Chapter 12
Digital Image Correlation for Timing Belts Dynamic Characterization: Potentials and Critical Aspects

P. Castellini, P. Chiariotti, M. Martarelli, and E. P. Tomasini

Abstract Characterizing the dynamic behaviour of timing belt represents a challenge among the engineering community. Even though there exists several numerical methods to predict the dynamics of these systems, the tuning of such models by experimental approaches still represents an issue. Indeed, an accurate characterization does require a measurement in operative condition since the belt mounting condition might severely affect its dynamic behaviour. Moreover, since the belt is moving, non-contact measurement methods are needed. In such context, Laser Doppler Vibrometry (LDV) and imaging techniques do represent valid candidates for such purpose.

This paper aims at describing the use of Digital Image Correlation (DIC) for the extraction of timing belts out-of-plane vibration and the recovery of Operational Deflection Shapes (ODSs). Results are compared with vibration data obtained by measuring on a moving belt with a standard LDV scanning, in step-scanning mode, over a grid points on the belt surface.

Keywords Digital image correlation • Laser Doppler vibrometry • Timing belts • Vibration analysis • Folded optics

12.1 Introduction

Timing belts belong to the synchronous drive category and therefore they can transmit large torques, withstand large acceleration and give the designer great layout flexibility, since the transmission components can be placed at large distance without paying a price penalty. This is true also in Internal Combustion (IC) engines, where the main use of timing belts is in synchronising the camshaft (governing the opening and closing of valves) to the crankshaft. When compared to chains and gears, timing belts present indeed better properties: they do not require lubrication, they are lighter and quieter (the composite rubber material they are made of does imply higher damping levels than in chains/gears). However, durability represents one of the main drawback of such systems. Indeed, the dynamic behaviour of the belt affects its durability: unwanted resonances of the belt that might occur during engine run-up or coast-down operations decrease the belt life and introduce vibration and noise phenomena.

Identifying a measurement technique that makes it possible an accurate and efficient measurement of the dynamic behaviour of the belt in operating conditions thus represents a useful tool for analysing the performances of the timing belt itself and of the whole transmission line.

Scanning Laser Doppler Vibrometry (SLDV) represents for sure a valid technique for tackling the belt dynamic characterization issue. This has been proved, over the years, by several researchers. Di Sante et al. [1, 2] were among the first addressing SLDV as a useful tool for assessing the dynamics of timing belt, even though they were more interested in showing the noise phenomena related to the belt vibration (at the timing belt meshing frequency) rather than on extracting Operational Deflection Shapes (ODSs) under the influence of whole body translation at constant speed. The latter subject was deeply analysed by Martin and Rothberg [3], who also further analysed the concept of pseudo-vibrations introduced by Rothberg et al. in [4] to address vibrations due to speckle pattern changes.

The progress in image-based measurement techniques has increased the interest of the scientific community in trying to use such methods in more and more challenging task. Among other approaches, Digital Image Correlation (DIC) [5, 6], does represent an appealing technique for estimating 2D and 3D displacements (and from that, for instance, velocity, deformation and strain) by analysing the changes of certain features on the images recorded. During the last decade, with the increased

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performances of recording cameras (frame rate and resolution), DIC has raised interest in the vibration field, especially for the reconstruction of Operational Deflection Shapes (ODSs) and Frequency Response Functions (FRFs). An example of such is reported in [7] and [8] where authors exploited 3D DIC on fan and turbine blades for the estimation of ODSs and FRFs and compared results thus obtained with data gathered from standard acceleration and LDV-based measurements. A 3D DIC system was also exploited in [9] to determine shape-descriptor frequency response functions of the field response of a complex-shaped object as a car bonnet. Dynamic point tracking using DIC has also been successfully demonstrated in [10], where operational modal analysis of helicopter rotors was conducted. In [11] a further step forward has been made by applying three dimensional point tracking (3DPT) and stereophotogrammetry to the rotor of a Robinson R44 helicopter.

