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3D Digital Image Correlation for vibration measurement on rolling tire: procedure development and comparison with Laser Doppler Vibrometer

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Abstract. Noise generated from rolling tire is strictly related to vibrations caused by the impacts of tread blocks on the road surface. Performing vibration measurements on rolling tires is a quite complex task and non-contact methods should be exploited. Laser Doppler Vibrometer (LDV) is the technique that has been mainly used so far, but it has some disadvantages, among which the measurement duration represents the main issue. Digital Image Correlation (DIC) could represent an appealing alternative for this kind of measurement. Recent developments in Digital Image Correlation combined with the modern fast cameras could represent an innovative instrument for vibration measurement at high frequency (up to about 1000 Hz depending on rolling speed). This paper analyses the possibility of using 3D DIC for vibration measurement on rolling tire by a direct comparison with LDV. The advantages and disadvantages of both the techniques are highlighted along the paper by analysing data of an impact test (static case) and a rolling measurement.

1. Introduction

Nowadays, the reduction of tire noise is one of the biggest and most difficult challenges for tire manufacturers both for the new severe limits imposed by regulations and for NVH requirements coming from car manufacturers. In order to design silent tires, it is necessary to understand how tires generate noise.

Even though a lot of researchers have worked on this topic, the phenomenon is still not well understood because it involves several mechanisms which interact with each other. It must be also considered that tire structure is very complex because it contains rubber and other materials and their combination determines tire behavior: this makes the understanding of noise generation mechanisms quite tough and, therefore, the definition of general rules for tire design become a difficult task.

Anyway, it is well known [1] that tire noise is generated by two main groups of mechanisms: the air-related and the vibrational ones.

Tire noise is generally divided into two groups, depending on the frequency range:

- Structure-borne noise: low frequency vibration results into hub force which are responsible for the so called in-vehicle noise, i.e. noise transmitted into the vehicle cabin;
- Air-borne noise is the high frequency noise and it is related to aeroacoustic phenomena (pipe, air pumping…) but also to the high frequency vibration caused by the hitting of tread blocks on the road.

This work focuses on tire vibration as noise generating driver. Since tire vibrations involves low and high frequency phenomena, an experimental characterization of the tire require the identification of a measurement technique able to cope with this frequency range (10 – 800 Hz) and with highly dynamic vibration amplitudes.

Moreover it should be pointed out that measurements on rolling tire are quite complex to perform. In literature there are some works on this topic presenting measurement performed by Laser Doppler Vibrometer (LDV). LDV can be considered as the state of art for this kind of measurement because it is a non-contact technique and its sensibility makes it possible to measure a wide range of vibration conditions (both in terms of frequency and dynamics). However, when going to tire vibration measurement, it shows some limits, especially due the length of the test, which makes the hypothesis of stationary condition under discussion. Indeed, if the number of points to measure is very high, measurement duration is very long and there could be variation in materials due to the variation of temperature, as well as wear effects that might change the tire structural behavior from point to point during the test.

The recent development in Digital Image Correlation (DIC) technique combined with the modern fast cameras could represent an alternative technique to LDV to perform this kind of measurement. Several works proved how this technique can be used for vibration measurement [6,7,8], with a comparison with LDV but only in static condition and for small and simple specimen, so it is necessary to understand if DIC can be used also in rolling conditions and with an object of a complex shape and a particular material, like a tire is. According to the authors knowledge, at the moment in which this paper is written there is only a paper about this topic [9] in which the mode shapes in static condition are extracted using 3D DIC system.

The main issues related to DIC, when considering rolling tire application, are related to the cameras resolution and frame rates with respect to the phenomena that have to be investigated. In fact, global tire modes require a full framing of the tire by the cameras to be appreciated. However, since DIC measures tire displacement and since high frequency tire vibrations are characterized by very small displacement (in the nanometer range), the same optical set-up (meant as camera view with respect to the tire) cannot be exploited for both global modes and local tread vibrations analyses.

Given this practical considerations, it should be pointed out that there are other reasons that make DIC attractive for this kind of vibration measurement:

- from a single measurement it is possible to extract information for a big number of points, so it could be used as a validation tool for the FE (Finite Element) models [5, 10];
- it is less dependent to shape factors (e.g. it gives the possibility to measure on tire sidewall, crown, tread and grooves indistinctly), surface optical characteristics, presence of geometric irregularities (e.g. textures on the sidewall) as LDV can be;
- DIC is less affected by large displacement that can take place due the initial loading of the tire at the contact patch area;
- being a full-field technique (all data are measured simultaneously) there is no need of reference signal for phase realignment as it happens for LDV measurement, given its sequential nature.

