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SYNOPSIS OF THE EXPERIMENTAL AND NUMERICAL TIRE DYNAMIC CHARACTERIZATION

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ABSTRACT – Both experimental as well as numerical analyses have been performed to establish the understanding of the influence of rolling on the tire dynamic behavior. The experimental analysis is based on accelerometer measurements on the inner liner of a tire. The numerical analysis is based on a highly detailed tire model, including complex material properties by means of frequency dependent viscoelastic material definitions. A comparative analysis is performed to evaluate the correspondence and differences between experimentally and numerically obtained modal parameters of a rolling tire.

The analyses also show how the footprint contact, established due to loading of the tire, acts as a boundary condition for the structural waves and thus influences the dynamic behavior of the rolling tire. The results show that a rotating tire is subjected to Coriolis accelerations which make the wave speed of the positive- and negative-going wave to diverge from each other. This leads to complex or travelling wave mode shapes. The experimental analyses confirm the numerically predicted effects of rolling on the tire dynamic behavior.

TECHNICAL PAPER

INTRODUCTION

This paper gives an insight in the complex dynamic behaviour of a tire and is a continued work based on previous research efforts [1]. Flexible rotating structures are subjected to gyroscopic effects which are well understood for simple structures such as rings and cylindrical shells [2]. Already in 1890, Bryan [3] described the rotating modes of a rotating bell or cylinder. However, the gyroscopic effects for more complicated structures, such as a loaded rotating tire in ground contact, are found to be more difficult and are not yet fully understood.

The tire models reported in literature range from analytical models [4] to highly sophisticated numerical models [5, 6]. However, no validated highly detailed model, which includes all the complex tire/road noise generation phenomena and effect of rotation on the tire dynamic behavior, has been proposed. Therefore, inside the European seventh framework program (FP7), an industry-academia partnership project, named TIRE-DYN [7], has been founded that brings together academic and industrial knowledge and technology to quantify the effects of rolling on the tire dynamic behavior. This paper presents numerical and experimental analyses that provide more understanding of the propagating waves in a rotating tire and the resulting resonance phenomena. All simulations and measurements are performed for a slick tire of size 205/55R16.

BASIC CONCEPTS OF WAVE PROPAGATION IN TIRES

Bolton et al. [8] characterized the wave propagation characteristics of a tire by means of a wave number decomposition of the radial tire vibrations. The dispersion relation expresses for each frequency, the wave numbers of the harmonic waves that can propagate in the structure. The graphical representation of the wave number decomposition is known as a dispersion graph. The dispersion graphs show the magnitude of the tire vibration velocity for each wave number/frequency combination due to a unit harmonic point force. Figure 1 illustrates the principle of such a dispersion curve for an unloaded and non-rotating tire excited by a unit force at the tread center. The horizontal axis represents the real part of the wave numbers. Both positive and negative wave numbers are considered since waves propagate in both directions along the tire circumference. Each branch of the graph corresponds to a particular wave type. The dispersion relation gives also information about the speed at which energy is transported by a wave. The group velocity is the speed at which the dominant part of a disturbance travels. This velocity can be obtained as the local slope of the dispersion curve. As indicated on Figure 1, the group velocity of the longitudinal waves is larger compared to the bending waves.

At certain frequencies, waves travelling in opposite direction will interfere constructively and cause a standing wave pattern. The circumferential resonances appear when the tire circumferential length equals an integer multiple n of wavelengths. The tire resonance mode naming convention used in this research uses two integer indices which describe the bending order of the belt package in two directions. The format of the notation is [n,a]. The first index n represents the number of circumferential bending wavelengths and is also known as the circumferential mode number. The second index a represents the number of half-wavelengths in the axial direction of the tread band at a circumferential location where the shape is at an extreme displacement. This convention is illustrated in Figure 1.