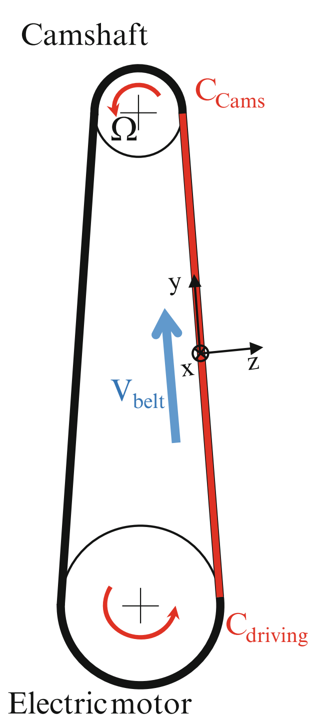
This paper represents a feasibility study to understand the potentials and the critical aspects of using DIC for measuring span vibration, i.e. out-of-plane ODSs, of timing belts in running condition. The paper is organised as follows: the test bench and its experimental characterisation in controlled conditions (impact hammer test) are presented in Sect. 12.2; Sect. 12.3 will describe the DIC experimental set-up used and the processing approach adopted; Sect. 12.4 will discuss the main results obtained. The main conclusions of the work are reported in Sect. 12.5.

12.2 Test Bench

12.2.1 Experimental Test Bench

The object under test is a timing belt for distribution driveline of IC engines. The timing belt investigated synchronizes the rotation of the crankshaft and the camshaft of a 4-cylinder engine head, fully equipped with four valves per cylinder and springs. An electrical motor drives the crankshaft and is controlled by an inverter in order to select the desired speed or speed profile for run-ups or coast-down tests. In this work, the vibration of the belt was measured in operating conditions at three camshaft constant speed, as reported in Fig. 12.1 together with the corresponding belt axial speed.

The excitation transmitted to the timing belt during rotation in operating condition is forced by the dynamics of the elements connected to the crankshaft and camshaft: such elements present bigger moving masses with respect to the belt mass and therefore they act as excitation sources on the belt. Moreover, the action of different cams on the camshaft induces strong torque fluctuation, concentrated at several harmonics of the camshaft rotation [12, 13]. The excitation will then result



Camshaft Speed [Hz]	Belt Axial Speed [m/s]
14.6	3.4
19.4	4.5
28.4	6.6

Fig. 12.1 Axially moving belt scheme and operating conditions tested

in a multi-harmonic excitation at the engine orders with the predominance of the fourth order and its harmonics. Such excitation implies that ODSs of the belt are not excited at the mode shapes natural frequencies, but they will show up at frequencies directly related to the engine/camshaft orders.

12.2.2 Test Bench Characterization

A modal test was performed to estimate natural frequencies and relative mode shapes of the timing belt under analysis. This test was intended to provide a baseline for validating and comparing results of discrete SLDV and 3D DIC. The Laser Doppler Vibrometer was placed 1.5 m far from the target belt, aligned in such a way to have the laser beam orthogonal to the target surface when the scanning mirrors are in their rest position. The laser spanned a total length of 0.500 m (±0.250 m) in the belt moving direction, *y*-direction in Fig. 12.1, and 0.028 m (±0.014 m) in the cross direction, *x*-direction in Fig. 12.1. This configuration made it possible to have good balance between mirror angle aperture and amount of light backscattered to the sensor.

The belt was excited via an impact hammer while a Laser Doppler Vibrometer, scanning sequentially over a 3×25 points grid, recorded out-of-plane vibration. The natural frequencies and corresponding mode shapes, estimated using PolyMAX curvefitting algorithm, are reported in Table 12.1. Mode shapes are given in terms of Nodal Lines (NL) in Table 12.1. Bending mode shapes amplitude and phase maps are provided in Fig. 12.2. The choice of reporting only the bending modes, skipping the torsional modes, is related to the optical set-up chosen for the DIC test, see Sect. 12.3, that does limit the resolution in the belt transversal direction and therefore does not make it possible a correct assessment of torsional ODSs.

Table 12.1 Timing belt natural frequencies

Mode N.	Natural frequency (Hz)	NL
I	64.76	00
II	130.16	10
III	195.77	20
IV	261.65	30