In this paper the capabilities of 3D-DIC technique are studied through a comparison with the TLDV, in order to define if it can be an effective tool for tire vibration measurement in rolling conditions. The comparison is made considering both a static (impact test) and a rolling case.

2. Experimental setup

All the results reported in this work refer to measurement performed on a commercial 18" tire with a real pattern on tread. This aspect is very important because in rolling condition the excitation responsible of the high frequency vibrations comes from the pattern: the impacts of tread blocks on the road, combined with other effect such as stick-slip or stick-snap, generates their movement which vibrate with a frequency of these blocks which vibrate with a frequency related to number of blocks, their length and rolling speed.

The tire is fixed on the hub of a so called tire-stand: it is a big mass that can be moved up and down in order to press the tire on the underlying surface to control the tire load. Under the tire there is a drum driven by an electric engine and it is covered by a replica road surface to replicate the excitation coming from real roads. The inflation pressure is 2.5bar and the vertical load is 6.0kN both for the impact test and the rolling condition and rolling speed is 80kph.

2.1. Laser Doppler Vibrometer

The measurement of a moving surface by means of LDV is based on the Doppler Effect which generates a frequency shift in the light beam when it is reflected by the moving surface itself.

In the static case, a median circumference of 80 points is defined in order to scan the tire sidewall and the FRFs of each point is defined by the average of 5 hammer impulse in order to reduce the noise of LDV signal.

Both the signals of hammer and LDV are acquired by LMS SCADAS Mobile while the laser spot is moved by a LabView VI which is used to define the measurement circumference and to move the laser spot trough these points. All the data are processed in LMS Test.Lab and mode shape and the modal parameters are obtained by means of the Polymax algorithm.

In rolling condition, the measurement setup is almost the same; the only differences are the excitations and the reference sensors (hammer impact/load cell in static condition and rolling tire/accelerometer fixed on the tire stand for the dynamic case).

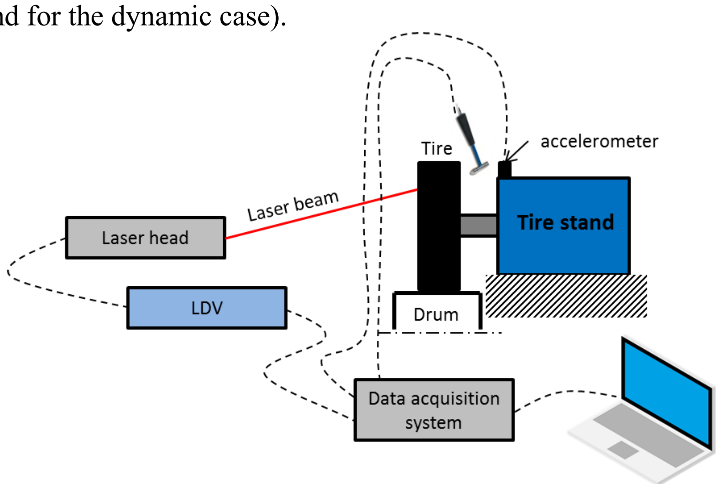


Figure 1 – LDV experimental setup.

2.2. 3D Digital Image Correlation

In this section the 3D-DIC setup is described with a theoretical introduction about the correlation algorithm used to perform this kind of measurements.

2.2.1. Theory. Digital Image Correlation (DIC) is a non-contact technique for full-field measurement of displacement and deformation based on the comparison between a reference image and an image in deformed condition: the tracking of measurement points defines the displacement and/or deformation map. These points are defined by painting a "speckle pattern" on the surface: it is a random pattern of points with high contrast with the surface (white dots on dark background for the case presented in this work). The points are organized in virtual areas, made by a certain number of pixels, called subset and for each of them the displacement is calculated with respect to the central point of the subset. Point P(x,y) moves to P'(x',y') where x' = x + u and y' = y + v are the new coordinates after the deformation, u and v are the displacement components in the reference system of the cameras.