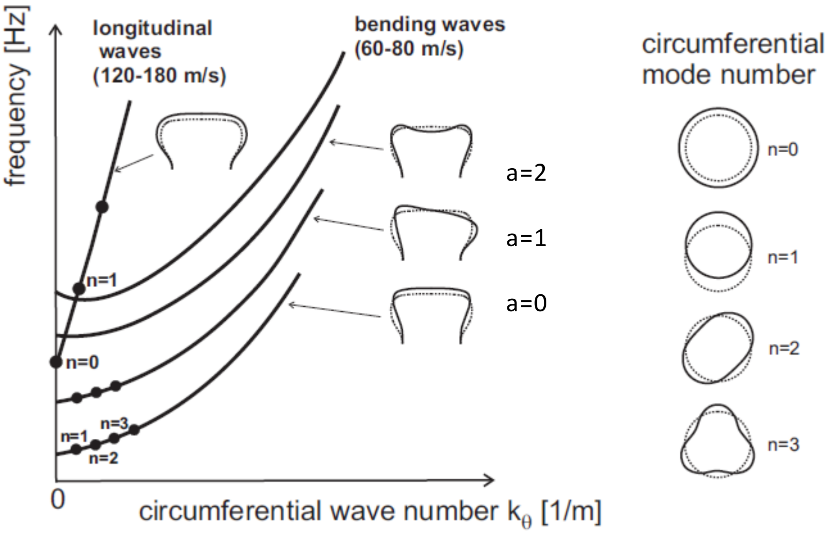


Figure 1 - Typical dispersion curves corresponding to different wave types that propagate in an unloaded and non-rotating tire.

NUMERICAL STRUCTURAL ANALYSIS OF A ROTATING TIRE

Finite Element Analysis

A commercially available finite element package (ABAQUS) is used to predict the dynamic response of a rolling tire. All calculations are performed on an advanced highly detailed (construction and material data) finite element model of a smooth (slick) tire with size 205/55R16. The tire has a full tread without grooves (tread pattern). The tire model includes the air cavity inside the tire and a rigid rim is assumed. The tire is discretized in 180 segments of approximately 11 cm in the circumferential direction. The tire cross-section is discretized in around 100 sectors. The mesh size of the model in circumferential and cross-sectional direction is a good compromise between the frequency range of interest and the CPU time. The detailed material data is taken from the Goodyear database and the model takes into account the visco-elastic nature of the tire components and the vibro-acoustic coupling effects. The wheel centre is free to rotate around its axis and all the other directions are constrained. The unloaded, non-rolling tire model is validated by comparing the measured natural frequencies to the natural frequencies from the frequency extraction.

The Frequency Response Functions (FRF's) and the dynamic response due to a harmonic radial excitation force (applied at a node) are obtained from a direct steady-state harmonic analysis. The direct method makes the analysis significantly more expensive in terms of calculation time, since it computes the steady-state harmonic response directly in terms of the physical degrees of freedom of the model. However, this approach offers the possibility to use visco-elastic material properties of the different compounds as a function of frequency. In the performed simulation the tire is excited in the radial direction with a point force at the centre of the tread-band and the vibration velocity is calculated at 180 equally spaced points along the tread-band centre line in an Eulerian coordinate system (the nodes of the mesh stay fixed in space while the materials flow through the mesh). Consequently, 180 mobility Frequency Response Functions (ratio between vibration velocity and input force) are obtained from the simulation. The frequency resolution and frequency range chosen for the simulation are 1 Hz and 1-1000 Hz, respectively.

Numerical Dispersion Graphs

The outputs of the simulations are analyzed in terms of dispersion curves or frequency-wavenumber spectra. These dispersion curves are obtained by applying at each frequency a Fast Fourier Transform (FFT) to the 180 mobility FRF's along the complete circumference. Consequently, the spatial domain is converted to the wavenumber domain. It should be noted, that since the excitation force is radial, only waves which respond to this excitation are manifested in the dispersion curves studied in this paper.