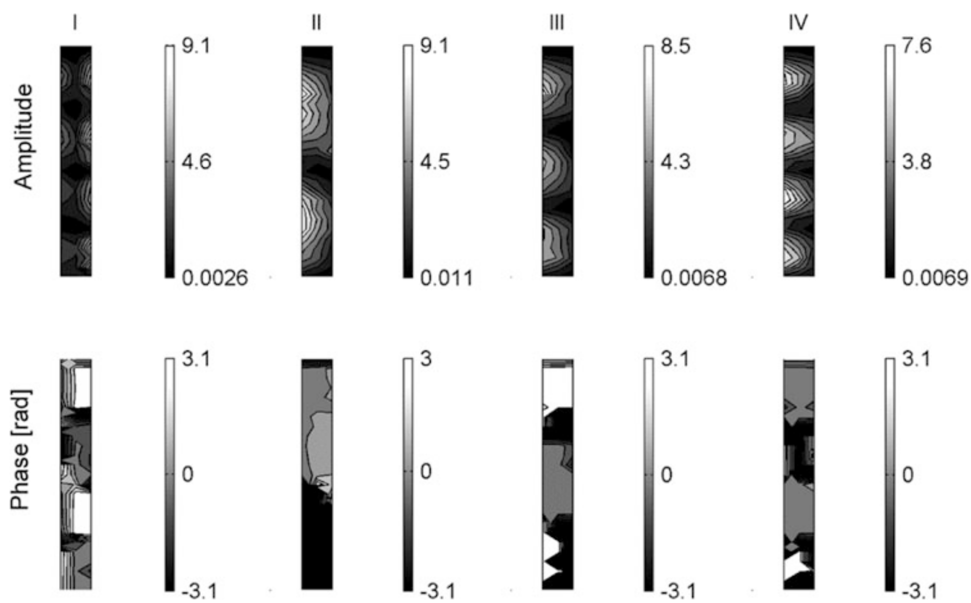


Fig. 12.2 Timing belt mode shapes

12.3 Digital Image Correlation Measurement

DIC is based on the observation of a random pattern characterising the surface of a structure as the latter vibrates. Typically, the pattern is a black and white speckle randomly distributed all over the target surface in order to ensure high contrast in the grayscale image formed in the digital camera (higher grey level intensity variations). Speckle pattern can be critical whenever a quantitative analysis is wanted in a DIC measurement. Pan demonstrated in [14] that indeed measurement error is strictly related to the speckle pattern morphology. Therefore, particular attention should be put in preparing the target surface, in order to ease the following pattern recognition step.

A black and white speckle pattern was created on the belt surface as reported in Fig. 12.3a, wherein the coordinate reference system adopted is also shown. Being the belt moving in the *y*-direction, the belt surface motion consists of the superimposition of the vibration pattern (with the most relevant component along the *z*-direction) and the "transport speed" (along the *y*-direction).

A stereo-DIC approach was exploited in order to estimate the out-of-plane (*z*-direction) vibration component. However, a folded optic solution, Fig. 12.3b, that makes it possible to use just one recording camera, was adopted. Indeed, a stereo set-up based on fast cameras is very expensive, due to the cost of high performance cameras. Moreover, cameras need to be synchronized, therefore the complexity of the whole measurement system increases. The folded optics solution is a good alternative that can be used for stereo photogrammetry whenever just one camera is available. This solution is realised by splitting the CMOS sensor line of sight into two projections by means of a set of mirrors, as shown in Fig. 12.3b. In such a way, two images of the object under observation form on the CMOS sensor. An example of folded image acquired on the timing belt is given in Fig. 12.3c where the Regions-Of-Interest (ROIs) selected are also shown. Despite the folded optics approach presents some drawbacks (the camera resolution is halved, the Scheimpflug condition is not respected and the amplitude of the angle between the two line-of-sight is limited) the advantages named above (i.e. low cost and no need of synchronization) make it a very interesting technique for 3D stereo image correlation. Anyway, it is to be clear that the halving of the number of pixels in the captured image and the halving of the spatial resolution in the *x*-direction limits the precision of the measurements, as described in [15].

The measuring system (camera—focal length f60 mm—and folded optic device) was placed 1 m far from the target surface. A proper lightning system was also set-up in order to increase the image contrast at an 840 fps frame rate.

A proper calibration of the whole DIC measurement system was done prior to perform any measurement on the belt. Calibration, as usual in vision based techniques, makes it possible to extract the intrinsic and the extrinsic parameters of the camera/cameras (camera resectioning). Such operation is fundamental for properly combining two images acquired from different lines of sight. Lens distortions were evaluated as well. The distortion effect induced on straight lines, which appears as curved lines on the sensor, is a quite common effect that takes place when wide-angle lenses are used. Compensating for such distortion becomes of primary importance in the folded optic configuration adopted, since the peripheral parts of the sensor are mainly involved in the image registration process. Despite different calibration procedures do exist, the common