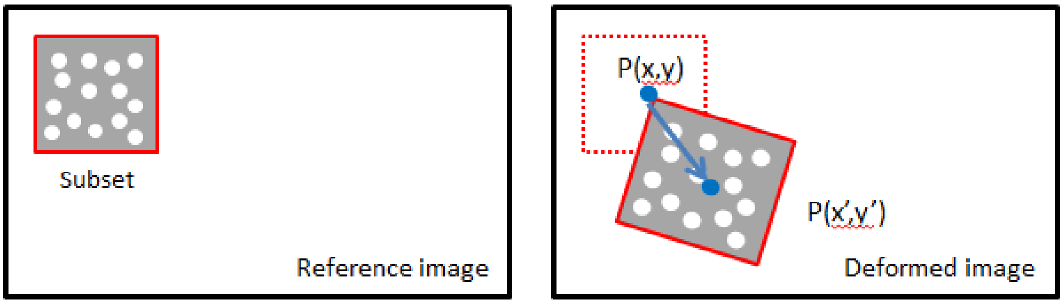


Figure 2 - DIC principle: the comparison between the reference and the deformed images defines the new coordinates of the measurement point P.

3D-DIC uses two cameras in order to measure displacement and deformation in three directions. The cameras must be placed at the same distance from the target object and they must have the same angle in order to have a correct 3D reconstruction. The distance between cameras and the object depends on the size of the object but also to resolution needed to measure the desired phenomenon which in turns depends on the excitation, as will be discuss later.

For the static case a classical Lagrangian approach is used, it means that the displacements are defined by following each measurement point and comparing the current image with the reference one; for the rolling condition an Eulerian approach is used (see section 4.3).

2.2.2. Experimental setup and procedure. The setup is made of two synchronized fast cameras characterized by a maximum frame rate of 4000fps, a maximum frame size of 1024 x 1024 pixels and an internal storage of 8GB which defines the number of acquired frames (5400) and accordingly the measurement time that is very short (1.35 seconds): the images are stored into the internal memory of the cameras and then transferred to the PC through a LAN connection. This operation requires less than 15 minutes. The illumination of the scene is provided by 2 LED lamps of 175 Watt each. A DAQ unit complete the system: it is used to acquire the load cell which will be used in post-processing for the calculation of the FRF and it is triggered with the master camera.

The cameras must be placed in order to respect the geometric relation presented in fig.4.

Finally the tire surface is prepared by means of a particular printer which generates a random pattern of white dots in contrast with the black surface of the tire.

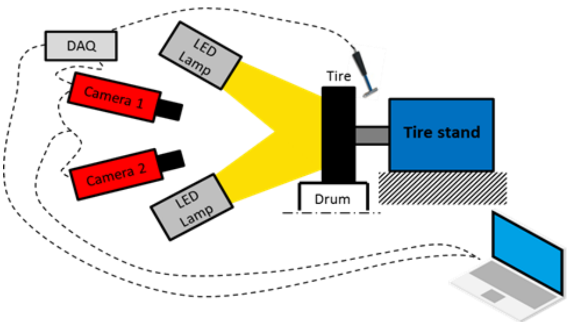
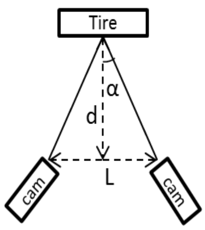


Figure 3 – 3D-DIC experimental setup.



$$\sin \propto = \frac{L/2}{d} \cong 0.25$$

Figure 4 – Cameras position.

Figure 5 – Example of speckle pattern.

The acquisition of calibration and measurement images is performed by the VIC-Snap software which is used for the setting of all the acquisition parameters, such as frames size, fps, exposure and son on.

All the images are processed with Correlated Solution VIC-3D software in order to perform the correlation and obtain the displacement field. In static condition this operation requires less than 30 minutes. After this step, all the data are exported into Matlab format files and post-processed with a script which select a median circumference of 80 points like LDV (DIC defines a displacement fields of thousands of points), convert the displacement into velocity time histories (for the comparison with LDV data) and generate a Test.Lab format file in order to use this software to perform the modal analysis. This file simulates the synchronous acquisition of 81 channels: the hammer and the 80 velocity signals.

3. Case study 1: modal analysis

In this section the comparison between the two techniques in static condition is discussed.

In literature so many works can be found on this topic, e.g. [12, 13] and [9] are just two examples of modal analysis performed on a tire measuring vibrations with non-contact techniques.

3.1. Excitation

The first comparison is made in static condition with a classic impact test with hammer hitting the sidewall. Since the focus is the measurement of sidewall out-of-plane vibration, it is very important to define the optimal hammering conditions because the excitation in that direction must be high enough to generate appreciable velocity or displacement in the measurement direction. The optimal solution in terms of high excitation and low noise is hitting the so-called opposite serial side that is the sidewall opposite to the one measured. In this way the hammer does not cover the measurement surface and it is avoided the saturation of DIC system: the displacements in the impact area are much higher than the other points so the range to measure would be too wide and the smallest displacement could not be correctly measured.