Figures 2 and 3 show the dispersion curves for an unloaded respectively a loaded tire rotating at 0, 60, 100 and 150 km/h. At 0 km/h, the positive- and negative-travelling waves with the same wavenumber have the same frequency. Consequently, at the resulting resonances a standing wave vibration pattern can be observed. Since a tire can be considered as a ring-like structure, the resonance modes are approximately found at the frequencies where an integer number of wavelengths equals the tire circumference. The rotating tire is subjected to Coriolis acceleration, hence the wave speed of the positive- and negative-going wave diverge from each other. The phase speed of a positive-going wave increases with the rotation speed, while the phase speed of a negative-going wave decreases by the same amount. Consequently, the resonance mode associated with the positive-going wave appears at a different frequency compared to the resonance mode associated with the negative-going wave when the tire is rotating. At the resonance frequencies of the rotating tire, a travelling wave vibration pattern (complex mode shape) can be observed.

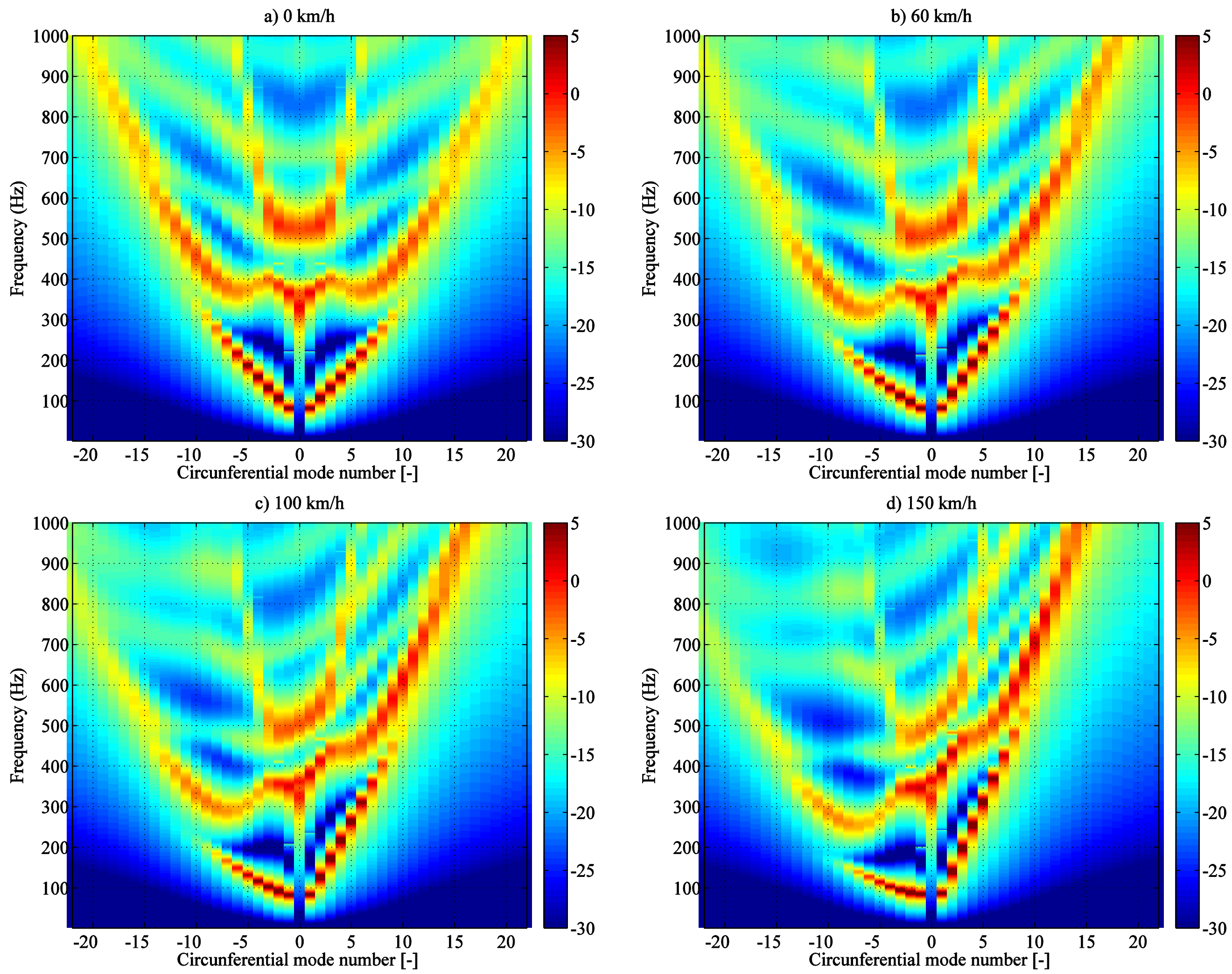


Figure 2 - Frequency-wavenumber plots [dB] of an unloaded tire for different speeds. The positive wavenumbers correspond to waves travelling in the tire rotational direction and negative wavenumbers to waves travelling in the direction opposite to the tire rotational direction.