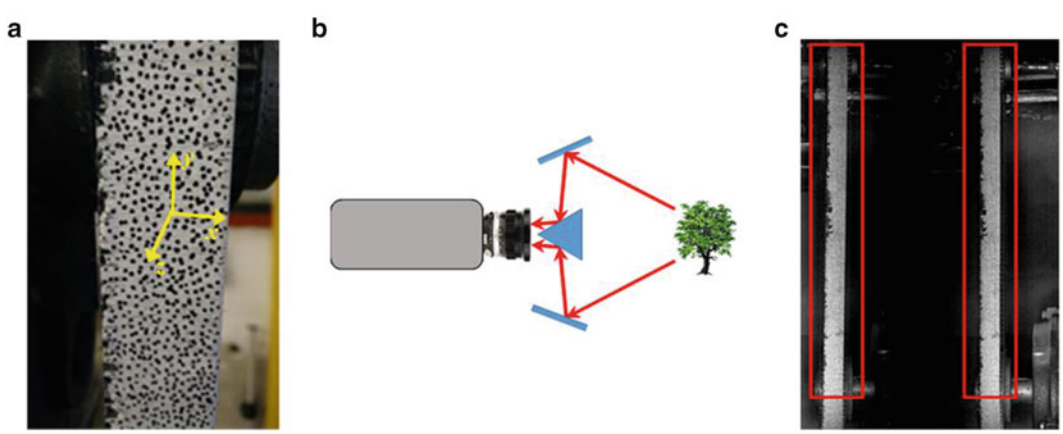


Fig. 12.3 DIC experimental set-up: speckle pattern applied on the belt surface and coordinate reference system adopted (**a**); folded optics scheme adopted for 3D motion measurement (**b**); belt folded image with the selection of *left* and *right* ROI (**c**)

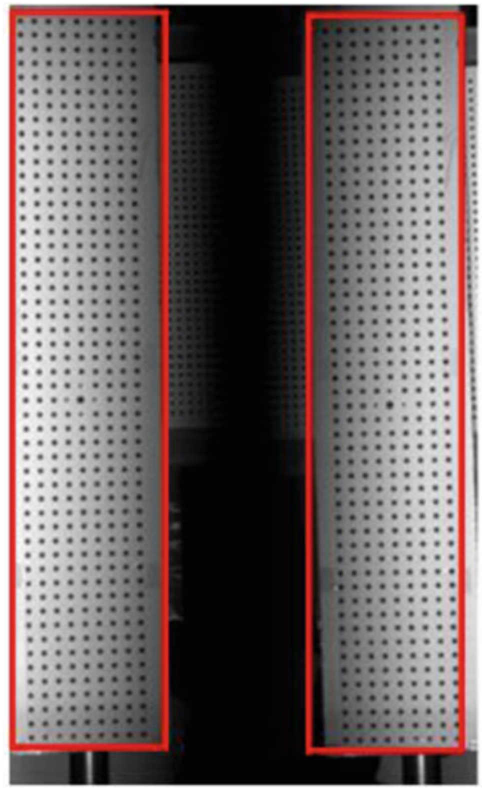


Fig. 12.4 Calibration panels with ROIs

approach consists in using a target with known dimensions that is framed by the camera/cameras from different lines of sight, under the condition of covering the whole volume wherein the structure of interest it is supposed to move. Different calibration target, having different calibration patterns, can be adopted. We used two panels characterized by equally spaced black markers (Fig. 12.4), the centre marker on each panel being bigger in size in order to ease its recognition by the calibration algorithm (third order XYZ Polynomial).

In order to cope with the belt translational movements an incremental approach was adopted. Such approach makes it possible to refer the ith frame to the $(i-1)$th frame and therefore to estimate the actual displacement of the target (or velocity, once the time increment is considered). An adaptive approach belonging to the Adaptive Correlation methods (see, for instance, [16]) was also exploited.

12.4 Results and Discussion

A DIC test was performed by exciting the belt with an impact hammer. Such test was intended to be the starting test in order to understand the DIC potentials and performances in extracting ODSs on a challenging target as the timing belt is. Figure 12.5 reports the ODSs extracted using the DIC processing described in the previous section. ODSs are well reconstructed in terms of amplitude and phase. This is not true for the third bending ODS, that does not recall the characteristic shape of the third bending mode neither in terms of amplitude nor in phase.

