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Experimental Modal Analysis of Tyres by ESPI

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Abstract

With help of the ESPI tool we have determined vibration modes of different tyres. In the paper we studied also the influence of the tyre inflation on the vibration mode dynamic. The obtained results were qualitatively compared with those obtained by application of the finite element method (FEM) in the Marc software environment.

Keywords: ESPI, vibration, tyre, simulation MKP.

1. Introduction

A tyre is designed to satisfy a number of functional requirements. The rubber structure must work reliably in a large spectrum of dynamic conditions – from static loadings to high frequency exciting of mechanical vibrations. From the viewpoint of mechanics there is a complicated dynamic system, where rubber material nonlinearities, as well as composite anisotropic structure, have to be taken into account. The performance requirements of the system cannot be adequately designed without knowledge of its real dynamic characteristics, where the experimental measurements are necessary. This holds also for the measurement of natural frequencies modes/shapes and damping properties. From the practical point of view the knowledge of natural tyre frequencies gives the constructors a chance to change the tyre construction in such a way so that the driving comfort connected with tyre noise is optimized.

The Electronic Speckle Pattern Interferometry (ESPI) is an optical technique which enables interferometric measurements of surface displacements on almost any surface and material. The non-contact and full-field measurement allows calculation of the three-dimensional distribution of the displacement and strain/stress of the object under test as a response to mechanical or thermal loading.

Works [1, 2] present the ESPI application for non-destructive measurement insitu displacement fields in micro-systems. A thermal vacuum chamber was designed to induce thermal treatments, including annealing. From the identification of the residual-stress-free state, they quantitatively modelled thermal strains/stress fields, relaxation stresses during annealing, and residual stress fields.

The ESPI is a fast-developing whole-field optical technique widely used to measure displacement components, their derivatives, surface roughness, shape and slope contours of surfaces etc. The salient feature of the ESPI is its capability to display the correlation fringes in real time on a TV monitor without the need of photographic processing or optical filtering. The paper [3] reviews the main developments in the field of Electronic Speckle Pattern Interferometry that have been published over the past 20-25 years.

There are two ESPI working modes: addition ESPI mode and subtraction ESPI mode [4]. Overcoming the disadvantage of the subtraction ESPI mode, which strictly requires that there is no movement among the optical parts in the ESPI system, in the addition ESPI mode, the movement of the measured material is frozen with a short-pulsed laser. Due to the fact the result can only be obtained when the interference fringe passes through special electronic filter. Its quality and central frequency influence the final interference fringe result. Therefore, series of the filters are designed as band-pass and high-pass filters, with a specific method applied. Subsequently, the result of the simulation for the NDT with double-pulsed ESPI method is acquired and analyzed.

The electronic speckle-pattern shearing interferometer (ESPSI) is proposed for measuring the free convection heat transfer coefficient in liquids. The heat transfer coefficient may be deduced by a simple manipulation of the speckle patterns. The theory of the method, as well as its application, are both presented. The advanced optical interferometric technology is mostly used for aerospace applications [5].

The paper deals with the application of the ESPI interferometry for the visualisation, as well as measurement, of the natural frequencies on personal tyres. By using of the method of electronic speckle correlation interferometry the mode shapes were observed under the dynamic excitation of the tyre vibrations. The experimentally observed mode structure for the given tyre type is qualitatively compared with that obtained by the FEM simulation.

2. Theory

The light wave interference in case of the opaque object is determined by phase difference of interfering waves $\Delta\theta = \vec{K}.\vec{d}$ where $\vec{d}$ is displacement vector for a point on the surface and sensitivity vector $\vec{K}$ is given by relation $\vec{K} = \frac{2\pi}{\lambda}\left(\vec{k}_2 - \vec{k}_1\right)$ (1)

where $\vec{k}_1$ is the illumination unit vector and $\vec{k}_2$ is the observation unit vector and λ is light wavelength.

