International Journal of Automotive Technology, Vol. 6, No. 2, pp. 149–159 (2005)


1229–9138/2005/020–09

# VIRTUAL PREDICTION OF A RADIAL-PLY TIRE'S IN-PLANE FREE VIBRATION MODES TRANSMISSIBILITY

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*(Received 20 February 2004; Revised 28 May 2004)*

**ABSTRACT**–A full nonlinear finite element P185/70R14 passenger car radial-ply tire model was developed and run on a 1.7-meter-diameter spinning test drum/cleat model at a constant speed of 50 km/h in order to investigate the tire transient response characteristics, i.e. the tire in-plane free vibration modes transmissibility. The virtual tire/drum finite element model was constructed and tested using the nonlinear finite element analysis software, PAM-SHOCK, a nonlinear finite element analysis code. The tire model was constructed in extreme detail with three-dimensional solid, layered membrane, and beam finite elements, incorporating over 18,000 nodes and 24 different types of materials. The reaction forces of the tire axle in vertical (Z axis) and longitudinal (X axis) directions were recorded when the tire rolled over a cleat on the drum, and then the FFT algorithm was applied to examine the transient response information in the frequency domain. The result showed that this P185/70R14 tire has clear peaks of 84 and 45 Hz transmissibility in the vertical and longitudinal directions. This result was validated against more than 10 previous studies by either theoretical or experimental approaches and showed excellent agreement. The tire's post-impact response was also investigated to verify the numerical convergence and computational stability of this FEA tire model and simulation strategy, the extraordinarily stable scenario was confirmed. The tire in-plane free vibration modes transmissibility was successfully detected. This approach was never before attempted in investigations of tire in-plane free vibration modes transmission phenomena; this work is believed to be the first of its kind.

**KEY WORDS :** Finite element analysis, Tire modeling, Tire transient response, Tire vibration modes

## 1. INTRODUCTION

Tires, from the standpoint of ride dynamics, behave primarily as springs that absorb the irregularities and roughness features on the roads. The tire is also a dynamic system with resonant vibrations, which will be associated with the transmission of the contact forces from the road to the vehicle and may interact with the vehicle's own resonances, affecting ride comfort and handling stability (Gillespie, 1992).

Tire vibration analysis has traditionally been divided into two categories (in-plane and out-of-plane vibration mode analysis) because of the different effects and characteristics of these modes (Clark, 1981). Because it is only appropriate to compare similar-sized tires with similar constructions under similar operation conditions, this research will only focus on the in-plane free vibration mode analysis of passenger car radial-ply tires.

Hammer impact, bumpy roads, oscillating platforms, or spinning drums produce vertical and/or longitudinal hub oscillations via tire tread and sidewall vibrations distributed along the tire circumference. The major part of the following literature review focuses on the question of whether a correlation exists between these distributed vibrations/inputs and the complex transfer phenomena of hammer/road/platform/drum input motion to hub motion.

The literature records many studies of tire in-plane free vibration modes transmissibility, carried out primarily by analytical derivation (Negrus *et al.*, 1997; Negrus *et al.*, 1998; Pacejka, 1981; Takayama *et al.*, 1984; Kung *et al.*, 1986; Ellis, 1989 and 1994; Huang, 1992) and four different empirical methods (the modal analysis hammer impact test (Negrus *et al.*, 1997; Negrus *et al.*, 1998), the real road test with a running vehicle (Barson *et al.*, 1971), the lab test with a tire on a vibration platform (Negrus *et al.*, 1997; Chiesa *et al.*, 1964; Barson *et al.*, 1967~68; Potts *et al.*, 1975; Pacejka, 1981), and the lab test with a tire on a spinning drum (Negrus *et al.*, 1998; Barson *et al.*, 1967~68; Takayama *et al.*, 1984; Scavuzzo *et al.*, 1993)). Generally similar results were obtained in every case, whether using an analytical or empirical approach, i.e. a vibration peak will appear around 85 Hz in the

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vertical direction, and a peak around 45 Hz will appear in the longitudinal (fore/aft) direction. Until the present time, a full rotating simulation had never been attempted for the investigation of these free vibration modes transmissibility phenomena. Therefore a virtual tire/drum testing system will be established in the present study, the tire spindle (hub) reaction forces will be recorded, and then the FFT algorithm will be applied to determine the transient response information in the frequency domain. The comparison of this simulation and all the above research showed excellent agreement, which will be addressed later.

## 2. SIMULATION APPROACH

Tire free vibration modes play a key role in vehicle ride comfort and handling stability, for applications ranging from passenger cars to earthmoving equipments. In this chapter, a full nonlinear FEA tire model was established, the tire in-plane free vibration modes transmissibility was successfully detected, using a virtual tire/drum rotating test machine created with PAM-SHOCK. The results of the simulation showed excellent agreement, quantitatively and qualitatively, with previous research.

Many parameters can affect the resonant frequencies of tire free vibration modes: tire size, construction, inflation pressure, and operating conditions such as load and temperature. In order to fully concentrate on the major issue of tire in-plane free vibration modes transmissibility detection, while still maintaining the numerical computations under a manageable level, several practical assumptions were proposed in this research:

- Any effects on or from the suspension system were neglected.
- No wind or temperature effects were considered.
- Only two-dimensional in-plane displacements and forces were assumed to occur when a loaded tire rolls on a surface, the surface was first considered to be free of obstacles, then to include an in-plane cleat. Displacements and forces out of the vertical plane were assumed to be negligibly small and therefore could be ignored.
- The rim/wheel assembly was assumed to rotate at the same angular velocity as that of the tire, so no slipping or velocity difference between the tire and the rim/ wheel assembly will be considered.
- Further, whenever the subject of tire vibration is mentioned, the effects caused by either built-in tire non-uniformities or any out-of-balance conditions of the tire-rim/wheel combinations come immediately to mind. These effects will not be discussed in this research, and therefore the tire model is assumed to be perfectly symmetric.