The challenging test was the one with the belt in running condition. The out-of-plane vibration of the timing belt was also measured exploiting Scanning LDV in discrete scanning mode. Such a measurement aimed at representing the reference measurement in terms of spectra and ODSs comparison. The scan grid consisted in 5×54 points evenly distributed over the belt surface. Since in discrete scanning mode a phase reference needs to be considered if looking at ODSs of a target, we used an accelerometer placed on the cylinder head to keep phase relations among the scanned points and to have possibility of performing complex averaging. The valve train dynamics produces a multi-harmonic excitation on the timing belt that is directly related to the engine orders (in the experimental set-up considered here, it is better to refer to the camshaft orders).

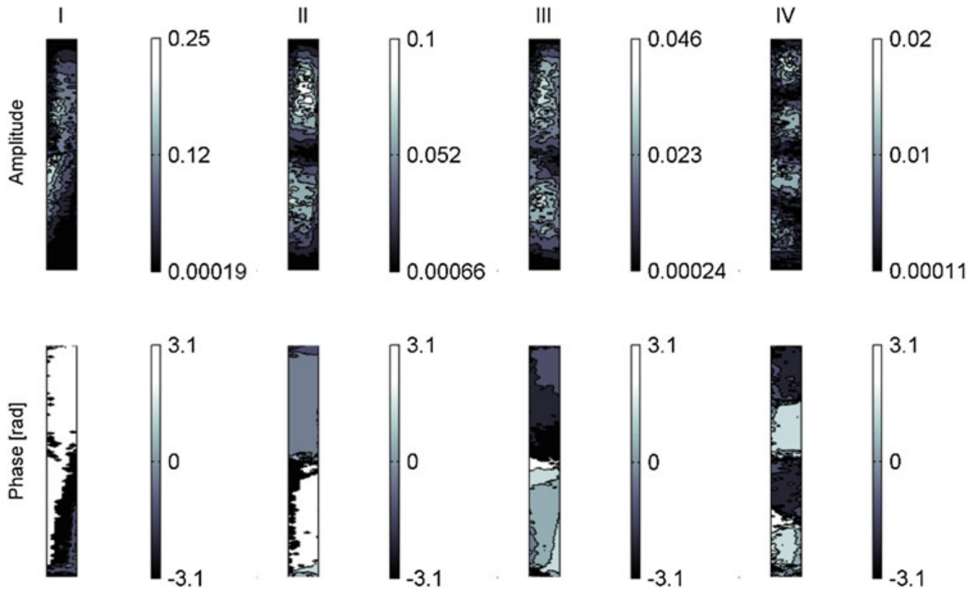


Fig. 12.5 Timing Belt ODSs obtained from Impact Hammer test processing

Table 12.2 Timing belt operating vibration frequencies

	Camshaft rotation frequency (Hz)						
	14.6		19.4		28.4		
ODS N	Vibration freq. (Hz)	Order	Vibration freq. (Hz)	Order	Vibration freq. (Hz)	Order	NL
I	58.4	4	58.2	3	56.8	2	00
II	131.4	9	135.8	7	142	5	10
III	189.8	13	194	10	198.8	7	20
IV	233.6	16	232.8	12	227.2	8	21

The ODSs reproducing shapes closest to the mode shapes will therefore show up at those orders that are the closest to the belt natural frequencies. This means that a particular ODS will show up only if a certain order gets close to the corresponding belt natural frequency. The resulting operating vibration frequencies do change with the camshaft rotation frequency, as reported in Table 12.2.

For sake of brevity, only ODSs obtained at the highest camshaft rotation frequency are presented hereafter. This represents the most challenging configuration in terms of DIC processing because of the high translational speed of the belt. These data, reported in Fig. 12.6, are to be compared with ODSs extracted using DIC processing (Fig. 12.7).

It is clear, comparing Figs. 12.6 and 12.7, that DIC can indeed correctly recover the timing belt ODSs even though some issues still remains. The ODS related to the 3rd bending mode cannot be resolved by DIC, it resembling a fourth bending mode (both in amplitude and phase). The authors have not understood this phenomenon yet. Moreover it is still unclear why the ODS related to the third bending mode cannot be well resolved in a hammer test either, where there is no translational movement of the belt. It is not a matter of aliasing (the ODS related to the fourth bending mode is well recovered) nor an issue related to superposition of velocity vectors belonging to different directions. The authors are currently trying to solve such issue, but these results will reported in future works.

