Study on the modal behaviour of contactless 11R22.5 truck tyre

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Abstract. The study of tyre vibration represents a field of interest for tyre and vehicle manufacturers, with respect to automotive comfort, rolling noise and safety, also concerning influences on ABS performance, as well as regarding the durability of vehicles, tyres and road. The study of tyre modal behaviour has been performed on an 11R22.5 truck tyre, both through experiments using the impact hammer method and through finite element analysis. The current paper focuses on the investigation of radial vibration modes for truck tyre without road contact. The model of the truck tyre has been elaborated and used for investigation of modal behaviour at different inflation pressures, and the natural frequencies for radial vibrations have been obtained, as well as the corresponding mode shapes. Experiments have been performed on an 11R22.5 truck tyre without road contact, mounted on the corresponding rim, separately from the vehicle. The impact hammer method has been used for obtaining the tyre natural frequencies corresponding to radial vibrations, through frequency analysis of acceleration measured on the tyre tread. The tyre natural frequencies obtained from the finite element analyses have been compared to the results of measurements and acceptable similarities have been ascertained. The differences can be explained by the fact that real properties for component materials of tyre finite element model have not been available, but also by the method of supporting the tested wheel. The experimental investigation of tyre modal behaviour contributed to partial validation of the finite element model, but further research is required to improve the finite element model.

1. Introduction

The pneumatic tyre is defined as a force and moment generating structure [1, 2] and the interaction between tyre and road represents the main interface of the vehicle with the environment [3, 4, 5]. In addition to transmitting forces between the vehicle and the road, as well as supporting both the sprung and the unsprung mass, the tyre has multiple essential functions, such as enveloping road irregularities, which represent a major factor generating forced vibrations. This purpose is achieved by the tyre through deflecting and thus absorbing, storing and then dissipating the elastic energy. Therefore, the tyre has a role complementary to the vehicle suspension, from the point of view of filtering road unevenness and damping road induced vibrations, with important effect on reducing the vibrations transmitted to the chassis. The elastic properties of the tyre are exerted not only in radial, but also in lateral and circumferential directions, thus influencing cornering behaviour, torsional vibrations, etc. Consequently, the study of tyre vibration represents a field of interest for tyre and vehicle manufacturers [6, 7, 8], with respect to automotive comfort, rolling noise and safety, also concerning influences on ABS behaviour, as well as regarding durability of vehicles, tyres and road.

Because the tyre is a complex mechanical structure, the dynamic behaviour of the tyre consists of multiple vibration modes, characterised by mode shapes and natural frequencies. These modes appear when forced vibrations occur under the disturbing effect of rolling and road irregularities, but also when free vibrations arise, for instance after a road obstacle [9],[10]. Several types of tyre vibration modes can be distinguished, corresponding mainly to the radial, lateral and circumferential directions. As in the case of any resonance phenomenon, the vibration modes generate problems concerning the amplitudes of transmitted displacements and accelerations, but they can also lead to additional issues, such as the standing waves [11, 12], which are associated to the tyre critical speed and can produce dangerous effects, to the extent of tyre destruction.

The study of tyre modal behaviour can be performed through experiments or using finite element models or analytical models. Experimental investigation of tyre vibrations can be achieved through several methods using accelerometers [13, 14], for example the impact hammer method, which allows measuring tyre natural frequencies [15, 16]. Finite element models can also be used for determining valuable information on the modal behaviour of tyres, such as natural frequencies and mode shapes [13, 17, 18, 19, 20]. The modes corresponding to vibrations in radial direction are the most significant from the point of view of durability and comfort. The purpose of the current paper is the investigation of radial vibration modes for truck tyres without road contact, using both finite element method and impact hammer method.