Inputs or stimuli to the tire from such things as rough road surfaces, tire non-uniformities, and tread patterns can potentially excite tire free vibration modes. The literature review about tire in-plane free vibration modes transmissibility, many such studies have been carried out, primarily by four empirical methods as discussed before. When road irregularities, such as single impacts from a bump or a pothole, or a series of small impacts from rough road surfaces, are enveloped by the tire, these impacts excite the tire free vibration modes in much the same way as a hammer impact does during a modal analysis test (Scavuzzo *et al.*, 1993). It has also been shown in previous research that the transmissibility of the force into the spindle of a rolling automobile wheel is very similar to that of a tire on a stationary vibration platform (Barson *et al.*, 1971; Potts *et al.*, 1975). It should also be noted that regarding the transmission of vibrations, qualitative similarity exists between results of the tests using the vibrating platform and the spinning drum (Barson *et al.*, 1967~68). These research suggested that all four different empirical methods would reach very consistent results. Therefore the widely adopted lab test in tire industry with a tire running on a 1.7-meter-diameter spinning drum was established in this virtual simulation research.

A passenger car tire P185/70/R14 operating under typical conditions was investigated in this research by applying a nominal vertical load of 4500 N with a recommended inflation pressure of 0.207 MPa. Tire in-plane free vibration modes and transmissibility, tire/drum FEA models, simulation procedures and the results and discussion will be presented in sections 3 to 6; the numerical stability verification will be demonstrated in section 7, and the conclusions will be addressed in section 8.

## 3. TIRE IN-PLANE FREE VIBRATION MODE AND TRANSMISSIBILITY

A relatively large portion of the tire mass is concentrated in the tread, which is connected to the rim/wheel by the compliant sidewalls. This combination of mass and compliance presents a typical vibration system as shown in Figure 1, which permits the tread to resonate when excited by road inputs, such as bumps and potholes (Gillespie, 1992).

Figure 2 shows examples of the first five free vibration modes of a tire in the vertical plane. The first mode, which will occur somewhere near 85 Hz in a passenger car tire, involves a simple vertical motion of the entire tread band without distortion. This mode can be easily excited by vertical inputs from the contact patch. Since the entire tread band moves up and down in unison, the force associated with this resonance is transmitted to the

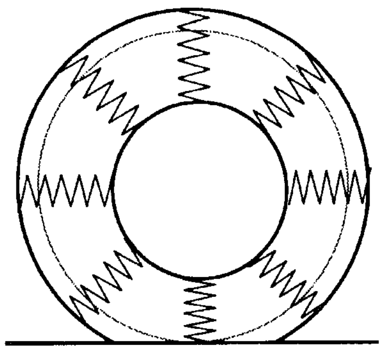


Figure 1. Tire radial rpring rodel (Gillespie, 1992).

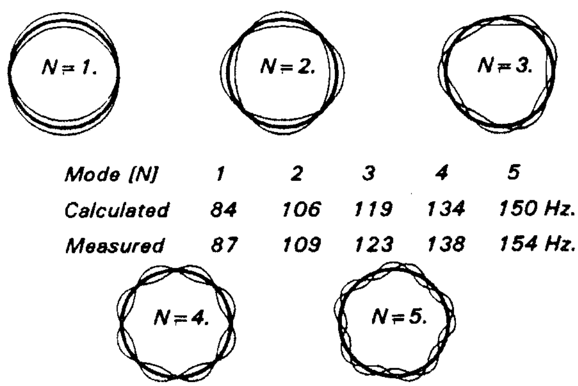



Figure 2. First five vertical free vibration modes and shapes of a tire (Ellis, 1989 and 1994).

rim/wheel, the tire axle, and therefore the chassis and the vehicle (Gillespie, 1992).

The second mode contrasts with the first one, in that the tread band is oscillating in an elliptical fashion, always remaining symmetrical about the vertical and horizontal axes. The top and bottom of the tread are always moving out of phase so that a net vertical force of zero is imposed on the tire spindle. Although this resonance can be excited by vertical inputs from the contact patch, the tire very effectively absorbs the inputs without transmitting forces to the axle because the phenomenon is completely symmetric. The third- and the higher-order modes also behave in a pattern similar to the second mode (Clark, 1981).

From this simple picture of a tire as a dynamic system, it is possible to begin building an understanding of the tire's dynamic behavior in transmitting road irregularities, how the tire vibrates the chassis of a vehicle, how the tire as a dynamic system with its own free vibration modes affects the transmission of vibrations to the vehicle, how the tire interacts with the vehicle's own resonances, and therefore how and why the tire's dynamic characteristics play a critical role in vehicle ride comfort and handling stability.

As mentioned above, only the first free vibration resonance in the vertical direction can be transmitted to the vehicle; all of the second- and higher-order modes' vibrations will be absorbed without transmitting forces to the tire axle because they are completely symmetric phenomena. This transmission behavior can be demonstrated by measuring the accelerations at the spindle of a tire as the tire envelops such an impact. The vibration transmissibility of the tire is defined as:

$$\text{transmissibility} = \frac{\text{tire axle force (aceleration) amplitude}}{\text{ground contact displacement (force) amplitude}} \qquad (1)$$

This quotient must be calculated for each input frequency in order to completely describe the tire's dynamic characteristics.

