8th European Workshop On Structural Health Monitoring (EWSHM 2016), 5-8 July 2016, Spain, Bilbao
www.ndt.net/app.EWSHM2016

Structural Health Monitoring through Video Recording

Manuel Zimmermann [1], Utku Gülan [2], Yunus Emre Harmanci [1], Eleni N. Chatzi [1], Markus Holzner [2]

[1] Institute of Structural Engineering, Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland,
[2] Institute of Environmental Engineering, Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland,

Keywords: Structural Health Monitoring, Deformation Monitoring, Low-cost Sensing, Image Processing, Particle Tracking Velocimetry, Video Magnification

Abstract

The monitoring of the dynamic response of structural systems can be invaluable for the extraction of information relating to condition assessment, possible damage detection or residual life prediction of a structure. In ensuring a high spatial density of data, dense sensor grids, accelerometers are often required. As an alternative to this approach, albeit at reduced resolution, lower cost alternatives such as optical or wireless schemes are gaining popularity. In this context, video technology has recently been suggested as a possible means for non-contact and relatively cost efficient measurements of high spatial density. This approach simply requires the use of HD Video Recorders, which are largely commercially available. In this work, the recently proposed Phase Based Motion Magnification (PBMM) is combined with an optical measurement technique, i.e., particle tracking velocimetry (PTV) for Structural Health Monitoring (SHM). The method is benchmarked on a laboratory tested beam structure, simulating a finite degree of freedom system. The vibration is recorded by means of two different sensing technologies namely, accelerometer, and high-speed video recording. The obtained response signals, natural frequencies and mode shapes are cross-compared demonstrating a good agreement. It is concluded that the combined use of PBMM and PTV results in a highly promising tool for the non-contact and low-cost structural monitoring of civil structures at low (ambient) vibration amplitudes.

1 INTRODUCTION

As ageing infrastructure is becoming more common within developed cities, Structural Health Monitoring (SHM) is gaining increased attention for assessing current condition, forecasting remaining lifetime, as well as detecting damage of the monitored structures. Benefiting from the continually growing availability of more accurate and affordable sensor technologies, a clear potential for improved structural monitoring solutions has surfaced (Chang et al., 2003). A structure may be monitored by means of various types of sensors such as accelerometers, displacement sensors, tiltmeters, strain sensors, etc., as well as optically (Balageas et al., 2006). The latter approach has recently received considerable attention due to the availability of low cost optical sensors and acquisition devices (e.g. optical lenses, DSLR cameras and HD video recorders). An advantage of optical methods is that they alleviate the need for a large number of contact sensors in ensuring high spatial resolution, while additionally operating in a non-intrusive manner. Another advantage pertains to lightweight structures, where added sensor mass may affect structural response, when the deployed sensor weight, e.g. micro-electro-mechanical systems (MEMS), may not be assumed as negligible. All advantages aside, the resolution of these systems inhibits the accurate tracking of low amplitude displacement response, usually available for with operational conditions. This naturally hinders the subsequent tasks of modal analysis and condition assessment that are critical to life-cycle analysis.

The recently proposed PBMM technique (Rubinstein, 2014) attempts to overcome the limitations of low amplitude displacement response in videos by applying temporal processing within selected frequency bands in order to magnify subpixel motion changes. This approach appears to be promising for structural applications, and to this end, initial attempts have been made in the community. Chen et.al. (2014) has conducted experiments in a laboratory setting on a cantilever beam to verify the method against accelerometer and laser vibrometer measurements and utilized PBMM for modal analysis of cantilever beams and extraction of mode shapes as well as mode shape curvatures as a basis for damage detection. In a further study, a new algorithm based on the Riesz transform has been employed for real-time application of motion magnification to normal-speed videos and again applied to a cantilever structure. (Chen, et al. 2015). Finally, Cha et.al. (2015) has employed high-speed video with PBMM and optical flow as input for a damage detection methodology using an unscented Kalman filter. For validation purposes, a numerical state-space formulation was derived for the structural system and experimental tests on steel cantilevers with bolt-loosening as a damage scneario were performed. This work proposes a novel SHM framework, relying on the use of a non-invasive optical measurement technique, namely Particle Tracking Velocimetry (PTV), for measuring the displacement of a 3-degrees-of-freedom (3-DOF) cantilever structure equipped with simple small-scale markers, painted on the structure. These markers are then tracked via PTV (Hoyer et al., 2005) to obtain high-resolution displacement, velocity, as well as acceleration-time response of the cantilever. Furthermore, the recently developed Phase Based Motion Magnification (PBMM) algorithm (Wadhwa et al., 2013) is herein adopted for two different purposes, (i) to magnify the motion where the structural response amplitude is low and render them traceable, (ii) to magnify the motion within a given frequency band and track these points in an attempt to capture the resonant frequencies and mode shapes of the structure. The aim of this work is to lay the foundation for a novel SHM framework and to demonstrate that recent imaging techniques, such as motion magnification and PTV, may be applied to reliably identify modal characteristics of structural systems in a non-contact fashion.