The averaged frequency spectra gathered from DIC and SLDV results are reported in Fig. 12.8. They have been obtained by averaging the spectra at the different DIC sensing pixels and SLDV grid's acquisition points. The DIC spectra have been scaled progressively with an attenuation factor increasing with the increase of the camshaft rotation frequency. The fact that the DIC procedure experiences a higher vibration level and therefore needs to be scaled is attributed to the sensitivity of the

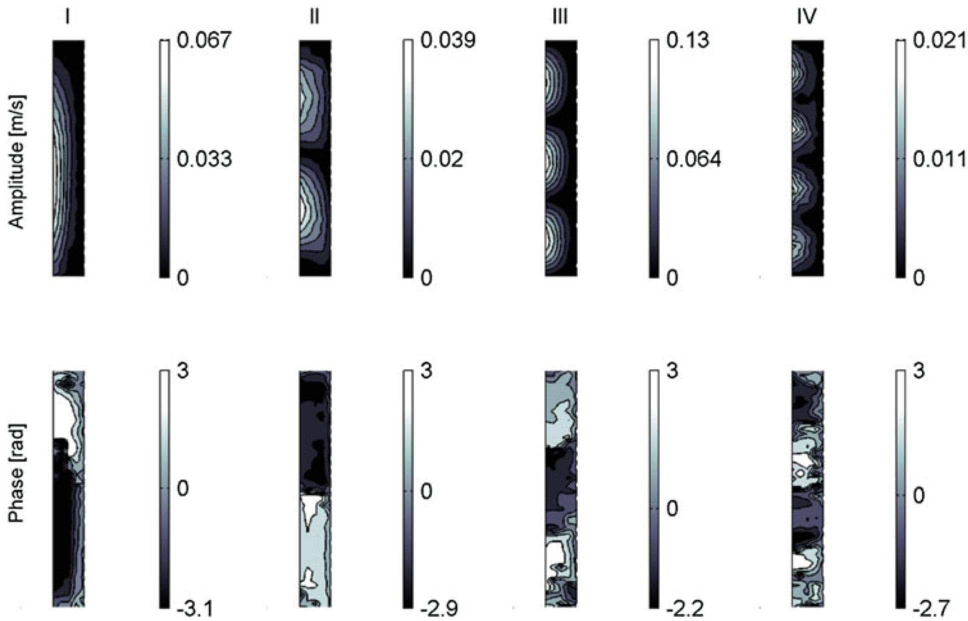


Fig. 12.6 ODSs for the camshaft rotation frequency of 28.4 Hz—Discrete Scanning

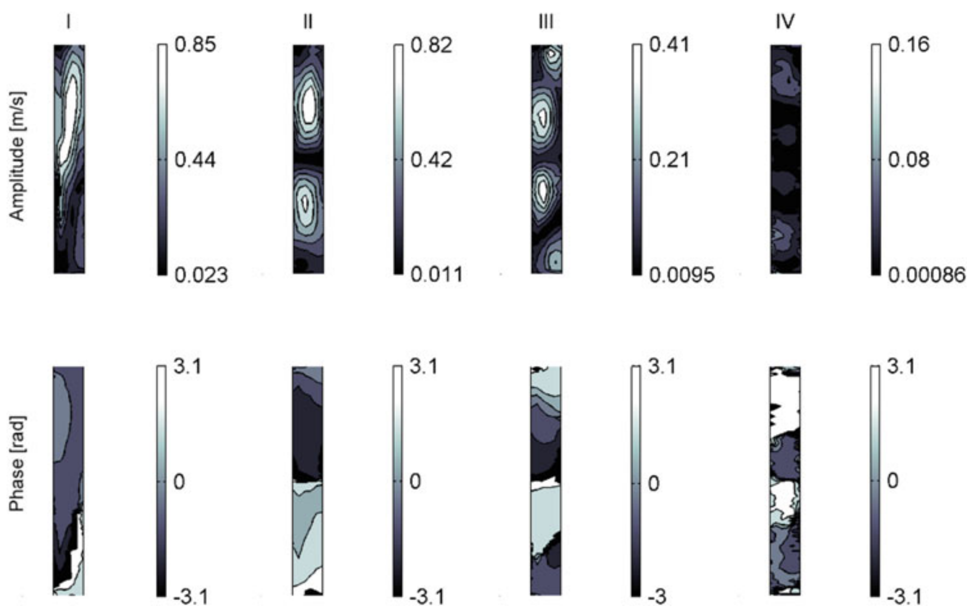


Fig. 12.7 ODSs for the camshaft rotation frequency of 28.4 Hz—DIC

image correlation to the transport speed of the belt that increases with increasing frequency. That means that the stereo-DIC is not able to completely decouple the vibration component in z-direction to the one in y-direction, strictly related to the transport speed. Nevertheless, it is clear that DIC and SLDV results are in good agreement when vibration amplitudes are high and therefore at the highest camshaft rotation frequency of 28.4 Hz. In this case, indeed, the large belt's displacements allow the image correlation algorithm to perform better.