This tire first vertical free vibration mode transmissibility relationship was proved by Barson *et al.* (1967–68). Figure 3 shows the typical spectra of forces measured when a passenger car tire encounters a small obstacle at a speed of 50 km/h (30 ft/min). Data are shown for both radial-ply and bias-ply tires for forces in both the vertical and longitudinal directions. The radial-ply tire shows increasing amplitude of the vertical force during the ranges of 20 to 30 and 80 to 100 Hz and reaches its peaks at frequencies of approximately 27 and 86 Hz. Since these data were collected from a road test of a running vehicle, the first peak at 27 Hz represents the axle hop (suspension system) resonance, therefore of greater interest is the second, higher-frequency peak at around 86 Hz. Clearly, from the previous discussion and

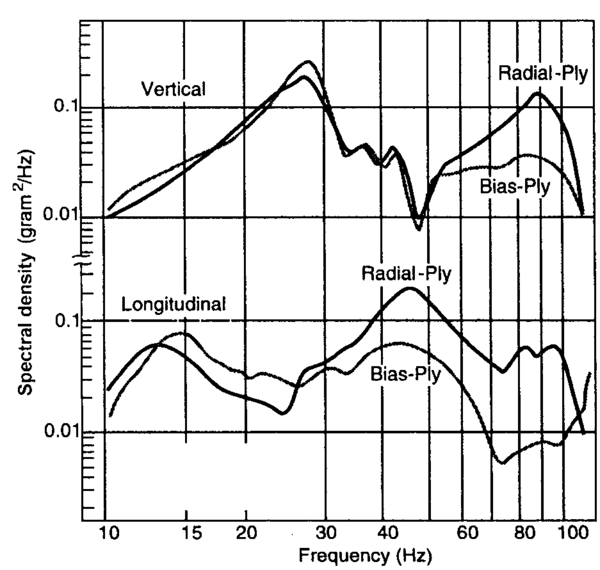



Figure 3. Spectra of forces measured when a tire encounters an obstacle. (Gillespie, 1992; Barson *et al.*, 1971)

Figure 2, it would be expected that this behavior is the result of the high transmissibility of the tire's first vertical free vibration mode.

The force in the longitudinal direction behaves similarly to the vertical curve. The amplitude of the longitudinal force increases in the ranges of 10 to 20 Hz, 40 to 60 Hz, and 80 to 100 Hz, and reaches its peaks at frequencies of approximately 14, 46 and 83 Hz. The first peak at 14 Hz will be due to the natural frequency of the system, just as in the vertical direction it is mainly owing to the longitudinal compliance of the suspension system. The third peak at 80 to 100 Hz corresponds to the mode found and matches with the first vertical free vibration mode. The second peak at 46 Hz represents the first rotational free vibration mode, i.e. the rotational (fore/aft) natural vibration resonance; this mode exhibits purely uniform rotational displacements of the tread band. These phenomena imply that the tire appears as a very stiff, rather than compliant, element with regard to road inputs at these specific frequencies.

A full nonlinear FEA tire model was simulated by a virtual tire/drum/cleat rotating test machine. The spinning

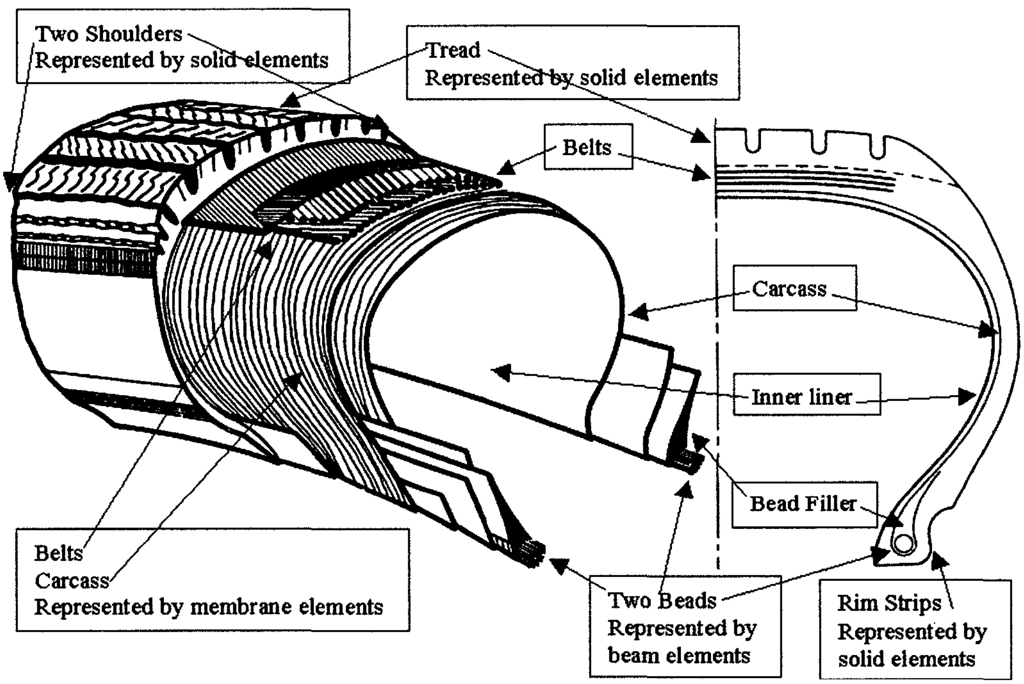



Figure 4. The FEA tire model elements.