3.2. Results

Figure 5 shows the FRFs obtained for the two systems in the same condition of load and inflation pressure. It can be seen that there is a good correlation between LDV and DIC both in terms of amplitude and frequency. There is a small frequency shift for some modes and a difference in terms of amplitude but this could be related to the number of averages: the FRF obtained by LDV is the results of the average of 5 impacts instead of the DIC's FRF which is the results of a single measurement. As expected the hammer is able to excite tire structure up to about 200Hz, where there is the biggest difference of the curves: due to its higher sensibility, the LDV is capable to detect the cavity mode (the peak at 200 Hz) instead of DIC where the peak is scarcely visible. However it must be noted that the cavity is well detected by DIC in the vertical direction, in fact the spectrum of displacement present a clear peak at 200 Hz, but it is not reported here since the comparison is made on the out-of-plane component. Moreover, the small frequency shift but it could be related to a higher noise level which characterizes the DIC technique if compared with the LDV one.

The results are summarized below.

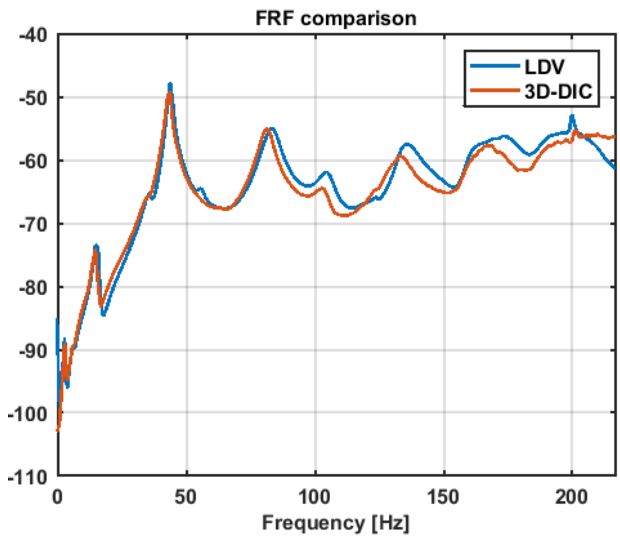


Figure 6 – FRF comparison.

	LDV	**3D-DIC**
	Frequency [Hz]	Frequency [Hz]
Mode 1	15.1	14.9
Mode 2	43.2	42.9
Mode 3	78.9	78.3
Mode 4	103.2	102.3
Mode 5	129.6	129.3
Mode 6	156.3	156.1

Table 1 – Frequency comparison for the detected modes.

4. Case study 2: Rolling tire

In this section the results obtained in rolling condition are discussed.

4.1. Scanning Laser Doppler Vibrometer – Approach and measurement grid definition

The measurement of tire vibration and the visualization of the operational deflection shapes is something known in literature: Castellini et al. performed this kind of measurement on a tire in free rolling condition by mean both of a Tracking LDV [3] and Scanning LDV [2]. In [4] the modes of a rolling tire are extracted considering the excitation coming from a cleat impact and measuring tire vibration with a single-point LDV.

SLDV measurement on rolling tire is performed using the Eulerian approach described in [2]: with TLDV a Lagrangian approach is used because the laser spot follows a single point along its trajectory, with the Eulerian approach the laser spot is fixed on a measurement point and the object is moving.

LDV measurements require stationary condition: the stationarity of the boundary conditions is guarantee by a continuous control of the load, the rolling speed of the drum and the temperature of the room. The only parameters that changes during the measurement are tire temperature and inflation pressure, so first of all it is necessary to evaluate if these parameters have an effect on the measurements. To do this, two circumferences of 80 points each have been considered, one closer to the rim and the second closer to external radius of the tire. In this way several aspects can be evaluated:

- effect of tangential velocity: points with different radius have different tangential velocities, so it must be understood if this causes a frequency shift;
- effect of tire temperature and inflation pressure: during rolling tire temperature and inflation pressure increase, so the increase generated during the LDV measurement could have an effect on the measurement.