Let us consider the experimental setup for the visualisation of displacements perpendicular to surface. The direction of the area vector is parallel with the observation vector in this case. The phase difference will be $\Delta\theta = 4\pi w/\lambda$ where w is a normal displacement vector component. At the double exposure holographic record at reconstruction the light wave intensity is

$$I(x,y) = 2I_0\left[1 + \cos(\Delta\theta(x,y))\right] \qquad (2)$$

where I_0 is object light wave in original state. From this fact we can conclude that two neighbouring maxima or minima differ as $\lambda/2$.

At the time-average method, the vibrating object can be recorded on the hologram. The intensity of the object wave is

$$I(x,y) = I_0\, J_0^2\, \left[\left(\Delta\theta(x,y)\right)\right] \qquad (3)$$

where $\boldsymbol{J_0}$ is the Bessel function. The nodes correspond with the brightest fringes on the holographic interferogram.

3. Experimental Procedure

The laser beam is divided into two parts, the reference and object beam, by a beamsplitter. The object beam travels to the specimen and then reflects to the CCD camera via the mirror and reference plate. The CCD camera converts the intensity distribution of the interference pattern of the object into a corresponding video signal. The signal is electronically processed and finally converted into an image on the video monitor (see Figure 1).

The experimental procedure of the ESPI technique is performed as follows. First, a reference image is taken, after the specimen vibrates, then the second image is taken, and the reference image is subtracted by the image processing system. If the vibrating frequency is not the resonant frequency, only randomly distributed speckles are displayed and no fringe patterns will be shown. However, if the vibrating frequency is in the neighbourhood of the resonant frequency, stationary distinct fringe patterns will be observed. Then the function generator is carefully and slowly turned, the number of fringes will increase and the fringe pattern will become clearer as the resonant frequency is approached. The resonant frequencies and corresponding mode shapes can be determined at the same time using the ESPI optical system.

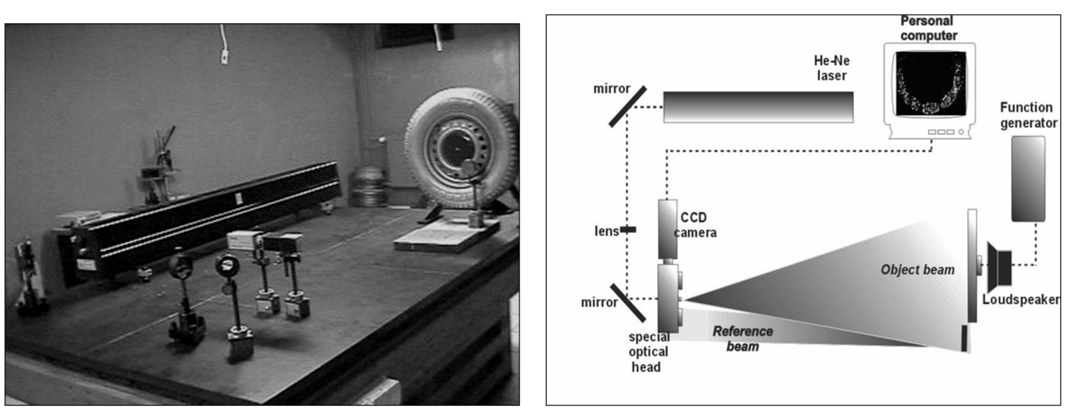

Figure 1. Experimental setup and scheme of the ESPI apparatus

4. Results and Discussion

In the first step we tested the whole accessible spectrum of vibration modes, their frequencies and amplitudes in both radial and axial direction. From the results presented in Table 1 it is possible to see that with the rising mode order (rising frequency) the amplitude of the mode decreases. The results were obtained for the tyre Matador MP 42 195/70 R14 91H

Mode	Frequency [Hz]	Amplitude [μm]	Amount of loops
Axial 1st mode	41	2.86	2
Axial 2nd mode	90	2.21	4
Axial 3rd mode	150	1.89	6
Radial 1st mode	90	1.97	2
Radial 2nd mode	113	1.56	4
Radial 3rd mode	133	1.32	6
Radial 4th mode	157	1.02	8
Radial 5th mode	183	0.95	10
Radial 6th mode	202	0.72	12

Table 1: Mode spectrum of the tested tyre

To study the dynamic changes of the mode spectrum we have changed the tyre inflation, and investigated changes in modes frequencies were registered. The results for first the first modes are presented in Figure 2. As it has been expected the mode frequency decreases with decreasing inflation for excitation in radial direction. Qualitatively very close results we obtained at the axial excitation of the tyre.

