Application of digital speckle interferometry for vibration analysis of a statically loaded vehicle tyre

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Vehicle noise has, as one of its main sources, tyres and their interaction with the road. Experimental analysis of tyre vibroacoustic behaviour may provide useful information on the contributions of various regions of the tyre to the resultant noise. Digital speckle interferometry represents a reliable and efficient choice for vibration analysis, providing full field and real time information on surface displacement. The optical configuration used for this study is a standard out-of-plane sensitive setup, based on a continuous wave YAG laser. A 4 bucket phase stepping algorithm is applied, with the use of a piezoelectric actuator, in order to eliminate the random phase difference between the object and the reference wave. The measurement results are images of the tested tyre, covered with interference fringes, representing contour maps of out-of-plane vibration amplitudes. This paper presents measurements for the case of a tyre subjected to a point excitation at the limit of the contact surface with the road, under statical load of 4 kN. The principal resonant modes and frequencies are presented, then difficulties related to sensibility vector variation over the test surface and coupled mode resonances are discussed

1. Introduction

Noise reduction has become one of the major concerns of automotive manufacturers as a result of the search for increased refinement in vehicle design. In recent years, due to a considerable effort dedicated to the reduction of noise emissivity in engines, tyres and their interaction with the road have become one of the major sources of vehicle noise.

For an increased driving speed (over about 50 km/h), the noise generated by the tyre – road interaction becomes dominates vehicle noise.

The main sources of noise are located at the sidewalls of the tyre for a lower frequency range, and at the thread band at higher frequencies (over 600 Hz). The noise sources can be classified into structure-borne sound sources (the sidewall vibrations) and air-borne sound sources.

The mechanical sources of noise are induced by time varying contact forces leading to the structural vibrations of the tyre structure. These vibrations are the main sources of noise at low frequencies. Under the rolling conditions, radial and tangential vibrations of the tyre are generally excited by road irregularities. As a consequence of the belt deformation, the sidewalls are bent like a membrane. This is supposed to contribute to the radiation of sound, especially in the out-of- plane direction [1].

An investigation on the vibration parameters of vehicle tyres allows finding its natural resonant frequencies and makes it possible to better understand their acoustical emissivity allowing to improve tyre design.

Knowing the resonant frequencies of the tyre can also offer the possibility to minimise the transfer of the vibration to the passenger cabin and to the steering.

To the purpose of an experimental analysis, non contact measurement techniques are preferred to traditional, transducer based methods; given an increased sensibility and the lack of mechanical contact with the analysed tyre structure. Among the available measurement techniques, speckle interferometry (SI) represents an efficient and reliable choice, providing direct and full field information on the vibrating surface.

In this paper, an off-plane SI system is employed to retrieve the necessary information on the dynamic properties of a non rotating vehicle tyre, under statical loading of 4kN.

2. Measurement technique

Speckle interferometry (SI) is one of the most widely employed measurement tools. It is based on the properties of coherent light to obtain the fields of the variation of optical phase at the surface of the analysed object, between two instants of time [2].

The setup for phase-stepped speckle interferometry employed for the experimental work presented in this paper is shown in Fig. 1.