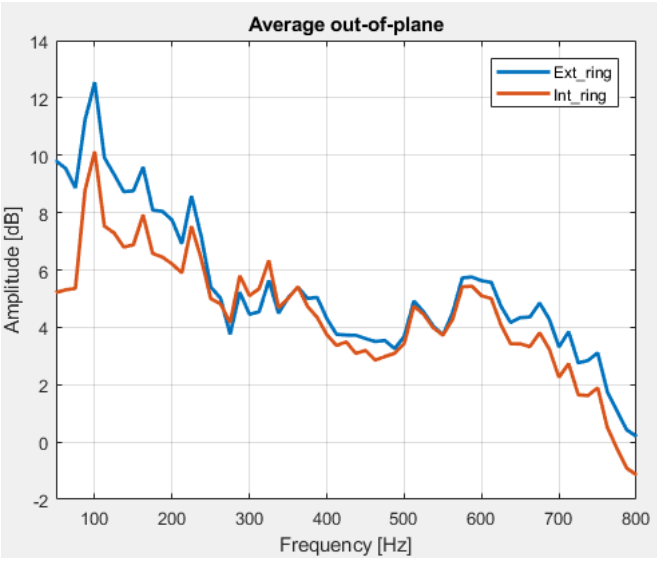


Figure 7 - Average AutoPower of the out-of-plane velocity for each circumference.

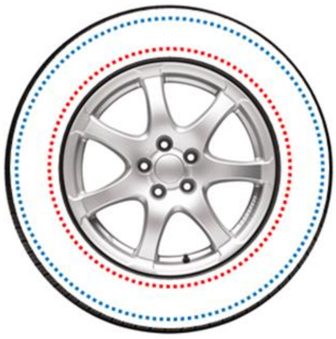


Figure 8 - Visualization of the measurement circumferences.

The figure shows the average AutoPower of the out-of-plane velocity for each circumference. This figure shows three main outcomes:

- the amplitude of vibrations depends on sidewall position: points closer to the rim have lower mobility if compared with external ones due to the rim constrain; there is no effect in terms of frequency so every circumference can be considered representative of tire behavior, the only difference is the amplitude level;
- tangential speed does not affect the frequency;
- the variation of tire temperature and inflation pressure during measurement does not affect the measurement; maybe the duration of the acquisitions is not so long to generate a significant increase of these parameters.

In conclusion, the measurement circumference can be chosen just considering the one which gives the highest level of signal.

Moreover, the sensibility of LDV allows a good measurement in the whole frequency range of interest, in fact it is able to measure both the low frequency vibration, responsible of the so called “Structureborne noise” (up to about 250Hz), and the high frequency vibration, responsible of the “Pattern noise” (the frequency range is related to the number of blocks, their dimension and the rolling speed; for the analyzed tire at 80 kph the range is 500 - 700 Hz).

It is interesting also to analyze the different contributions coming from different area of the rolling tire.

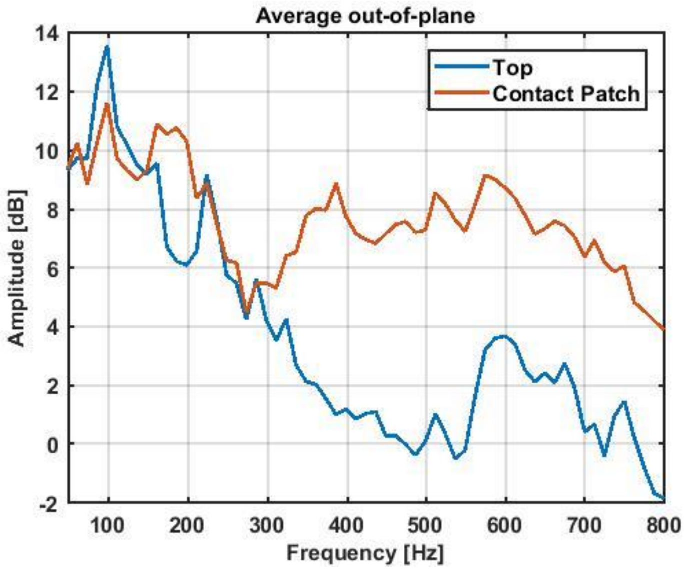


Figure 9 - Average AutoPower of the contact patch area and superior part of the tire to evaluate the contributions in the frequency range of interest.

Figure 10 - Visualization of contact patch area and top area of the tire.

From this figure, the main contribution in the high frequency range comes from the portion of sidewall that is closer to the contact patch, while the spectra in the low frequency range are comparable. The reason is the excitation: at low frequency the whole structure receives the same excitation, but at higher frequency the small displacement due to the contact with road generates waves propagating for a short stretch of sidewall both toward the Trailing and the Leading Edge. This effect will be more and more noticeable with 3D-DIC measurement.

