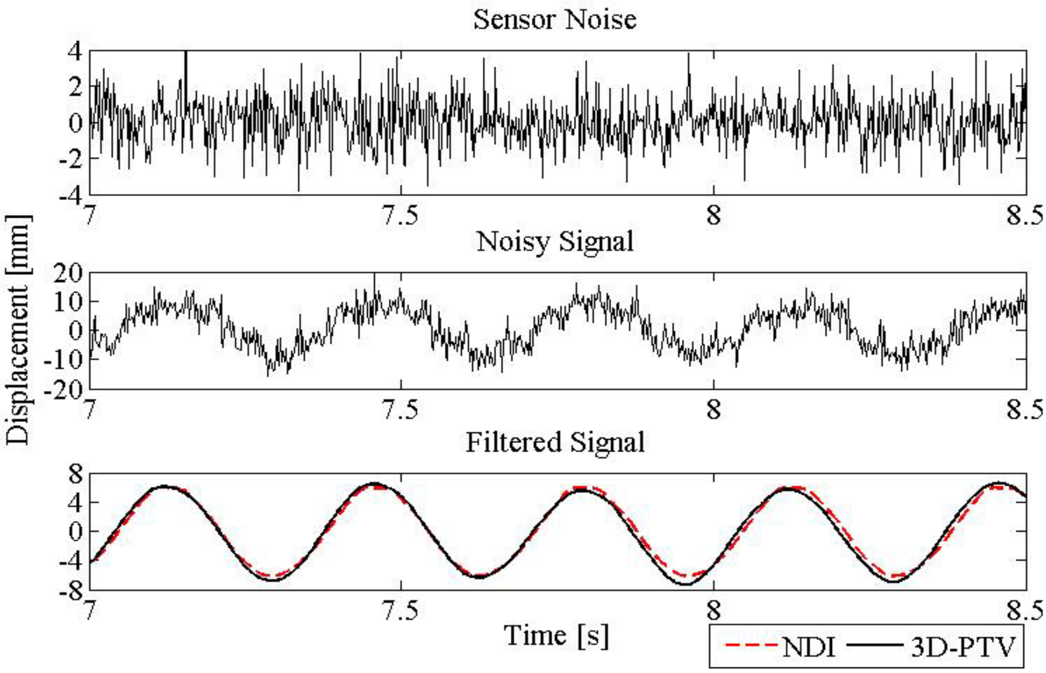

Figure 3: Sensor noise level (top), noisy measurement of the sine excitation (middle), and the same excitation after adaptive LMS filtering and smoothing (bottom) in x-direction.

As a second step, the frequency-domain response of 3D-PTV was compared to results obtained through accelerometer measurements. For this purpose, measurements from a sine-sweep excitation with constant acceleration (ergo decreasing displacement) were used. 3D-PTV without motion magnification occasionally revealed the first peak in the frequency domain, likely due to the high displacement amplitude at low frequency rates of the sweep sine excitation. Subsequently, videos recorded by the high-speed camera were provided as input to the PBMM, after downsampling from 500 to 100 Hz, solely due to high memory demands set by this magnification algorithm. The video was magnified at a frequency band of approximately ±1 Hz around the peaks detected by the accelerometers with a factor between 20-100. These magnified videos contain individual mode shapes of the frame (as visualized in Figure 4), since the motion is only amplified within that frequency band. Following this step, videos were tracked by the 3D-PTV algorithm. Resultant power spectral densities are presented in Figure 4, and peak frequencies are summarized in Table 1. As expected, only a single frequency peak for each magnified video was observed, which lies within the amplified frequency band. Considering the shorter signal length of magnified 3D-PTV signals, the difference is very well within acceptable limits.