2 EXPERIMENTAL INVESTIGATION AND METHODOLOGY

2.1. Experimental Investigation

For the carried out experimental investigation, a cantilever beam was utilized (width = 60 mm and thickness = 15 mm), with addition of three extra (lumped) masses of 8.7 kg each. The masses are fixed onto the cantilever at a spacing of 250 mm. The beam is made of steel S235, produced according to the Swiss guidelines (SIA, 2003). The sample preparation involved painting of the beam with a matte black color and addition of the white tracking markers. Tracking markers were placed at an approximate spacing of 50 mm and a diameter of 1 mm. The beam was then set up as a cantilever, with a span length of 1 meter, fixed on a rigid steel support structure as illustrated in Figure 1.

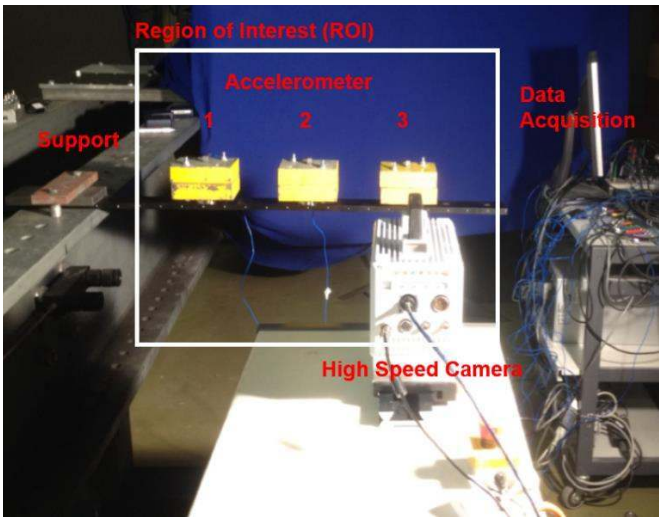

Figure 1: Three DOF cantilever beam experimental setup.

Three MEMS accelerometers were mounted atop each mass, serving as a higher precision reference measurement. Excitation was induced by means of an impact hammer. Time synchronization between the accelerometer devices and the camera was achieved manually by means of peak matching. A Photron SA5 (Tokyo, Japan) high-speed camera is employed to acquire images with high temporal resolution. The high-speed camera allows recording 1.56 s at full resolution of 1024 x 1024 pixels and 7,000 fps with 16GB memory. A 12-bit analog digital converter (ADC) (Bayer system color, single sensor) equipped with a 20 nm pixel sensor provides higher light sensitivity for high-speed recordings. A Nikon AF Micro-Nikkor 60 mm f/2.8D lens is utilized. The camera was synchronized with the impact hammer for triggering the recordings. The measurement field of the camera was selected so as to capture movement in the range of three lumped masses and not for the whole structure, allowing for a higher spatial resolution, while still capturing the range of interest.

2.2 Structural Identification Methodology

The dynamic response of a structure may be employed to extract important information regarding its characteristics, as well as its current state. In this work, accelerometer and high-speed camera measurements are employed for structural identification, with the aim of verifying applicability of the non-contact system (camera). To this end, displacement-time histories of original, as well as motion magnified videos were delivered through adoption of a PTV algorithm. A preliminary calibration of the displacement data obtained via the PTV is carried out via a correction factor, which correlates the spatial distance of the video (in pixels) to a known reference spatial distance of the tracked object. Natural frequencies were determined from power spectral density plots (Welch 1967), while mode shapes were extracted via use of a subspace identification algorithm (n4sid) (Ljung 1999). The natural frequencies of the structure finally serve for determining the spectral range of the motion magnification algorithm.