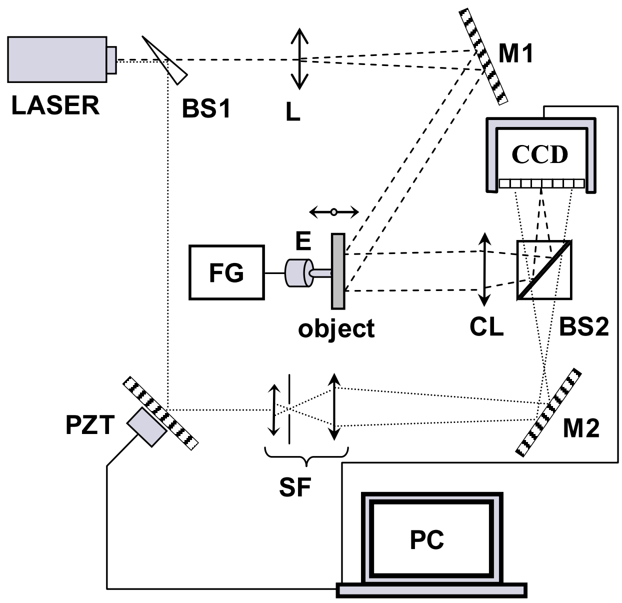

Fig.1 Phase stepped ESPI setup

The test object is illuminated by the continuous wave laser beam transmitted by the beam splitter BS1, the expanding lens L and redirected by mirror M1. The reference beam is reflected by beam splitter BS1 and PZT mirror, expanded by a spatial filter and redirected, through mirror M2 to the beam splitter BS2, where it is recombined with the object beam. The interference field thus obtained is imaged onto the CCD detector.

The instantaneous intensity available at the CCD plane is given by:

$$i(t) = A + B \cdot \cos(\varphi_{OR} + \Delta\varphi_R - \varphi_v(t)) \qquad (1)$$

Where A, B are the background intensity terms, φ_{OR} is the high spatial frequency random phase due to the speckle phenomenon, $\Delta\varphi_R = (k-1)\dfrac{\pi}{2}$, k=1,..,4 is the phase step of the reference wave, $\varphi_v(t) = A_v \cdot \cos(\omega \cdot t + \phi)$ is the vibration induced optical phase. As the camera's acquisition time is considerably higher than the object's vibration period time ($T >> \dfrac{2\cdot\pi}{\omega}$), the recorded images will correspond to an average intensity over several periods of vibration:

$$I = \frac{1}{T}\int_0^T i(t)\cdot dt = A + B\cdot\cos(\varphi_{OR} + \Delta\varphi_R)\cdot J_0(A_v) \qquad (2)$$

where $J_0(A_v)$ is the Bessel function of 0th order, first kind having as argument the dot product between the sensibility vector and the off plane displacement field:

$$A_v(x,y) = \vec{K}\cdot\vec{A}_v(x,y) \qquad (3)$$

The sensitivity vector has a magnitude $|\vec{K}| = 2\cdot\pi/\lambda$ and is directed, for any point (x,y) on the object surface on the object, along the direction bissecting the illuminating direction and the observation direction.

By applying a 4-bucket phase step algorythm, we obtain sets of 4 phase stepped images, from which the time-average interferogram can be calculated from:

$$I_{TAV} = \sqrt{C^2 + S^2} \qquad (4)$$

where C and S are the complex orthogonal fields:

$$C = I_1 - I_3 = 2\cdot B\cdot\cos\varphi_{or}\cdot J_0(A_v) \qquad (5)$$

$$S = I_4 - I_2 = 2\cdot B\cdot\sin\varphi_{or}\cdot J_0(A_v) \qquad (6)$$

Eq (4) describes the digital images of the vibrating object covered by the interference fringes.

There is no generally accepted algorithm for the passage from the time-averaged fringe patterns to the optical phase maps in the case of vibration-related interferograms. The existing procedures for the static deformations phase maps may not be applied. In order to interpret time averaged interferograms quantitatively, we need to determine the argument of J_0, that is the optical phase. This can be achieved by applying a semiautomatic fringe indexing method (developped at the INSA Photomecanics laboratory) which allows obtaining directly the unwrapped optical phase distributions.

In eq. (5,6), the trigonometric terms are results of the speckle effect and represent a noise that affects the Bessel fringes containing the information. In [3] an alternative technique is described, based on the elimination of the high spatial frequency content from the orthogonal components of the time-averaged hologram.

3. Experimental setup

The test setup is shown in Fig. 2. The statical load is applied with a rod and verified with 2 dynamometers placed on the 2 sides of the test table. The size of tyre exceeds the usual size for this optical system within our laboratory, therefore visibility was reduced due to the laser beam energy dissipation. In order to obtain good quality holograms, the surface of the tyre was covered with white paint.