Moreover, the correspondence of the spectra in the low frequency range suggests that LDV sensibility make possible to measure in the whole frequency range of interest.

The same effect appears considering the circumference closer to the rim, the only difference is a downward shift in terms of amplitude moving from tire treads towards the rim, so spectra are not reported just to avoid redundancy.

The analysis of LDV data proved that the high frequency is mainly caused by the contact patch area of the sidewall and this consideration will be helpful for DIC case (see paragraph 5).

4.2. 3D-DIC – Approach for dynamic measurement

In rolling condition the images are processed using an Eulerian approach instead of the classical Lagrangian approach used in DIC algorithms. Classic DIC uses a Lagrangian approach: the first frame is used to define the geometry of the object and the initial positions of the measurement points. The measurement area is divided in a certain number of interrogation areas called subset and the displacement field is defined by following each subset along its trajectory and the displacement is defined by the difference between the current position of the points and its position in the initial frames. The results are the absolute displacements of the points, frame by frame.

The approach used here is the so called incremental DIC [11]: incremental DIC was developed for those cases in which the deformation is too wide that it is not possible to find the correspondence of points in current frame and the reference one, so an intermediate reference frame is needed. With the Eulerian approach the reference image changes step by step, so frame by frame the measured displacement it is not an absolute displacement, but it is delta of displacement. The idea is to fix the observation area and analyse what happens behind that area, in the same way as the LDV measurement.

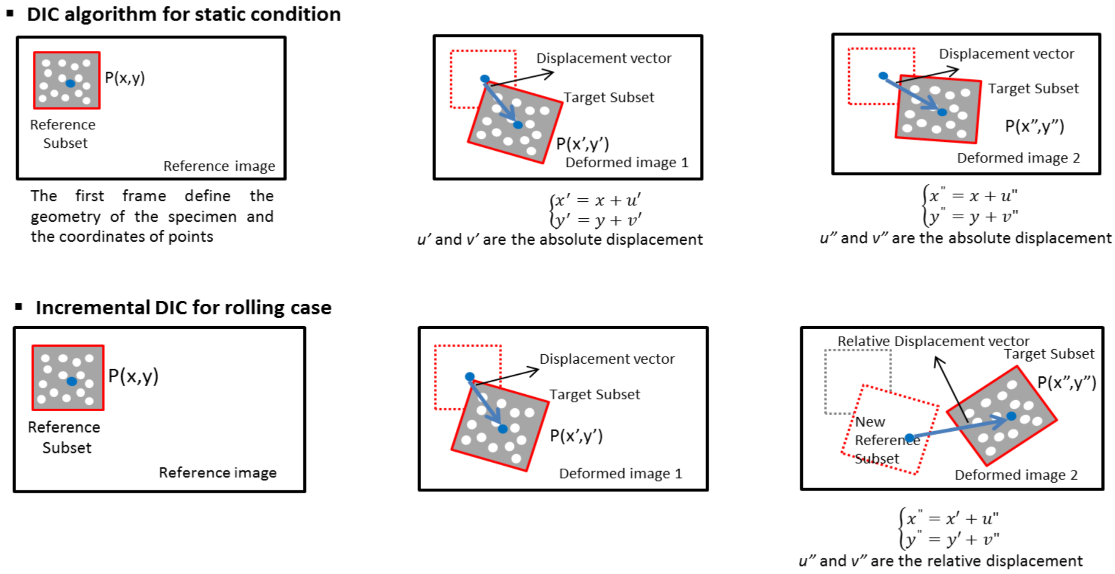


Figure 11 - Scheme of classic and incremental DIC algorithms.

To obtain good results with 3D-DIC, the frequency range of interest must be defined first, because this choice defines the optimal framing.

One of the major advantages of 3D-DIC is that it is a full-field, but the system resolution is defined by the ratio of the dimension of the framed area and the number of pixels of the camera, so the full-field framing could not be the optimal one. Tire generally has a diameter of about 600 mm and the sensor used has just 1 megapixels, so it is not possible to have a very high resolution: it means that bigger displacement will be measured but the smallest ones will not. The resolution can be increased using a sensor with a higher number of pixels or changing the framing as will be described below.

This kind of framing can be used if the idea is to measure the low frequency vibrations and it is useful to visualize how the contact with the road excite tire.

The following image is an instantaneous map of the out-of-plane displacement when the tire is rolling. The effect described analysing the LDV spectra is confirmed: the excitation coming from the contact with the road generates two small areas in the lower part of the tire characterized by higher displacement if compared with the rest of the structure.