2.3 Particle tracking velocimetry

PTV is a flexible non-intrusive image-based flow measurement technique that allows characterizing the motion of particles both from an Eulerian and a Lagrangian point of view. Furthermore, velocity and acceleration can be extracted along particle trajectories. PTV has been in use for several decades as a Lagrangian flow measurement technique. In a series of steps, Maas et al. (1993), Virant et al. (1997), Wilneff et al. (2002), Lüthi et al. (2005), Holzner et al. (2008) and Gülan et al. (2012) have developed and applied PTV in different contexts, where the motion of tracer particles in liquids was analyzed to investigate hydrodynamic turbulence, medical flows etc.

The basic principle of the PTV algorithm lies in determining the position of each particle (tracking point) for individual frames and subsequently computing the trajectories between different time steps. The velocity of the tracked particle may be described via the following simple finite difference expression:

$$u_i(t) = \frac{x_i(t + \Delta t) - x_i(t)}{\Delta t}$$

where u_i denotes the velocity, $x_i(\Delta t)$ and $x_i(t + \Delta t)$ the position of the particle at consecutive time steps, and Δt the inverse of the imaging frequency of the camera. For the efficient data extraction the following needs to hold:

- The particles/tracking points remain within the imaged plane.
- The coordinates of each marker are known for a sufficient number of consecutive time steps.
- The links between consecutive positions of particles are accurately established by the PTV algorithm.

Depending on the dimensions of the investigated volume, the optimal diameter of the tracking points may vary. Tracers should be large enough for ensuring detection during the image processing stage, that is, they should cover a minimal 3-4 pixels, while remaining small enough to reliably follow the motion. For the reported study, a resolution of 1024x1024 pixels was used and a subpixel accuracy of 0.2 pixels was achieved for a framerate of 500 fps.

2.4 Phase-Based Motion Magnification (PBMM)

When implemented within the context of SHM for civil infrastructure, the tracking procedure becomes non-trivial, due to the commonly low response amplitudes induced during operational conditions. Since this motion commonly lies within sub-pixel levels, the obtained video measurements are expected to result in compromised precision. In order to implement the formerly described PTV approach, the motion needs to be amplified. To this end, a phase-based motion magnification technique is herein employed. This adopts an Eulerian motion approach, which applies temporal processing on images within selected frequency bands, with the aim of amplifying subpixel motion changes. This approach is well-suited for structural applications, since it can amplify sinusoidal motion very accurately, while at the same time not amplifying image noise. More detailed information on the magnification technique can be found in the study of Rubinstein (2014).

3 RESULTS AND DISCUSSION

The results reported herein are organized along two main directions. The first one pertains to the validation of PTV as an accurate method to derive displacement data from high-speed camera recordings. As a second goal, the ability to reliably extract the mode shapes of the monitored system in a global manner, as opposed to the discrete plots associated with accelerometer results is sought. In the comparisons that follow, displacements obtained via accelerometers are extracted by means of double numerical integration of the high pass filtered signal. The signal was filtered with a 4^{th} order Butterworth filter using a cutoff frequency of 1Hz. On the other hand, displacements obtained via use of the PTV algorithm are assessed by tracking the original and/or magnified videos.

The displacement response signals obtained from the PTV correlate well to those inferred via accelerometers for all three reference locations, as observed in Figure 2. It should be kept in mind that the integral displacements obtained from accelerometers, via a suitable filtering procedure, are not necessarily "error free" and thus minor deviations of PTV should not necessarily be attributed to inaccuracy of the latter. Additionally, the small, albeit existing, spatial deviation of the accelerometers and tracking points may result in some results' divergence. In alleviating these issues in the comparison process, a laser vibrometer is to be employed in future experimental work.