2. Finite element analysis of truck tyre modal behaviour

2.1. Finite element model of the 11R22.5 truck tyre

The complexity of tyre structure requires detailed finite element models, leading to many difficulties in the initial phases of model development [21, 22]. The sources of nonlinearities comprise the tyre geometry, materials, and boundary conditions. The model of the 11R22.5 truck tyre elaborated for investigation of modal behaviour has been developed using ABAQUS software. The finite element model is based on the coordinates measured on the exterior contour of the tyre presented in figure 1. The section of a similar 11R22.5 truck tyre, shown in figure 2, has been used for measuring coordinates of the interior contour and for identifying the components of tyre structure. This information was necessary for adequately defining the nodes and elements which compose the 2D model of the tyre section, presented in [23]. The model takes into account the nonuniformity and anisotropy of the structure, including the reinforcing layers with section area, distance and angle defined accordingly. The 2D model of the tyre section has been defined without symmetry conditions, so that the effect of asymmetrical belts under the tread can be noticed.

**Figure 1.** The 11R22.5 truck tyre used for developing the finite element model.

Figure 2. Section of 11R22.5 truck tyre used for measuring contour coordinates.

Through the rotation of the section model with respect to the axis, the 3D tyre model has been generated, consisting of 72 sections distributed uniformly around the circumference, figure 3. The tread pattern is slightly different from that of the real tyre, because it has only circumferential grooves.

Linear elastic behaviour has been assumed for the cord plies and beads, while the properties of rubber components have been defined using a hyperelastic model, presented in [24]. Boundary conditions comprise the rim modelled as a rigid body, with nodes corresponding to the tyre nodes that seat on the rim and with a single node at the centre used for constraining motion. The inflation pressure has been applied in a static analysis performed on the 2D model of tyre section [25], and then the results have been transferred to the 3D model, to save computational time.

2.2. Analyses of modal behaviour of the 11R22.5 truck tyre model

The investigation of modal behaviour has been performed on the finite element model of the 11R22.5 truck tyre for different values of inflation pressure. The finite element analyses have determined vibration modes corresponding to the radial, lateral and circumferential directions, in addition to the rigid body modes. Only the radial modes have been selected for this study, therefore the mode orders and natural frequencies obtained for the first 15 radial modes are presented in figure 4 and in table 1.
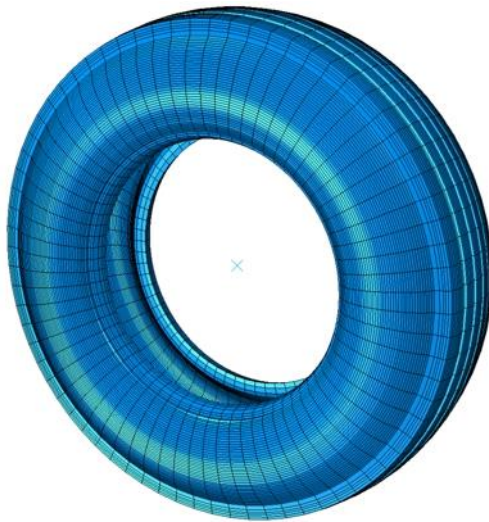
**Figure 3.** Finite element model of the 11R22.5 truck tyre [26].
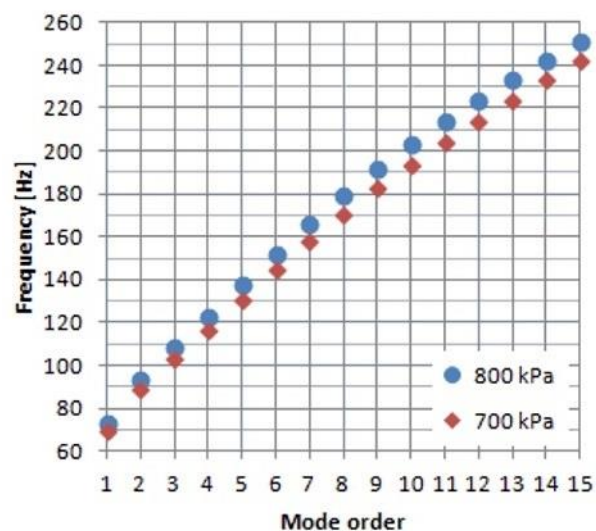
Figure 4. Natural frequencies corresponding to radial vibrations obtained by finite element analysis.