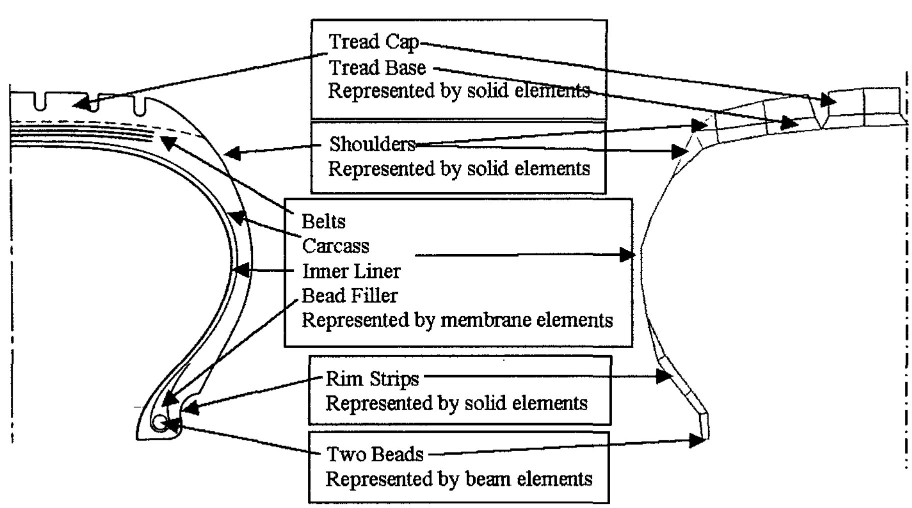



Figure 5. The cross-section of the P185/70/R14 FEA tire model.

test drum with cleat will serve as an impact input in order to excite the tire in-plane free vibration modes. Since this simulation only modeled and focused on the tire itself without the axle or the vehicle suspension system, as stated before, only the first vertical/rotational free vibration modes transmissibility detections were expected.

## 4. TIRE/DRUM FEA MODELS

A tire consists primarily of reinforced rubber composites and rubber materials, therefore the tire has been modeled as an assembly of three-dimensional Mooney-Rivlin hyperelastic solid finite elements (bricks) for rubber material, fiber-reinforced layered membrane finite elements for reinforced rubber composites, and beam elements for two beads as shown in Figure 4.

In order to develop the FEA model of a general passenger car radial-ply tire, a real tire was disassembled/dissected, all dimensions measured, and material properties tested in detail. Therefore, this FEA tire model construction is based on a specific passenger car tire, namely a P185/70/R14 tire. Its construction specifications, which are typical of any tire in its class, are:

- Maximum outer radius: 301mm
- Section width: 180 mm
- Total weight: 9.5 kg (Rim/wheel assembly is 2.7 kg, tire itself is 6.8kg.)

The cross section of the P185/70/R14 FEA tire model is symmetric against the centerline of the tire and consists of three types of elements built under the PAM-SHOCK environment as shown in Figure 5. The complete three-dimensional tire model was established by rotating this cross section one full revolution around the tire axle axis and then cutting it into 60 slices. The P185/70R14 virtual finite element radial-ply passenger car tire model was built successfully as shown in Figure 6, includes over 18,000 nodes and 24 different material definitions.

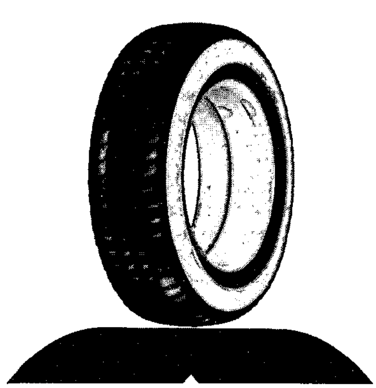


Figure 6. The complete tire/drum/cleat fea model.

## 5. SIMULATION PROCEDURES

The main purpose of this simulation is use a sophisticated FEA tire model to simulate and detect the tire in-plane free vibration modes transmissibility in the computer virtual testing environment. The simulation includes three stages; total simulation time is 0.5 second.

### 5.1. Simulation Phase I

Phase I is only about preparing the tire to be rotated on the test drum. This stage includes four major goals: inflation, loading, stabilizing, and totally resting the tire on the drum statically. The whole simulation time is from 0 to 0.1 second for phase I. The strategies of phase I are as follows:

- Apply a standard recommended tire inflation pressure 0.207 MPa to the inside surface of the tire during the interval from 0 to 0.001 second.
- Load with nominal 4500 N downward at the tire spindle (axle), approximately one-fourth the weight of a mid-size passenger car, during the interval from 0.001 to 0.002 second.
- Adopt a virtual global damping effect in order to stabilize all the energy and motion vibrations due to the sudden inflation process and loading rate during this simulation, and also to keep the entire computation process stable within this phase.
- Rest the tire statically on the test drum/cleat with a static deflection.

The virtual global damping effect adopted during this stage is simply a temporary measure taken within the numerical simulation environment; its only goal is to mimic the actions of a real tire/drum test and shorten calculation time simultaneously. In the real world, a tire could be inflated to a standard inflation pressure 0.207 MPa and loaded by 4500 N gradually over ten seconds in order to maintain a reasonably stable condition; but this long simulation time would represent tremendous cost and waste in the virtual simulation environment. There-

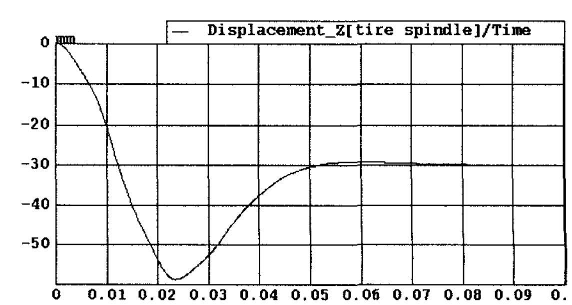



Figure 7. Tire spindle vertical deflection time history.

fore in this research both inflation and loading were applied during a very short period to reduce the simulation time to an acceptable level, and a virtual global damping effect was adopted to dampen and eliminate the inflating and bouncing vibrations caused by sudden inflation and loading.