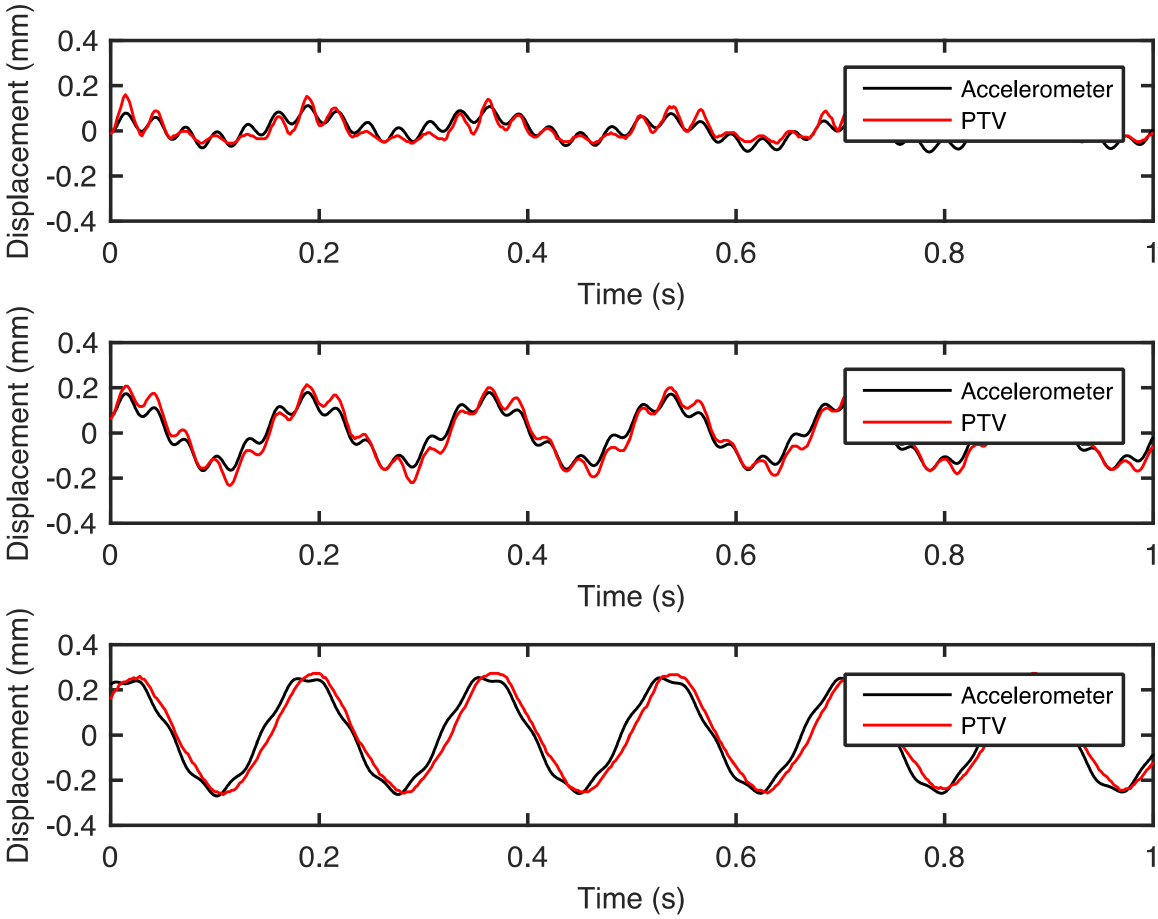

Figure 2: Comparison of displacements derived via accelerometers and PTV at the first (top), second (middle) and third (bottom) accelerometer location.

The natural frequencies are inferred on the basis of the accelerometer recordings via adoption of Welch’s method and result in accordance with analytical calculations for a 3 DOF cantilever structure. The natural frequencies extracted via the PTV spectral plots prove successful in identifying the first two natural frequencies with sufficient precision. However, the third mode is not captured, as a result of the low amplitude motion. To overcome this limitation, the video is first magnified using the PBMM technique, and then tracked again via use of the PTV. The magnified results indicate distinct peaks in the frequency domain, as shown in Figure 3, where the third resonant frequency is now clearly visible, and agrees with the reference accelerometer estimate.