The effect of higher inflation pressure consists of increasing the tyre stiffness and consequently increasing the natural frequencies. It can be noticed that the values of natural frequencies are not linear with respect to mode orders, an observation that has also been mentioned in literature [11, 13].

Table 1. Natural frequencies corresponding to radial vibrations obtained by finite element analysis.

Mode	Frequency [Hz]		Mode	Frequency [Hz]		Mode	Frequency [Hz]	
	800 kPa	700 kPa		800 kPa	700 kPa		800 kPa	700 kPa
1	72.8	69.5	6	152.1	144.4	11	213.5	204.0
2	93.8	89.2	7	166.2	157.9	12	223.5	214.0
3	108.2	102.8	8	179.4	170.6	13	233.0	223.6
4	122.6	116.4	9	191.7	182.5	14	242.3	233.0
5	137.4	130.4	10	203.0	193.6	15	251.4	242.3

The mode shapes for radial modes up to ninth order are shown in figure 5 as relative displacements, plotted in two different moments throughout a period of the vibration, corresponding to the extreme values of displacements. The results of the finite element analysis are shown together with a schematic theoretical representation of the deformed shape.
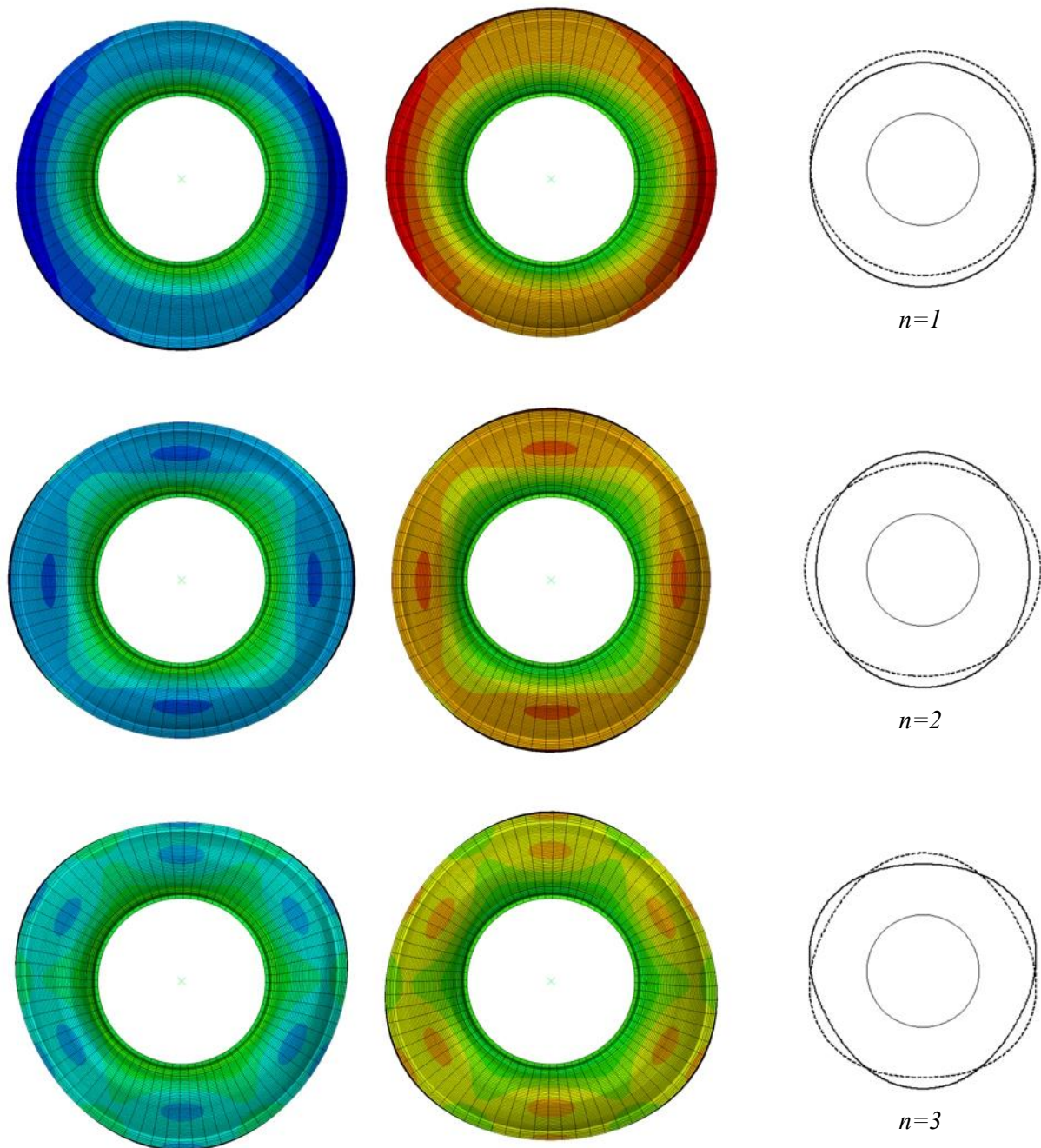
Figure 5. Mode shapes corresponding to radial vibrations.