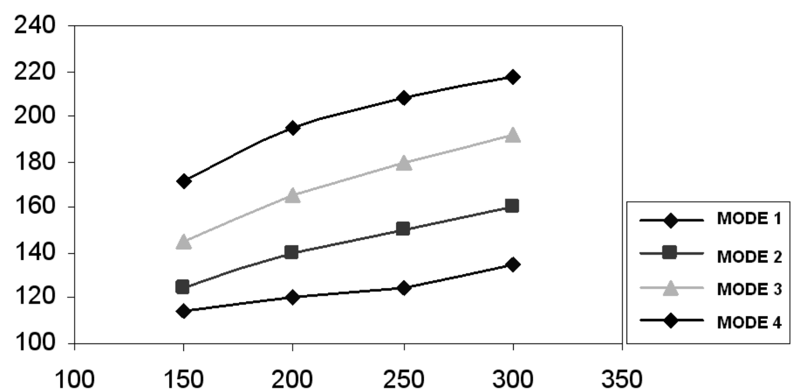

Figure 2: The mode changes versus inflation

For testing the inflation influence on the mode structure, the tyre type175/65 R14 82T GOOD YEAR – GT2 was used.

To obtain qualitative evaluation of the mode structure we model by the FEM the tyre vibrations in Marc software environment. The Mooney constants were used as material parameters and rubber plasticity model for big deformation was applied. We started the simulation on the model presented in Figure 3. Experimental results were obtained on the tyre CONTINENTAL 205/55 R16 91W

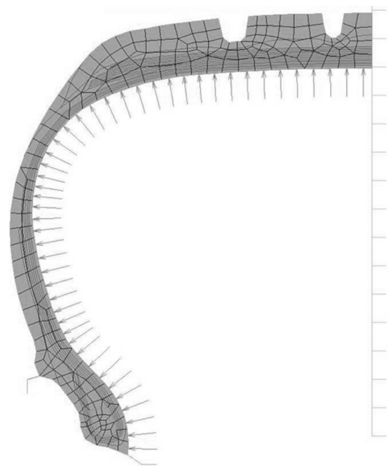

Figure 3: The FEM network on the model

Both experimental and simulation results are in very good qualitative coincidence. Nevertheless for quantitative agreement of the experiment and simulation results it is necessary to know the details of the tyre material composition and construction which is very difficult to obtain because producers usually do not disclose this information.

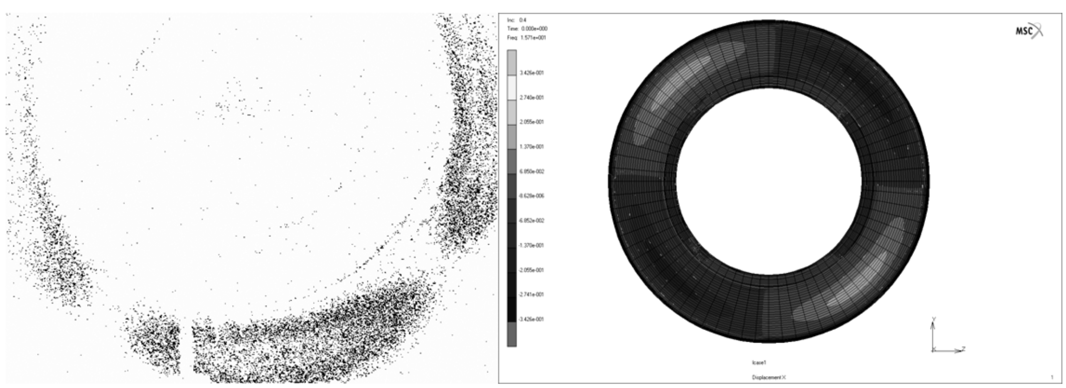

Figure 4: Measured (left) and simulated (right) vibration field at the frequency 119 Hz, 4 antinodes

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