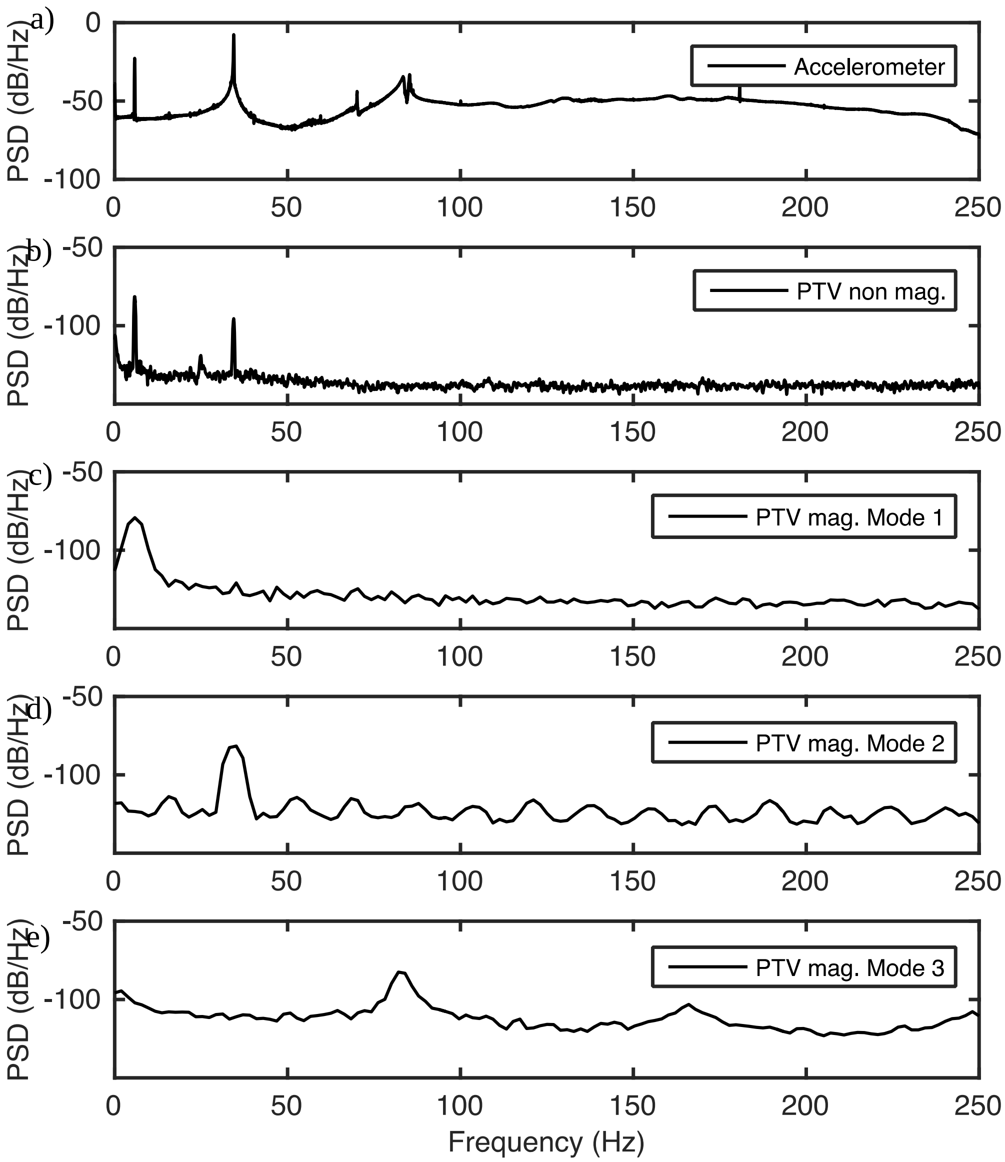

Figure 3: PSD plots of (a) accelerometer data; (b)PTV results of the un-magnified video; and PTV of the magnified videos for the first (c), second (d) and third (e) natural frequencies.

The mode shapes of the magnified videos are then computed via use of a standardly employed System Identification technique suited for impulse excitation, namely a subspace identification approach (n4sid), and are then compared to the results attained from the accelerometer measurements. As observed in Figure 4, the accelerometer records yield similar results to the not-magnified PTV results in terms of mode shapes, with the exception of the non-existent third mode. Therefore, provided the motion is sufficiently strong, PTV delivers an adequate tool for SHM purposes. On the other hand, magnification allows for extracting the "latent" and not sufficiently excited third mode as well. This implies that combination of the two promises a unique SHM tool, capable of replacing higher-cost and more invasive technologies. It should be noted that the PTV results have been chosen at marker locations close to the accelerometer locations in order to ensure a valid comparison. However, the major benefit of employing the PTV lies in extraction of continuous mode-shapes as indicated in the plot of Figure 5. It is therein evident that magnification ensures a better reconstruction of the structural modes, as revealed by the smoother red curve (PBMM with PTV) versus the blue (PTV alone) curve.