n=4

n=5

n=6
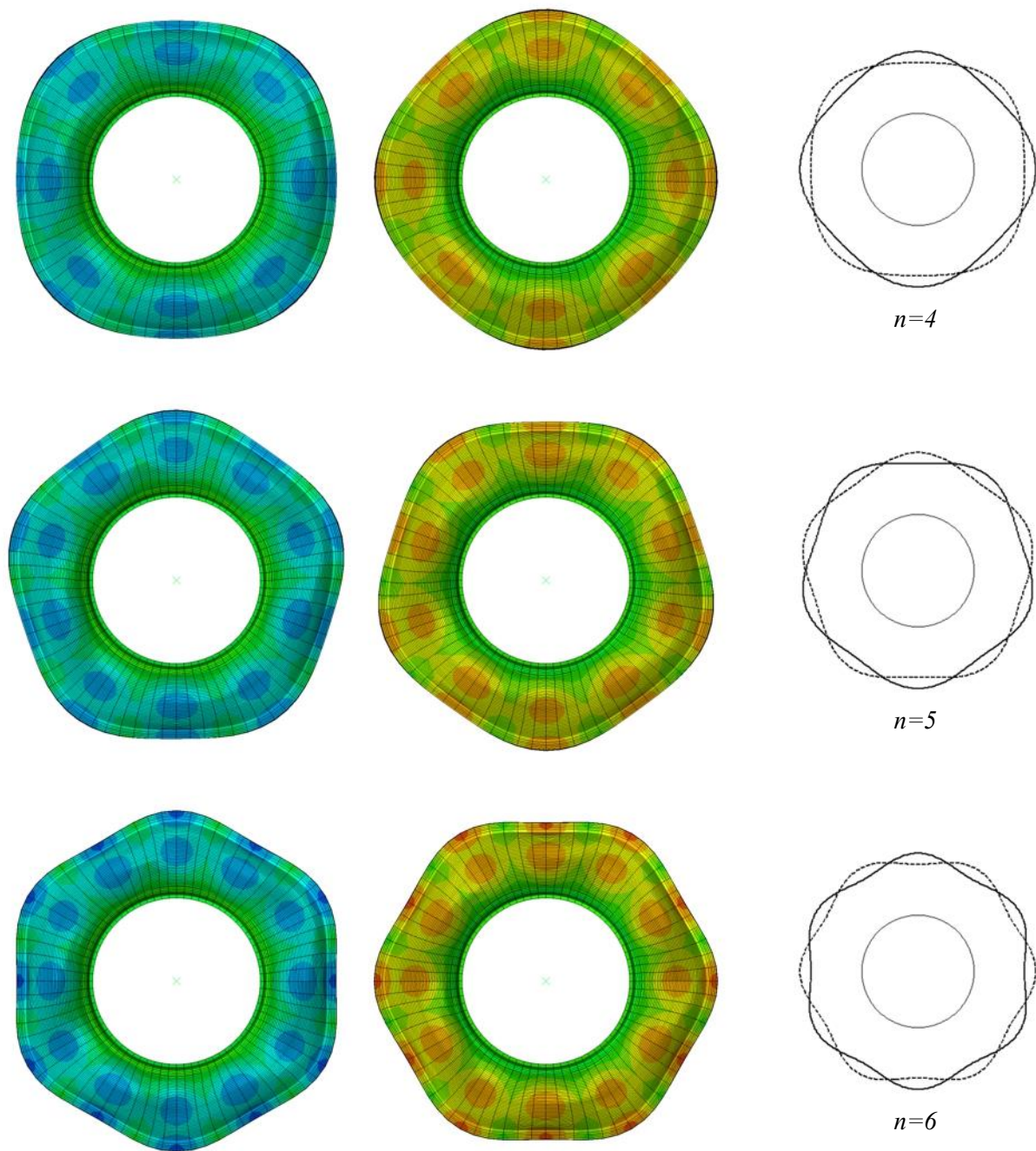
Figure 5. Mode shapes corresponding to radial vibrations (continued).