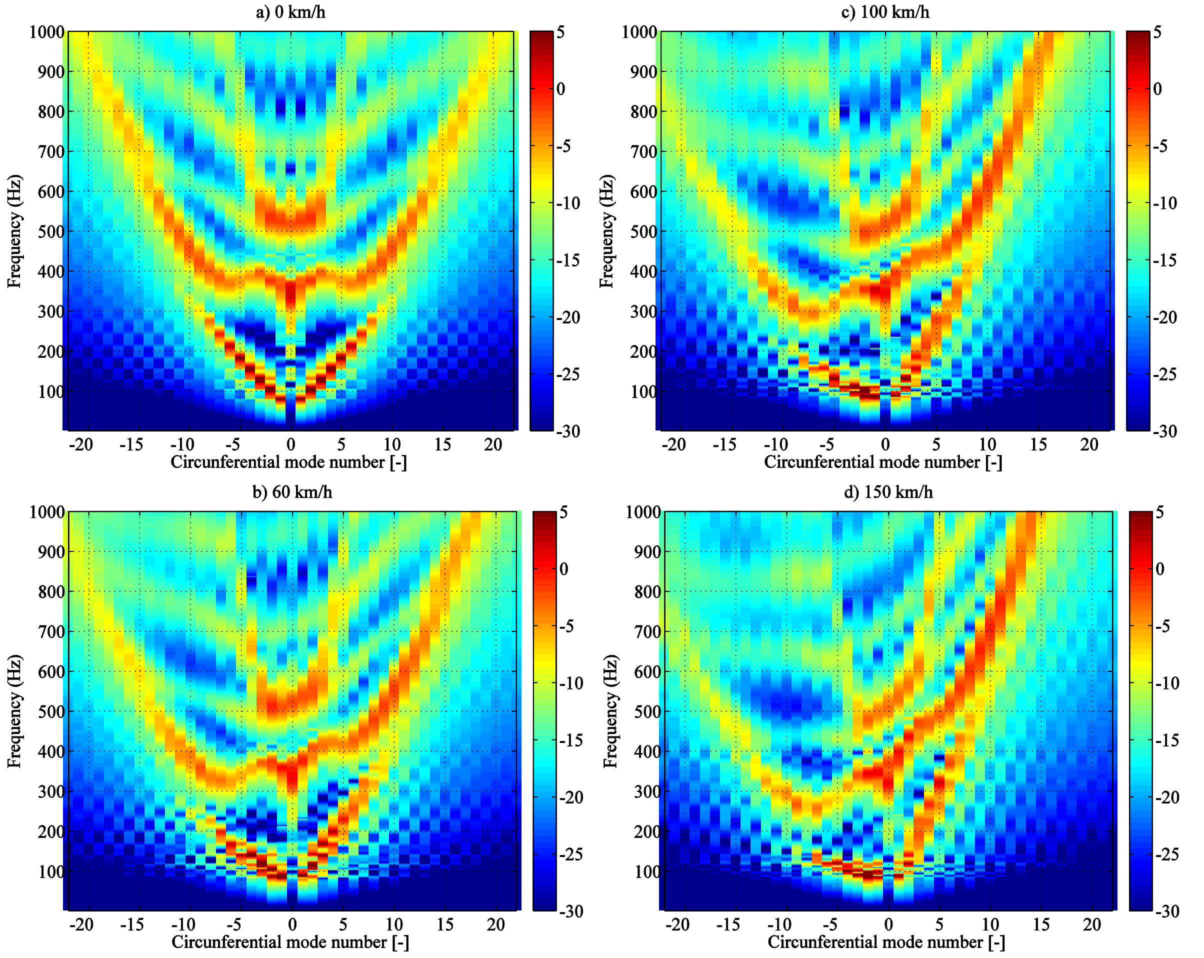


Figure 3 - Frequency-wavenumber plots [dB] of a loaded tire (4000 N) for different speeds. The positive wavenumbers correspond to waves travelling in the tire rotational direction and negative wavenumbers to waves travelling in the direction opposite to the tire rotational direction.

EXPERIMENTAL STRUCTURAL ANALYSIS OF A ROLLING TIRE

Tire Vibration Response Measurement

A 205/55R16 slick tire (2.2 bar inflation pressure and 4000 N load) is rolling on a steel drum of 2 m diameter and excited by a 3x25 mm straight cleat attached to the drum (Figure 4). The tire structural response is obtained from a uni-axial accelerometer mounted in the radial direction at the center of the inner liner. The tire response has been measured for three different rolling speeds (40, 60 and 80 km/h).

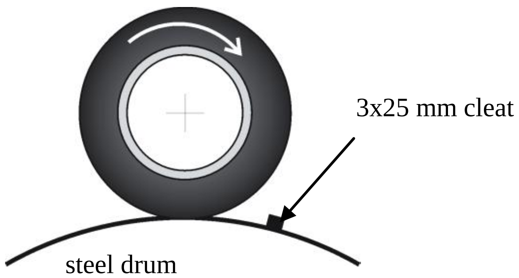
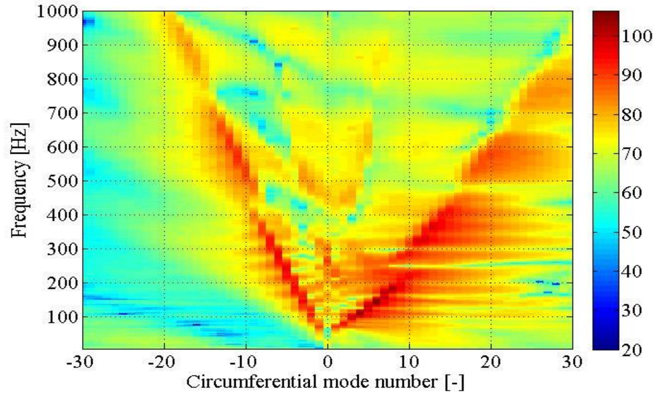