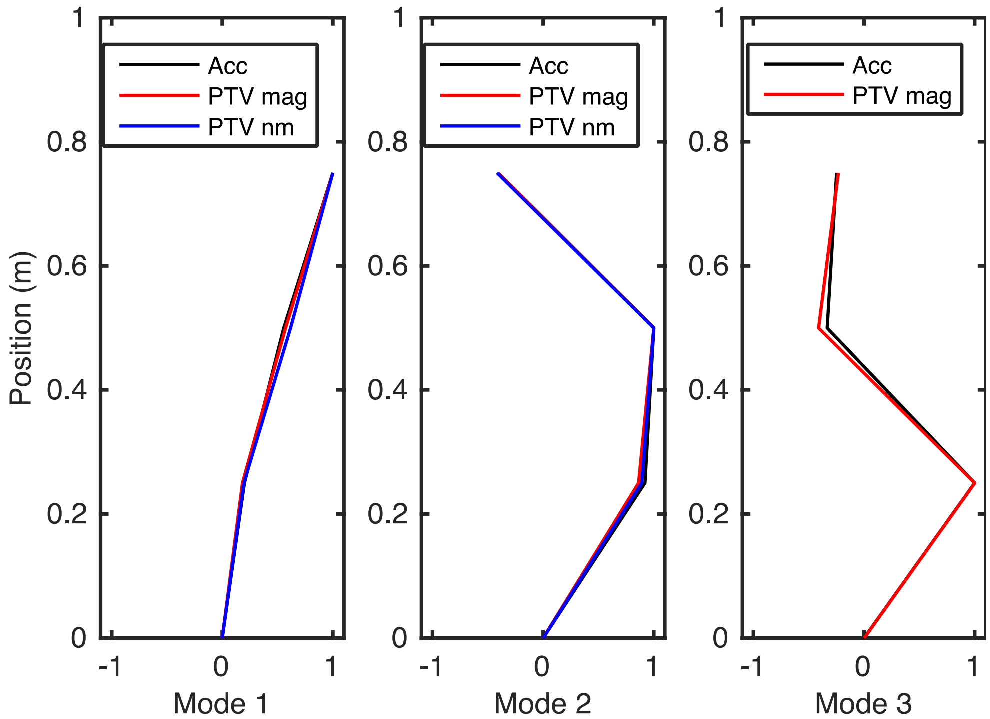

Figure 4: Mode shapes obtained through FDD for modes 1, 2 and 3.