Each shape exhibits the periods of the harmonics, distributed around the tread circumference, whose number is equal to the mode number or mode order. The mode order represents half of the number of nodes for each shape, or half of the total number of extremum points (maximum points and minimum points). Although these mode shapes correspond to radial vibrations, some displacements of the tyre sidewalls can also be noticed.

3. Experimental investigation of modal behaviour for the 11R22.5 truck tyre

The modal behaviour of the 11R22.5 truck tyre has been investigated experimentally through the impact hammer method. This method consists of measuring the vibrations of a mechanical system, such as the tyre, generated by applying an impact with a special hammer equipped with a force transducer. The vibratory response is measured simultaneously with the impact force, so that the frequency response function of the tyre can be ascertained. From the frequency analysis of the results, natural frequencies of the tyre are determined experimentally.

Measurements have been performed on the same 11R22.5 truck tyre, already presented in figure 1, which has been used for developing the finite element model. The tyre has been mounted on a corresponding steel rim and the inflation pressure has been adjusted to 700 kPa. The tyre-rim assembly has been suspended to allow free vibrations, but elastic support could not be achieved, because of the considerable mass of the wheel assembly.

The tyre has been instrumented with a ceramic shear accelerometer with one measuring direction. The transducer has been mounted on the central rib of the tyre tread, with the measuring direction oriented on radial direction in the tyre median plane, as can be seen in figure 6. The accelerometer has been mounted using the dedicated adhesive (petro wax) supplied by the manufacturer. The impact force has been measured using a specialized impact hammer equipped with piezoelectric force transducer. The signals from the accelerometer and from the force transducer fitted on impact hammer have been processed using a 3-channel signal conditioner for piezoelectric transducers. The impact force has been applied on the central rib of the tyre tread, oriented on radial direction in the tyre median plane. In addition to the impact hammer, transducers and signal conditioning device, which can be seen in figure 7 together with the tested tyre, the measuring system also included a data acquisition card with multiple analog input channels and a computer.

**Figure 6.** The tyre instrumented with a piezoelectric accelerometer.

Figure 7. The measuring system for investigation of tyre modal behaviour using the impact hammer method.

The applications for data acquisition and data processing have been developed in LabVIEW software. The data acquisition application uses two analog input channels of the data acquisition card to measure the impact force and the acceleration of tyre radial vibrations, then converts the voltages to force and acceleration using the respective sensitivity constants of the transducers, and finally stores the results files on a computer. The data processing application retrieves the stored data, computes the

frequency response function, performs the frequency analyses and plots the results, so that the natural frequencies can be identified.