Figure 4 - Setup for the experimental structural analysis. The rolling tire is excited by a 3 mm high cleat which is 25 mm long. The tire structural response is measured by an accelerometer attached to the center of the tire inner liner.

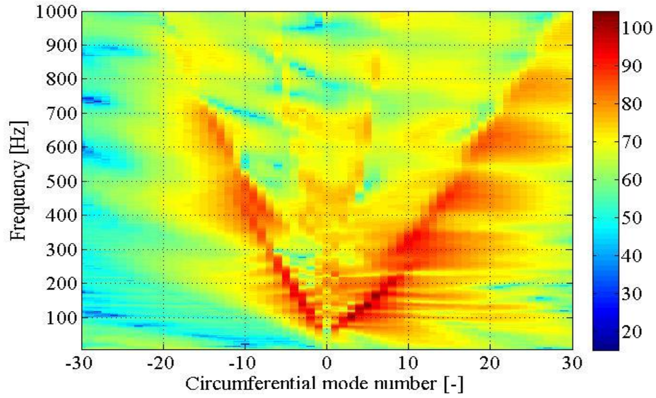
In case the drum radius is not an exact multiple of the effective tire radius, which is practically always the case, the accelerometer position with respect to the cleat impact shifts for every drum rotation. To determine the phase relation between the accelerometer and cleat, for every single measurement point, the tire tacho and drum tacho signals are recorded. The measured radial tire vibration data in the co-rotating axis system is converted into the

fixed axis system to yield the acceleration responses to the cleat impact in 360 distinct fixed points equally spaced around the circumference of the tire. The resulting spatial resolution of 1º is largely sufficient for the wave number range investigated in this paper. The obtained frequency resolution on the other hand, equals the inverse of the acceleration response signal time length.