Figure 7 illustrates the tire spindle vertical deflection time history; the tire spindle deflection history showed that the tire was resting on the test drum stably with a static deflection 30.09448 mm. Now the tire is ready to be rotated on the test drum and the simulation can progress to phase II.

### 5.2. Simulation Phase II

With the drum and the tire ready to be rotated, phases II and III are the major simulation stages. The primary goal of phase II is to accelerate the tire and drum to the speed of 50 km/h linear velocity at the contact surface. The whole simulation time for phase II is 0.05 second, from 0.1 to 0.15 second. The strategies of phase II are as follows:

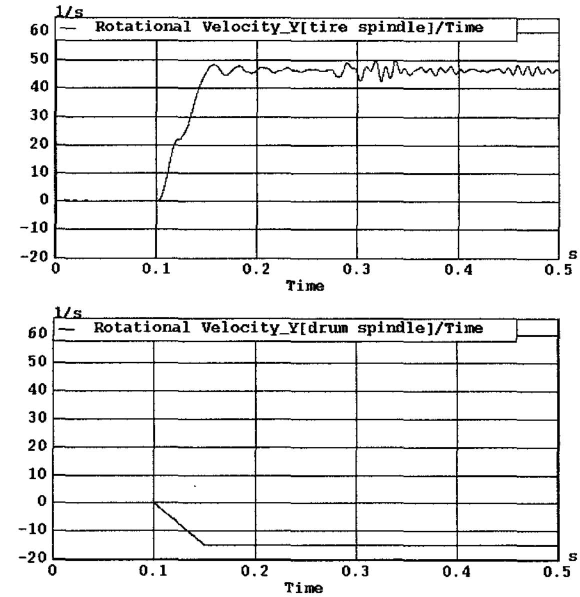
- The drum will be accelerated from 0 to 50 km/h linear velocity in 0.05 second at a constant rate.
- The friction force will be generated between the contact surface of the tire and drum by applying an appropriate and sufficient friction coefficient, so that the tire will be driven to the same speed as the drum at all times during the whole simulation period.

### 5.3. Simulation Phase III

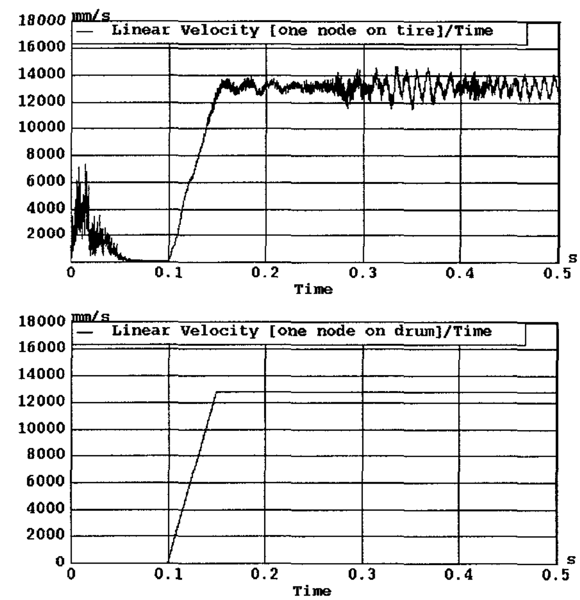
The drum and the tire reached the speed of 50 km/h in phase II, and then was kept rotating at this constant speed until the tire encountered the cleat on the drum, which is the primary goal of phase III. The whole simulation time for phase III is 0.35 second, from 0.15 to 0.5 second. The strategies of phase III are as follows:

- Both the drum and the tire reached the speed of 50 km/h, and maintained this constant speed before and after the tire encountered the cleat on the drum.
- The tire met the cleat successfully without any penetrations or numerical errors.
- The tire spindle reaction forces in both vertical and longitudinal directions, i.e., the Z and X axes, were recorded and the FFT algorithm was applied to extract the tire transient response information in frequency domain. The tire in-plane free vibration modes transmissibility was detected successfully.

Because it is critically important to make sure the above goals and concerns are under control as planned, four index velocities were monitored during stages II and III. They are the spindle node of the tire, the spindle node of the drum, one node on the surface of the tire, and one node on the surface of the drum. The axle will transmit the forces to the chassis and the whole vehicle. Therefore, by defining two spindle nodes exactly at the centers of the tire and the drum, they can be used to monitor the angular velocities of the whole tire-rim/wheel assembly and the test drum, respectively, as shown in Figure 8(a). Two surface nodes can be defined and used to check their linear velocities as shown in Figure 8(b).