The natural frequencies for radial vibration modes of the abovementioned 11R22.5 truck tyre obtained experimentally using the impact hammer method are presented in figure 8 and in table 2, in comparison with the results obtained from finite element analysis of the corresponding tyre model. The natural frequencies for the first and second mode order have not been determined experimentally, as they could not be identified in the frequency analyses, possibly because of the method of supporting the wheel during the measurements.
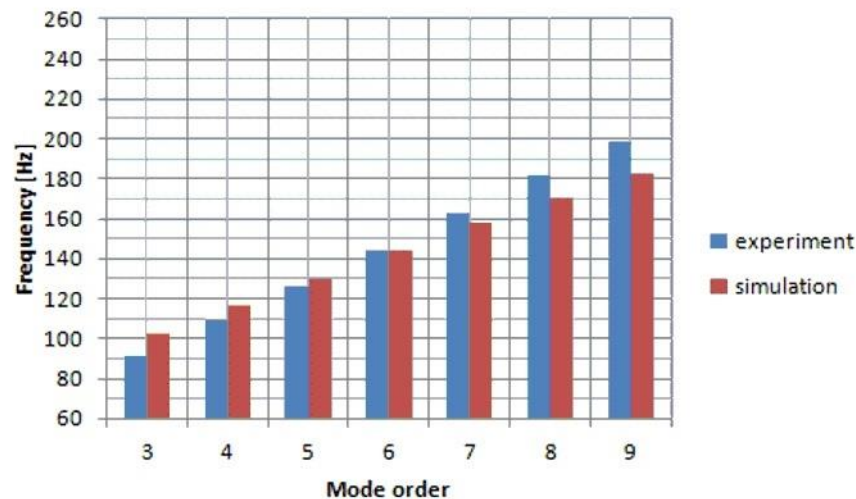
Figure 8. Natural frequencies corresponding to radial vibrations; comparison of results obtained from experiment and simulation.

The best correlation between the natural frequencies obtained from experiment and those from finite element simulation occurs for the sixth order mode. It can be noticed that the results from finite element analysis have smaller sensitivity to the mode order than those obtained experimentally. The dissimilarities between simulation and experimental results tend to increase at higher order modes and also at lower order modes, with the most important relative difference occurring for third order mode. The differences can be explained by the fact that real properties for component materials of tyre finite element model have not been available, but also by the method of supporting the tested wheel.

Table 2. Natural frequencies for radial vibrations, obtained from experiment and simulation.

Mode	Frequency [Hz]		Relative difference [%]
	experiment	simulation	
1	-	69.5	-
2	-	89.2	-
3	91.8	102.8	-11.98
4	109.7	116.4	-6.11
5	126.0	130.4	-3.49
6	144.4	144.4	0.00
7	162.8	157.9	3.01
8	181.4	170.6	5.95
9	199.1	182.5	8.34

4. Conclusions

The investigation of modal behaviour performed on the finite element model of the 11R22.5 truck tyre has provided natural frequencies and mode shapes corresponding to radial, lateral and circumferential directions, in addition to the rigid body modes, but only the radial vibration modes have been analysed in this study.

The effect of higher inflation pressure consists of increasing the tyre stiffness and consequently increasing the natural frequencies. The values of natural frequencies are not linear with respect to mode orders, and this observation is similar to those previously published in literature. Each modal shape exhibits a number of harmonics, distributed around the tread circumference, which is equal to the mode number. The total number of extremum points, which coincides with the number of nodes for each shape, is double with respect to the mode order.

The impact hammer method has allowed investigating experimentally the natural frequencies of the 11R22.5 truck tyre. The comparison between the natural frequencies obtained from experiment and those from finite element simulation has shown acceptable correlation for some of the modes, but also large differences for the third and ninth order modes. The results from finite element analysis show smaller sensitivity to the mode order than those obtained experimentally.

The differences between simulation and experimental results tend to increase at higher order modes and at lower order modes. The causes could reside in the fact that real properties for component materials of the tyre finite element model have not been available, but they could also pertain to the method of supporting the tested wheel. The experimental investigation of tyre modal behaviour contributed partially to the model validation, but further research is required to improve the finite element model.

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