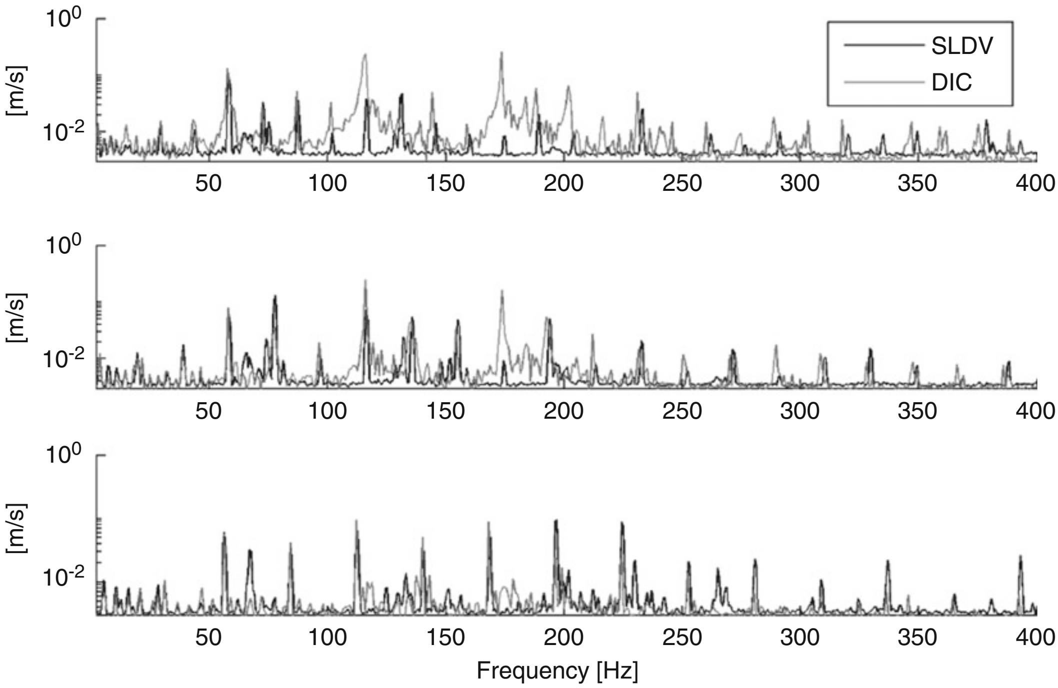


Fig. 12.8 Averaged spectra obtained from DIC and SLDV for the camshaft rotation frequency analyzed: 14.6 Hz (*top* plot), 19.4 Hz (*central* plot), and 28.4 Hz (*bottom* plot)

12.5 Conclusions

This paper aimed at showing the applicability of a full field technique as Digital Image Correlation for measuring out-of-plane vibration of timing belts. Timing belts represent a challenge for vibration analysis, mainly because of the superposition of out-of-plane and translational movements when the measurement is performed in operating conditions. The other critical point is excitation that is order-driven in timing belts. Different belt speeds and different orders have to be considered in the experiment for a complete identification of the ODSs of the belt. The stereo-DIC approach presented in this paper has shown interesting results in terms of potentials and critical issues. Operational Deflection Shapes can be generally well reconstructed even though some open questions remain regarding the inability of the method to recover the third bending mode both in steady and in running conditions. It has been also enhanced that, despite the incremental approach and the adaptive correlation method adopted, an overestimation of the out-of-plane vibration amplitude still exists. Such overestimation seems to be proportional to the belt translational speed. This phenomenon suggest that actual correlation algorithms are still not able to correctly decouple the out-of-plane vibration displacement (velocity if the time vector is taken into account) from the in-plane one. Nevertheless, potentials of the technique on such a challenging test case are evident and this represents a stimulus for keeping investigating in order to overcome current limitations.

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