(a) Angular velocity

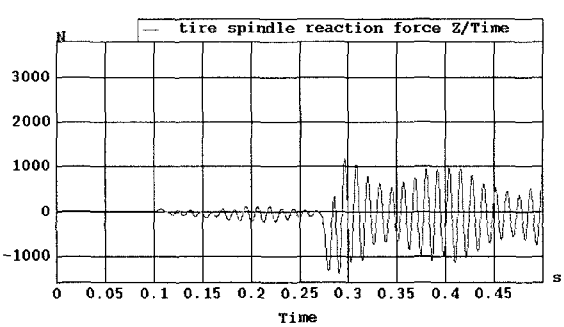



(b) Linear velocity

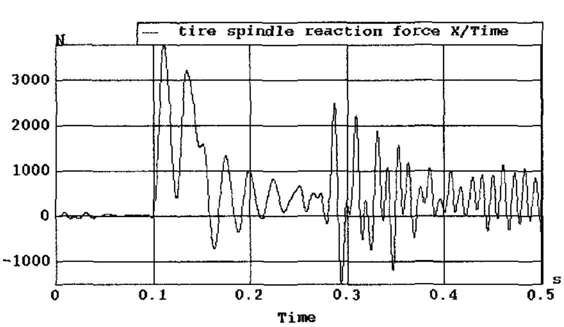
Figure 8. Monitoring angular and linear velocities during phases II and III.

As Figure 8 shows, the angular velocity of the drum increases at a stable and constant rate, as the input is shown in Figure 8(a). The tire is always adjusting its speed and still proportionally following the rotation of the drum according to their radius ratio, in the opposite direction of course, and increasing at a smooth and stable rate as expected in this simulation. Both surface nodes' linear velocities followed each other very well, which means there is no velocity difference or slip phenomenon happening between the contact surface of the tire and the drum, both of them reaching the same speed at any given time during the whole simulation as planned.

Again, the drum's acceleration was a steady rate as input planned, but the tire's was not because the extremely fast acceleration rate in such a short simulation time was imposed, but the tire's stiffness and compliance interact with each other to reach the desired speed of 50 km/h at the same time as drum does. In order to prove that this extremely high acceleration rate (accelerating drum/tire from 0 to 50 km/h linear velocity in 0.05 second) can be efficiently and effectively achieved without facing any numerical difficulties, the numerical stability verification was established in section 7. This involved rotating the tire at the constant speed of 50 km/h and meeting with the cleat seven times in an extended simulation. The same results were obtained, the tire model proved to be numerical stable. The whole simulation process was successfully achieved.




(a) Vertical direction (Z axis)




(b) Longitudinal direction (X axis)

Figure 9. The reaction forces acting at the tire axle.

## 6. RESULTS AND DISCUSSIONS

The tire in-plane free vibration modes transmission phenomena were simulated and presented in this section. This approach was never before attempted in investigations of tire in-plane free vibration modes transmission phenomena; this work is believed to be the first of its kind.

### 6.1. Tire In-Plane Spindle Vertical and Longitudinal Reaction Force Curves

As shown in Figure 9, the tire reaction forces acting at the tire axle in both the vertical and longitudinal directions begin vibrating wildly at around 0.27 second, which is when the tire starts meeting the cleat on the drum (as shown in Figure 10).

In order to make sure that there were no penetrations when the tire met the cleat, and throughout the whole simulation, the simulation data from the interval 0.275 to 0.3 second were carefully examined. Figure 11 shows the tire deformations during cleat impact. There were no penetrations found.

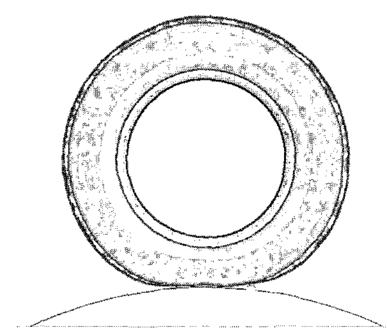



Figure 10. The tire starts meeting the cleat at 0.275 second.

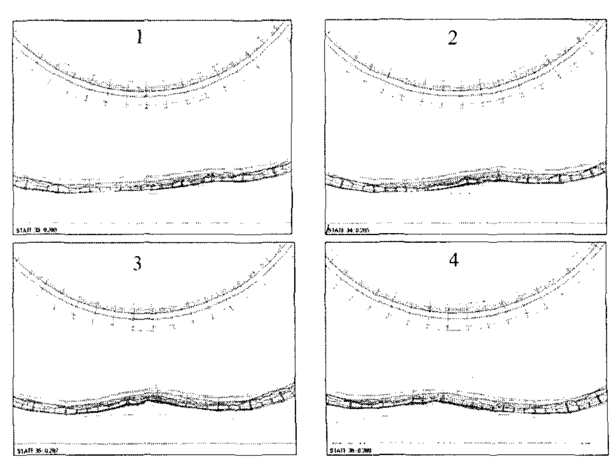



Figure 11. Tire deformations during cleat impact.

6.2. FFT Results of the Tire Spindle In-Plane Reaction Force Curves

Since the cleat on the test drum provides an in-plane input to the tire, i.e. in both vertical and longitudinal directions, tire in-plane free vibration mode excitations were expected. The FFT algorithm was applied to the tire reaction forces' curves in Figure 9 to extract information in the frequency domain; the results are shown in figure 12.

By comparing Figures 12 and 3, the simulation results in Figure 12 are seen to be nearly identical to the free vibration modes transmission phenomena of a real vehicle test in Figure 3. The FFT results in Figure 12 show the amplitude increasing in the vertical direction and reaching its peak at a frequency around 84 Hz. As mentioned before, there was no suspension system effect modeled and considered in this simulation; hence this is the only peak that would be expected (there could be no axle hop), and this behavior is the result of the high transmissibility of the tire first vertical free vibration mode. In the longitudinal direction, the amplitude is increasing and reaches its peaks at frequencies of approximately 1 to 4, 45 and 90 Hz. Again, without considering the suspension system's longitudinal compliance effect in this simulation, the first peak between 1 to 4 Hz is the impact input frequency from the cleat on the drum. (The drum's angular velocity is 15 rad/sec from Figure 8(a), i.e., around 2.5 Hz) The third peak at around 90 Hz corresponds to the first vertical free vibration mode. The second peak at 45 Hz represents the first rotational free vibration mode.