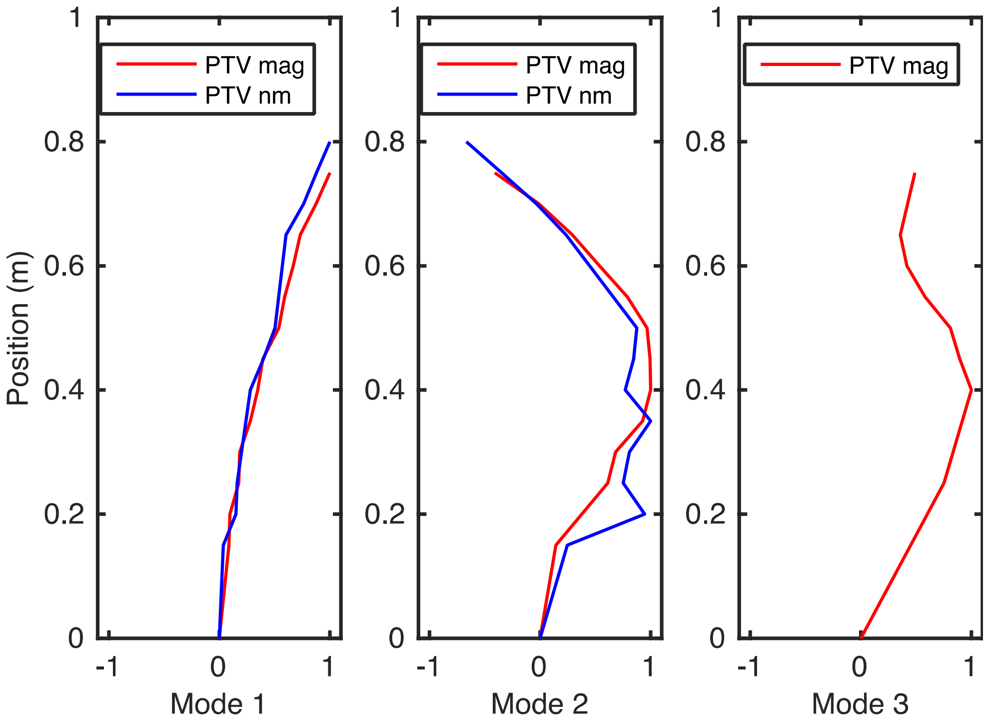

Figure 5: Continuous mode shapes obtained through FDD for modes 1, 2 and 3 with and without magnification.

4. CONCLUSIONS

As demonstrated in this work, lower-cost non-contact technologies may be employed for deriving structural displacements at high spatial resolution, via use of video recordings and implementation of a PTV algorithm. In case the displacements of the monitored system lie below a prescribed threshold, preventing identification of certain “latent” characteristics, as is the case herein for the 3rd natural frequency, the PBMM algorithm can be used as a complimentary technique to PTV, for selectively amplifying subpixel motions of a certain frequency band. Tracking of the motion-magnified videos reveals that the amplified frequency band becomes the dominant response of the structure and the mode shapes correlate well to accelerometer data. It is concluded that the combined use of PBMM and PTV results in a highly promising tool for the non-contact and low-cost structural monitoring of civil structures at low (ambient) vibration amplitudes.

REFERENCES

(SIA), Schweizerische Ingenieur- und Architektenverein. 2003. «SIA 263: Stahlbau.»

Balageas, D., Fritzen, C. P., & Güemes, A. 2006. Structural health monitoring. London, UK: ISTE.

Chang, P. C., Flatau, A., & Liu, S. C. 2003. «Review paper: health monitoring of civil infrastructure.» Structural health monitoring 257-267.

Gülan, U., Lüthi, B., M. Holzner, A. Liberzion, A. Tsinober, und W. Kinzelbach. 2012. «Experimental study of aortic flow in the ascending aorta via Particle Tracking Velocimetry.» Experiments in Fluids, 53: 1469-1485.

Holzner, M., A. Liberzon, N. Nikitin, B. Lüthi, W. Kinzelbach, und A. Tsinober. 2008. «A lagrangian investigation of the small-scale features of turbulent entrainment through

particle tracking and direct numerical simulation.» J Fluid Mech 598: 465–475.
Klaus Hoyer, Markus Holzner, Beat Lüthi, Michele Guala, Alexander Liberzon, Wolfgang Kinzelbach. 2005. «3D scanning particle tracking velocimetry.» Experiments in Fluids 923-934.
Ljung, L. 1999. System Identification: Theory for the User. . Upper Saddle River, NJ: Prentice-Hall PTR.
Lüthi, B., A. Tsinober, und W. Kinzelbach. 2005. «Lagrangian measurement of vorticity dynamics in turbulent flow.» J Fluid Mech 528: 87–118.
Maas, H.G, A. Gruen, und D. Papantoniou. 1993. «Particle tracking velocimetry in three-dimensional flows.» Experiments in Fluids 15 (2): 133-146.
Rubinstein, Michael. 2014. Analysis and Visualization of Temporal Variations in Video. Cambridge: Massachusetts Institute of Technology.
Virant, Marko, und Themistocles Dracos. 1997. «3D PTV and its application on Lagrangian motion.» Measurement science and technology 8 (12): 1539-1552.
Wadhwa, N., Rubinstein, M., Durand, F., & Freeman, W. T. 2013. «Phase-based video motion processing.» SIGGRAPH2013. California: ACM Transactions on Graphics (TOG). Article No. 80.
Wech, Peter D. 1967. «The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms.» IEEE Transactions on audio and electroacoustics 70-73.
Welch, Peter D. 1967. «The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms.» IEEE Transactions on audio and electroacoustics 70-73.
Wilneff, J., und A. Gruen. 2002. «A new spatio-temporal matching algorithm for 3d-particle tracking velocimetry.» The 9th international symposium on transport phenomena and dynamics of rotating machinery honolulu. Hawaii, USA.