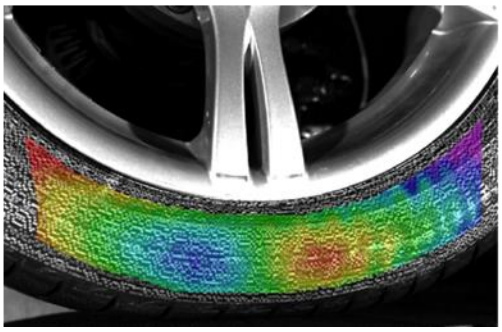



Figure 12 - Out-of-plane displacement field for full-field framing (left) and closer framing (right).

When the framed area is smaller, the resolution increases since the pixels are focused on a smaller area and smaller displacement can be correctly measured.

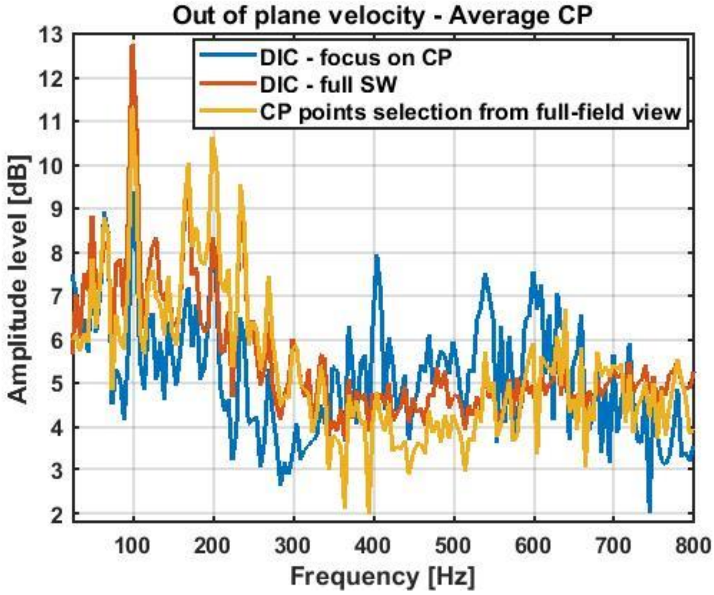


Figure 13 - Comparison of the average AutoPower of out-of-plane velocity for the two configurations of 3D-DIC system.

In figure 8 are reported the average AutoPower of out-of-plane velocity for the following case:

- an external circumference of 80 points, like LDV case (red curve);
- a group of 20 points in the contact patch zone starting from the full-field view (yellow curve);
- a group of 20 points for the closer view (blue curve).

Focusing the cameras on the contact patch area it is possible to measure the high frequency vibrations, with a loss of information at lower frequencies: main peaks are detected in terms of frequency, but the amplitude is lower if compared with the full-field view and the measurement in that region is noisier.

It must be remarked that, to measure the high frequency vibrations, it is not sufficient to measure the entire sidewall and perform the FFT just on the points localized in the contact patch area (yellow VS blue spectra). In fact, working with global framing the range of the displacement field is very wide and the DIC's sensibility it is not so high to measure it. This is probably the main disadvantage of DIC with respect to LDV.

5. SLDV VS 3D-DIC: techniques comparison in rolling condition

This paragraph presents the comparison of the measurement performed with the two techniques to evaluate the effective capabilities of DIC technique for this kind of measurement.

The figure below shows the comparison of the SLDV with the DIC measurement performed with a framing on the entire sidewall. The LDV spectrum is the average of the 80 points along the measurement circumference; the same for the DIC's one: this measure provides information about thousands of points, so a circumference of 80 points is selected.

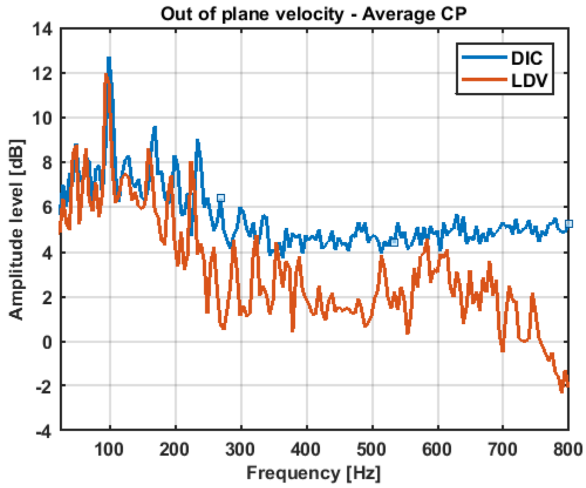


Figure 14 - Comparison of AutoPowers obtained with full framing DIC and the entire circumference of LDV.