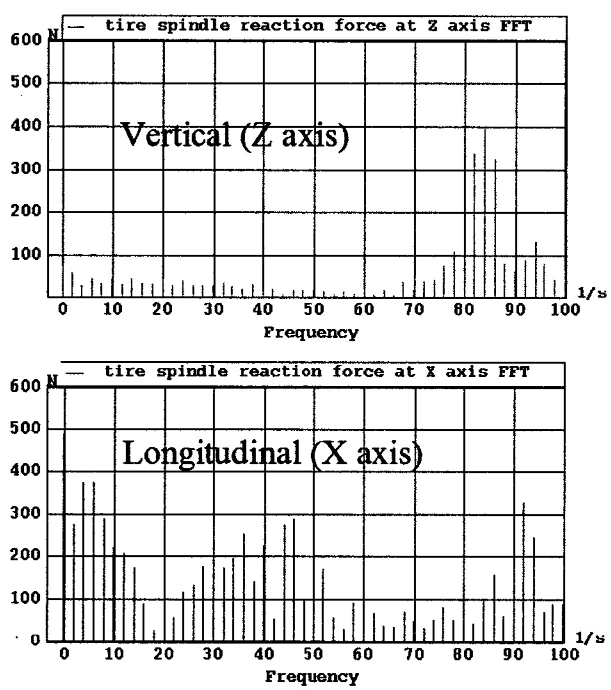


Figure 12. FFT results of tire in-plane reaction forces.

6.3. Comparisons and Discussions

The conclusion can be drawn from this simulation that this tire has its first vertical and rotational free vibration modes at 84 and 45 Hz respectively, and transmitted these vibrations to the vehicle tire axle in the vertical Z and the longitudinal X directions. The simulation and the detection were complete and successful.

In order to verify this simulation result quantitatively and qualitatively, comparisons with more than ten previous research studies are summarized in Table 1 and show excellent agreement:

Since all of these researchers dealt with similar size passenger car tires with similar radial-ply constructions under similar loading and inflation conditions, a rather clear and consistent transmissibility can be expected at 85 and 45 Hz vertically and longitudinally. The conclusion of this simulation is that the first vertical and rotational free vibration modes and their transmissions are 84 and 45 Hz. The correspondence between this simulation and previous research is extremely reliable. PAM-SHOCK promises to be a valuable tool in cascading a series of small changes in vibration performance, in a series of test designs, into an overall optimal tire.

## 7. NUMERICAL STABILITY VERIFICATION

In order to verify the numerical convergence and computational stability of this FEA tire model simulation, the tire's post-impact response was investigated in this section. This tire model was kept running at the constant speed of 50 km/h on the spinning test drum and met the cleat seven times consecutively, corresponding to 21 tire revolutions. As shown in Figure 13, the tire remained in an excellent, stable condition without any separations, distortions, or numerical instabilities being observed.

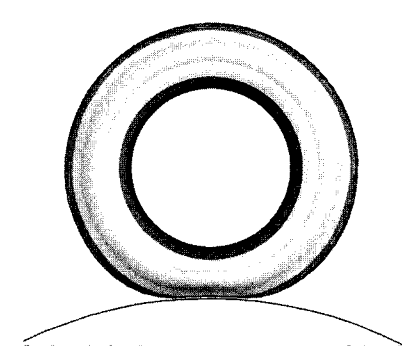


Figure 13. Tire shape after seven cleat impacts at 3 second.

Table 1. Tire in-plane free vibration resonances/transmission.

| Authors | Tire type (Tire model) | Load | Pressure | Methodology | Vertical resonance | Horizontal resonance |
|---|---|---|---|---|---|---|
| Chiesa (1964) | radial-ply | a single tire fitted to a car | 150 kPa | radial sinusoidal excitation | 90 Hz | *N/A* |
| Barson *et al.* (1967, 68) | radial-ply | *N/A* | *N/A* | sinusoidal excitation & sinusoidal spinning drum | 90 Hz | 50 Hz |
| Barson & Dodd (1971) | radial-ply | *N/A* | *N/A* | road test at 50 km/h meets a cleat | 86 Hz | 46 Hz |
| Potts & Csora (1975) | H78-15 radial-ply | *N/A* | *N/A* | radial sinusoikal excitation | 60–80 Hz | *N/A* |
| Pacejka (1981) | cylindrical beam on elastic foundation 135–13 radial | *N/A*<br>*N/A* | *N/A*<br>125 kPa | anaytical radial sinusoidal excitation | 83.7 or 87 Hz<br>83 Hz | 45.5 Hz<br>*N/A* |
| Takayama & Yamagishi (1984) | rigid ring elastic foundation 165SR13 | 3776 N | *N/A* | analytical & test on spining drum with a cleat at 40 km/h | 75 Hz | 40 Hz |
| Kung *et al.* (1986) | ring-spring P185/80R13 | *N/A* | 206.7 kPa | analytical & FEA model | 78 or 86 Hz | *N/A* |
| Ellis (1989 & 1994) | cylinder with tension on elastic foundation | *N/A* | *N/A* | analytical measured | 84 Hz<br>87 Hz | *N/A* |
| Huang (1992) | ring on elastic foundation | *N/A* | 206.7 kPa | analytical at 0 km/h<br>at 70 km/h<br>at 140 km/h | 83 Hz<br>80 Hz<br>73 Hz | *N/A* |
| Scavuzzo *et al.* (1993) | P205/70R14<br>P185/75R14 | 4890 N<br>*N/A* | 207 kPa<br>*N/A* | FEA model dynamometer with cleat | 84 Hz<br>80 Hz | 46 Hz<br>30–35 Hz |
| Negrus *et al.* (1997) | P175/70R13 | 3000/4000 N | 150/200 kPa | radial sinusoidal excitation, FEA model & hammer impact moda test | 85–100 Hz | *N/A* |
| Negrus *et al.* (1998) | P175/70R13 | 3000 N | 200 kPa | FEA model, spinning drum at 0 & 200 km/h & hammer impact modal test | 80 Hz | *N/A* |
| Chang *et al.* (2002) | P185/70R14 | 4500 N | 207 kPa | FEA rotating model on spinning drum with a cleat at 50 km/h | 84 Hz | 45 Hz |