40 km/h



60 km/h



80 km/h

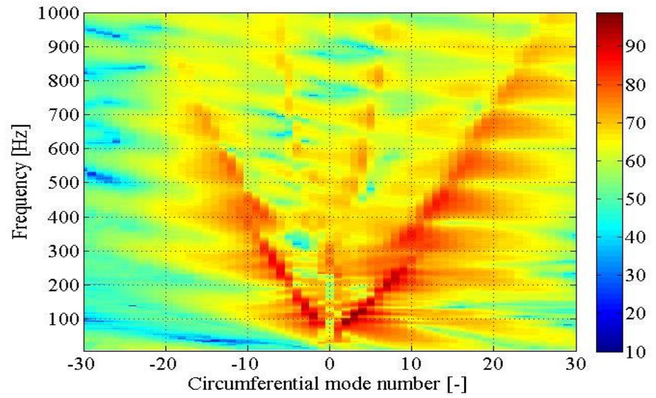


Figure 5 - Experimental dispersion graphs for speeds 40, 60 and 80 km/h. The positive circumferential mode numbers correspond to waves travelling opposite to the tire rotational direction and negative wave numbers to waves travelling in the tire rotational direction.

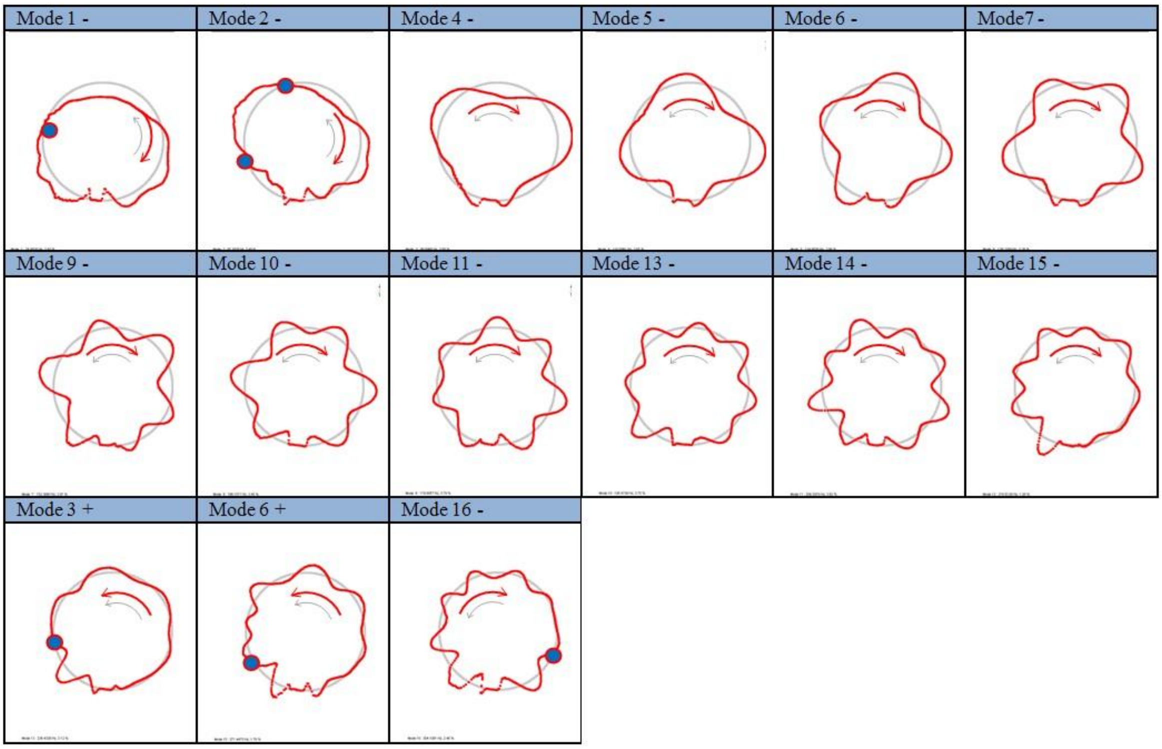


Figure 6 - Experimentally identified mode shapes of the considered tire at the following conditions: 60 kph, cleat 3x25mm, 4000 N, 2.2 bar. The solid arrows indicate the tire rotation direction while the slim arrows indicate the direction of the travelling wave.