A supplementary mirror was added to the setup, serving a double purpose: extending the illumination to the side of the tyre and allowing observation of that region by the CCD camera.

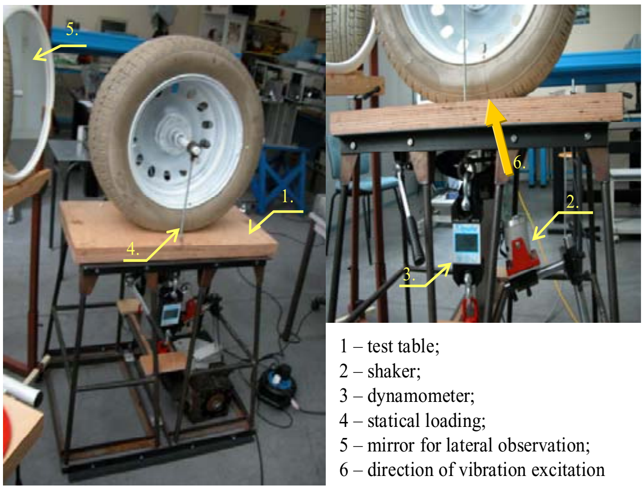

Fig.2 Test setup

The excitation is provided by a shaker driven trough an amplifier by the signal generator. The vibration is applied in one point at the limit of the tyre footprint, as indicated in Fig.2

4. Experimental results

Most of the tyre's resonant modes are situated in the 40 – 1100 Hz frequency range.

Between 40 and 170 Hz most of the measured modes engage the rim and parts of the test table and statical loading mechanism (plane, rods, dynamometers, …), as shown in Fig.3

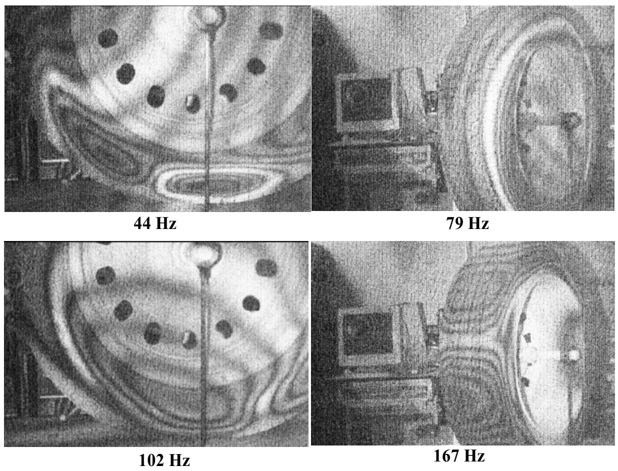

Fig.3 Vibration modes for 40 -170 Hz frequency range

The tyres eigenmodes are situated in a frequency interval of 170 – 1100 Hz, with an increased density between 170 and 650 Hz. Some of these modes can also excite the vibration of the rim. They are presented in Fig.4.

The resonance curves for the most part of the modes are wide and poorly separated in frequency, this causing the coupling of modes. The mode shapes are highly variable with excitation frequency shift.

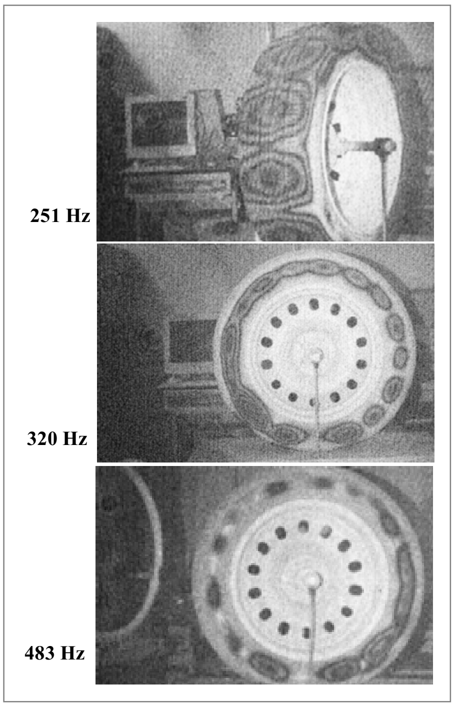

Fig.4 Several mode shapes in the 170 -650 Hz interval

Generally the vibration amplitudes are decreasing from the excitation point to the opposite end of the tyre's diameter. We could also observe that in most of the cases, the vibration amplitudes on the thread of the tyre are more important than those situated on the sidewalls.