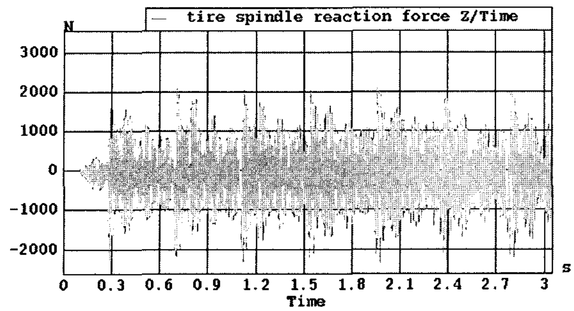
The corresponding tire spindle force curves in the vertical and longitudinal directions are shown in figure 14, where all seven impacts are shown together with the associated force decay and stability, confirming the extraordinarily stable character of this scenario.

Then the FFT algorithm was again applied to the tire reaction force curves to examine the information in the frequency domain; the results are shown in Figure 15. Comparison of Figures 12 and 15 reveals clear similarities: the peaks are sharpened and enhanced after seven impacts with the cleat. This tire's transmissibility from the first vertical and rotational free vibration modes occurs at 84 and 45 Hz in the vertical (Z) and the longitudinal (X) directions.

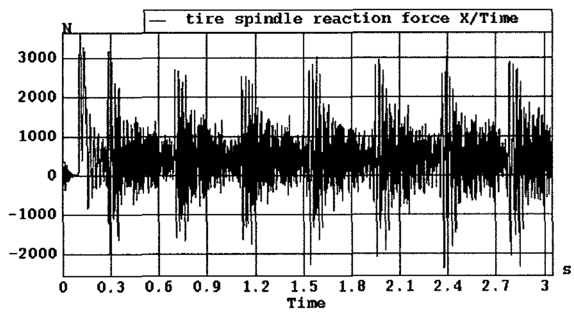
## 8. CONCLUSIONS

Conclusions of this research can be summarized as follows:

(1) A sophisticated FEA model of a general passenger car radial-ply tire was built.
(2) The artificial rotating tire/drum/cleat testing system was established thoroughly.
(3) The tire in-plane free vibration modes transmissibility at 84 Hz vertically and 45 Hz longitudinally were detected successfully. The simulation results are




(a) Vertical direction (Z axis)




(b) Longitudinal direction (X axis)

Figure 14. Reaction forces acting at the tire axle for seven impacts with the cleat.

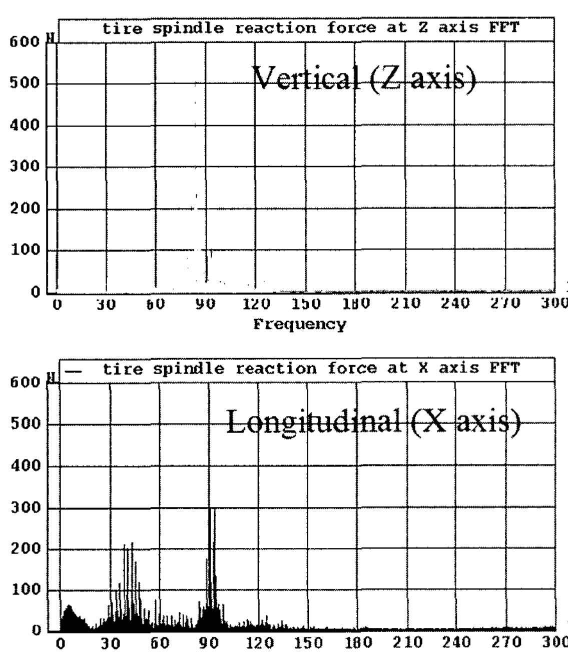



Figure 15. FFT results of tire in-plane reaction forces (with seven impacts with cleat).

listed in Table 1 and show excellent agreement with more than ten previous analytical and experimental studies.

(4) This simulation shows the promise of PAM-SHOCK to be a valuable tool, functioning without any penetrations or difficulties of numerical instability.

Research about tire vibrations is valuable since they are lightly damped and in some cases even amplified because of some local resonances occurring in the vehicles. The results of this study are beginning to reveal the true nature of what happens when a tire meets irregular road inputs. The challenge facing vehicle manufacturers and tire suppliers is to apply the knowledge of tire vibration resonances and transmissibility to the task of defining and optimizing the tire-vehicle system's performance.

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