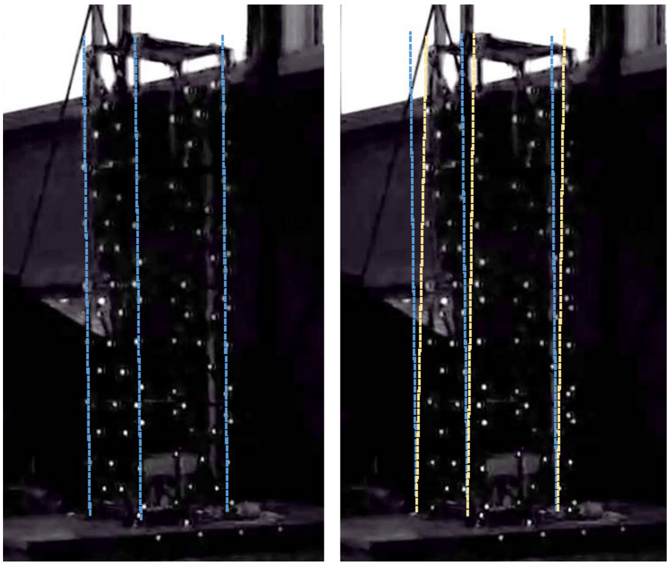

Figure 4: Still image captured from the raw video (left) and after motion magnification around its first eigenfrequency (right). Modes 2 to 5 (not shown) also exhibit their mode shapes after motion magnification.

4 CONCLUSION

An experimental campaign has been carried out to validate the feasibility of an optical dynamic measurement system offering 3D high spatiotemporal information. Displacements are obtained via the 3D-PTV method. Despite high noise levels, it was seen to correlate well with reference displacement measurements. A recent computer vision technique, PBMM, was utilized to magnify imperceptible motion in recorded videos. Based on resonant peaks observed in accelerometer measurements, recorded videos were motion magnified and tracked with the 3D-PTV method. The resonant frequencies were retrieved successfully after motion magnification, which indicates that PBMM does not distort 3D information after magnification.

Further work will focus on ways to increase spatial resolution, which would allow to conduct modal analysis that includes torsional modes as well, offering an improvement to currently trending optical methodologies using 2D single camera arrangements.

Table 1: Resonant frequencies identified by accelerometer and 3D-PTV (of magnified videos) results.

	Identified Resonant Frequencies (Hz)		
Peak #	Accelerometer	3D-PTV	Difference (%)
1	3.63	3.40	- 6.34
2	11.88	12.20	+2.69
3	20.38	20.60	+1.08
4	27.25	27.20	- 0.18
5	32.13	32.20	+0.22

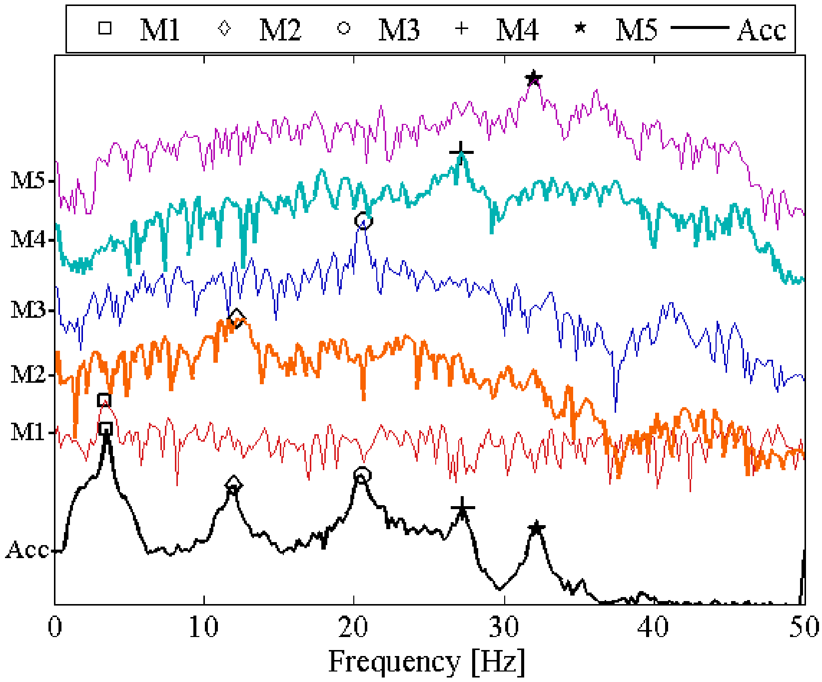

Figure 5: Welch's power spectral density of accelerometer and 3D-PTV with video megnification. (Mxx denotes magnified video around xxth peak (marked in Figure). Spectral amplitudes shifted in y-axis for better visualization.) (Bottom curve represents the PSD obtained via accelerometers)

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