As previously stated, this comparison confirms that the full field view measurement is not capable to measure in the whole range of interest: the vibrations in the frequency range of pattern noise (500 – 700 Hz in this case for the considered rolling speed), but the low frequency vibrations are well detected. There is an amplitude shift in the whole measurement range, but this could be related to number of averages: DIC measurement is very fast (1.35 sec) so it is intrinsically affected by an higher noise level with respect to LDV technique, so it could be reduced by performing several measurement and averaging them or using a bigger subset dimension during image processing.

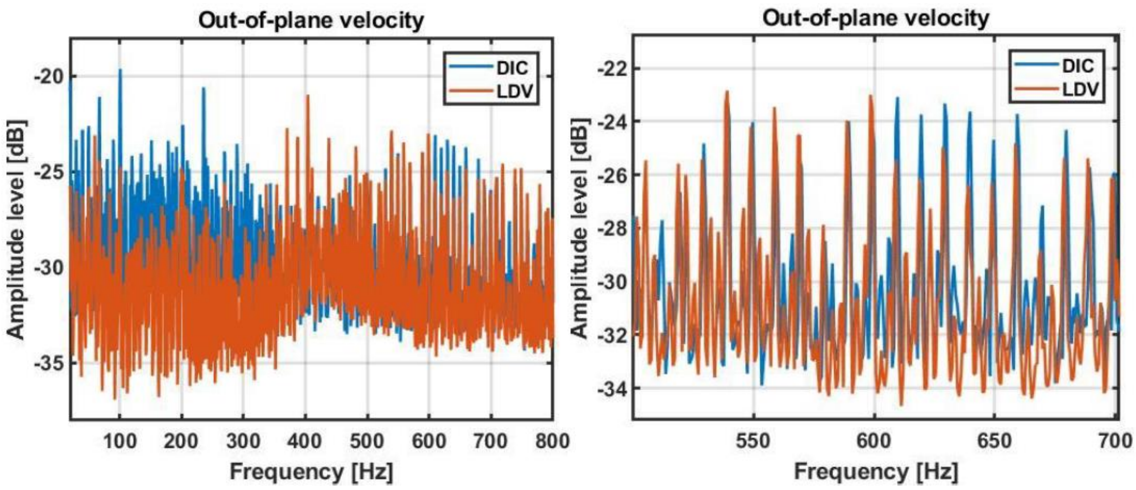


Figure 15- Comparison of AutoPowers obtained with closer framing DIC and the portion of circumference localized in the contact patch area of LDV (left); zoom in the frequency range of interest (right).

The figure above, instead, shows a good correlation between LDV and the 3D-DIC measurement performed with the cameras focused on the contact patch of the tire. The shape of the spectrum is well reproduced, the amplitude levels are more comparable in the high frequency region (above 500 Hz) and the noise level of the signal is significantly reduced if compared with the previous case. The resolution increase due to closer framing allows measuring the small displacements which characterise the high frequency vibration and a reduction of noise level.

6. Conclusion

The comparison between LDV and 3D-DIC measurement suggests the possibility to use this new technique as an effective tool for vibration measurement both for the low and the high frequency, the static and the dynamic case. In static condition there is a very good correlation in terms of amplitude and frequency, there is just a little difference between spectra, but it could be reduced increasing the number of averages in order to reduce noise (with LDV 5 impacts for each point are considered, while DIC measurement is performed with a single hammer impact) and with a better optimization of the speckle pattern. In this case the DIC technique seems to be better than LDV because the post-processing time is not so long so the very short acquisition time can be effectively can be considered an effective advantage because we can perform a stationary measure without variation in terms of boundary conditions.

For the rolling case further investigations are needed, especially the difference in terms of frequency must be understood. The main advantage of DIC technique (it is a full-field measurement) can't be exploited when measuring at high frequency due to the resolution of the cameras. It is necessary to consider a smaller area, which can be analyzed with a high spatial resolution since thousands of measurement points can be detected. In this case the long post-processing time is the biggest limitation if compared with LDV, but in order to obtain a comparable number of points with LDV the measurement should last about an hour with significant temperature variation which affect material behaviour.

In conclusion, a new procedure for tire vibration measurement using 3D-DIC has been developed and validated with a direct comparison with LDV, both in static and dynamic conditions, and two different setups have been described according to the frequency range of interest.

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