The rim can also be engaged into vibration of the tyre, in radial direction as well as in out-of-plane direction.

For frequencies higher than 650 Hz, there are fewer resonances.

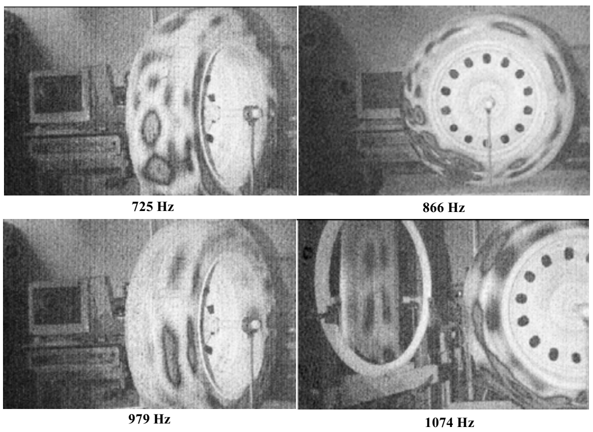

Fig.5 Vibration modes over 650 Hz frequency

The amplitude decrease rate around the circumference of the tyre becomes faster. The values of the vibration amplitudes are generally reduced, compared to the lower frequencies.

Measurement difficulties are related to the variation of the sensibility vector over the surface of the tyre. Moreover, in the case of complex modes of vibration (Fig.6) the acquired fringe patterns become ambiguous with increased difficulty of interpretation.

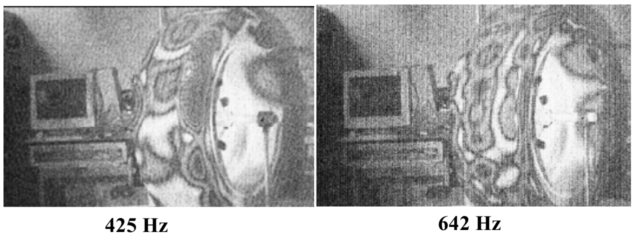

Fig.6 Coupled modes of vibration

5. Conclusion

In this paper we presented the measurement results for the statically loaded vehicle tyre, with a pointwise harmonic excitation at the limit of the contact region with the road.

This work aimed at obtaining the maximum number of the tyre's mode shapes and resonant frequencies.

We found that most part of the resonant modes are situated between 40 and 1100 Hz, with the highest density of eigenmodes between 160 and 650 Hz. For this frequency interval, we observed that the vibration amplitudes on the thread of the tyre are more important than those on the sidewalls and that there is a decrease of vibration amplitude as we move away from the excitation point.

For the lower frequencies, the sustain mechanism can also be engaged into resonance. The rim is brought into vibration all along the fore-mentioned frequency range.

Acknowledgments

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References

[1] Bécot, F., “Tyre noise over impedance surfaces-Efficient application of the Equivalent Sources method”, Ph. D. Thesis, 2003, Chalmers University of Technology, G¨oteborg, Sweden & Insa – Scientific and Technical University, Lyon, France

[2] Lokberg, O. J., “ESPI-The ultimate holographic tool for vibration analysis,”, J. Acoust. Soc. Am., 1984, vol. 75, no 6, pp. 1783-1791

[3] Borza, D., "Mechanical vibration measurement by high-resolution time-averaged digital holography", *Meas. Sci. Technol.*, 2005, 16, pp.1853-1864