Experimental Dispersion Graphs

The transformation of acceleration responses from time to frequency and space to wavenumber domain respectively, yields the dispersion graph of the tire at the specified measurement conditions. Figure 5 shows the dispersion graphs for speeds 40, 60 and 80 km/h. Figure 6 shows the mode shapes for the reference case at 60 km/h, identified with an operational modal analysis. As previously indicated, the dispersion graph contains information on the wave propagation properties which determine the tire dynamic behavior. The measured dispersion curves show that the waves travelling opposite to the tire rotational direction have higher response amplitudes with respect to the waves traveling in the rotational direction. In addition, the vibration response amplitude is low around certain frequencies. This is related to the non-uniform excitation force spectra as a result of the rolling over the cleat. Figure 7 shows the simulated spectrum of the vertical and longitudinal excitation force due the rolling at 60 km/h over the 3x25 mm cleat. The spectra clearly show that waves at certain frequencies are hardly excited. Consequently these waves will not show up in the experimentally determined dispersion curves. The shape of the excitation spectra is mainly dependent on the cleat geometry, rolling speed and tire stiffness properties.

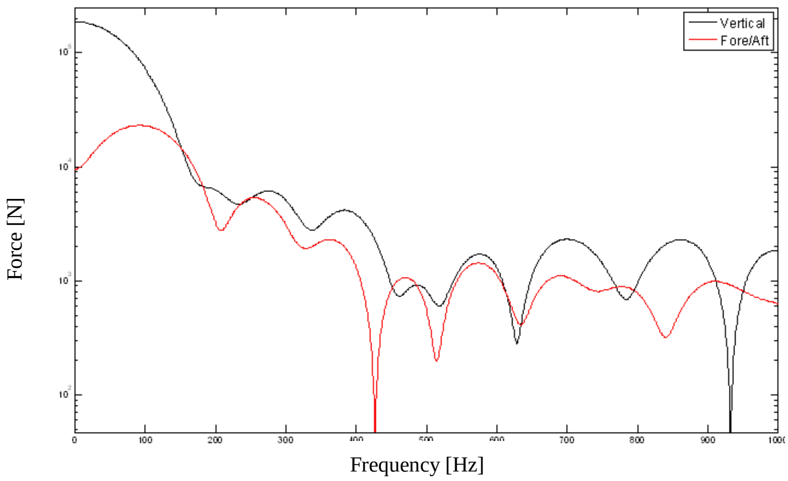


Figure 7 - Simulated spectrum of the vertical and longitudinal input force for the considered tire rolling at 60 km/h over a 3x25 mm cleat.

CONCLUSIONS

The presented numerical analysis of the dynamic behavior of a loaded tire is based on a highly detailed tire model, which includes all the complex material behavior. The results show that a rotating tire is subjected to Coriolis accelerations which make the wave speed of the positive- and negative-going wave to diverge from each other. This leads to an asymmetric shape of the dispersion curves. The dispersion curves of a non-rotating tire are symmetric with respect to the zero wavenumber axis.

The experimental analysis of the influence of rotation on the dynamic behavior of a loaded and rotating tire is based on acceleration measurements on the inner liner of a tire. Similarly as to the numerically predicted dispersion curves, the experimentally determined dispersion curves become more asymmetric as the rolling speed increases. This is due to the wave speed of the waves travelling in opposite direction of the tire rotation to diverge from the speed of the waves travelling in the rotational direction.

In contrast to the numerically analysis, it is more difficult to control the tire excitation spectra during experimental analysis. As a result, certain waves are less well excited due to rolling over a cleat.

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