Shell Mesh Based FE Analysis for Free Vibration Analysis of Radial Pneumatic Tire

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Abstract

The natural frequencies and mode shapes of pneumatic tires are predicted using a geometrically accurate, three-dimensional finite element modeling. Tire rubber materials and cord layers are represented independently using "shell element" available in COSMOS. The effects of some physical parameters such as the inflation pressure tread pattern, thickness of belts and ply angles to the natural frequencies of tires are investigated. By imposing equivalent centrifugal forces, the effect of translational speed on vibrating behavior of the tire is also studied in this work. Comparisons of numerical and experimental results are given to show the validity of the proposed model.

Keywords: *free vibration, natural frequencies, tire, FEM, shell element.*

Introduction

Structural vibrations resulted from tire/road interaction is currently the most important source of traffic noise at speeds over 40 $^{km}/_{h}$ for passenger cars and over 60 $^{km}/_{h}$ for heavy lorries [1, 2]. In addition to noise and acoustic pollution, these vibrations are also transmitted through suspension system towards the vehicle body and cause mechanical problems [3]. So, the study of tire dynamic and vibrational behavior is becoming more important with increasing requirements of vehicle performance.

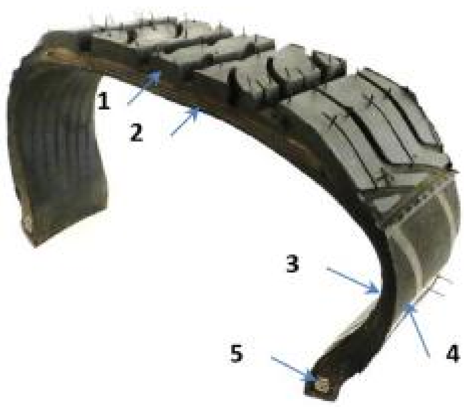
A pneumatic tire as a composite structure of low modulus and high elongating cords of rubber and high modulus and low elongating steel cords, exhibits very complex nonlinear behavior (Fig. 1). Moreover, the tire-road interaction leads to additional complexity. All of these factors make accurate analytical tire modeling very difficult. Accurate empirical tire models can be obtained using experimental results. However, experimental techniques are expensive and require significant analyses.

The finite element method, however, is an efficient and low-cost numerical technique that can be used for complicated tire analyses. Several approaches have been used for analyzing the vibrations of pneumatic tires. These methods include the simple mathematical models of a ring on a viscoelastic foundation [4, 5], the cord-network model [6], as well as the more sophisticated models, such as the membrane model [7], the two-dimension axisymmetric model [8], the two-dimension thin shell and the thick shell model [9], the three-dimension solid model [10]. In all these works it has been demonstrated that the modal analysis and evaluating the natural frequencies is very essential for investigating the dynamic behavior of tire under various conditions [11-13].

In this article, the effects of some physical parameters such as inflation pressure, tread pattern, thickness of belts and ply angles to the natural frequencies of radial tire 185/60R15 are investigated by COSMOS. A special attention is paid for modeling the complex geometrical structure of the tire. Using the capability of "shell mesh", available in COSMOS, the rubber and steel cords, carcass layer, belt layer and tread blocks are independently modeled for evaluating the natural frequencies and Eigen modes of the tire. The results obtained from this analysis are found to be in a good agreement with published experimental data for the same tire.

Details of the analysis

In this section, finite element model of radial tire 185/60R15 is prepared for modal analysis and evaluating the natural frequencies. The main components of the tire, namely the carcass, the bodyplies and the outer tread layers are considered in the models (Fig. 2). Although the tire structure exhibits different stiffness in circumferential and cross-sectional directions, neglecting the orthotropic behavior of the components is reasonable and leads to accurate evaluation of natural frequencies [14]. In this



1- Tread
2- Steel belt layers
3- Carcass
4- Sidewall
5- Bead

Fig1. Structure of a common radial-ply tire (185/60R15).

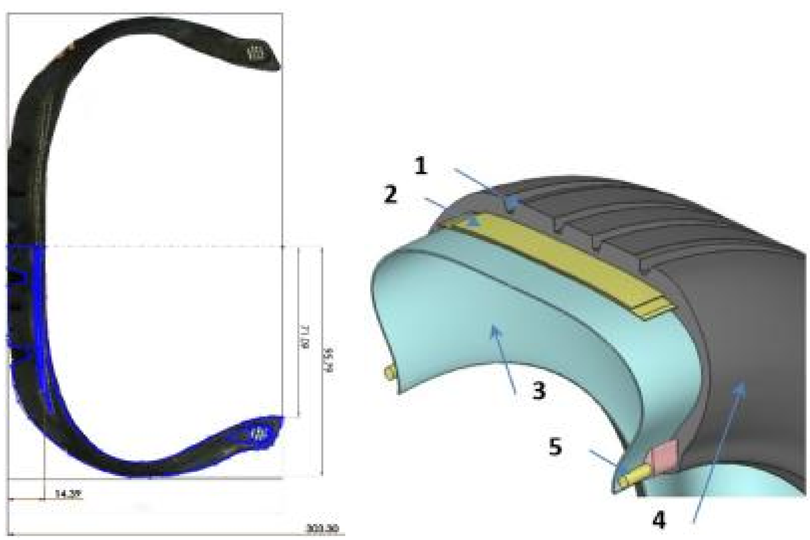


Fig2. . (a) Cross section of tire constructed according to the actual size of radial tire 185/60R15, and (b) 3-D model of the tire components obtained by 360° revolving the tire cross section.

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analysis, the body-ply layers and tread blocks are both treated as two isotropic bodies with variable thickness. The nonlinear mechanical behavior of tread blocks is described by Mooney-Rivlin material model while the body-ply layers are considered to be linear elastic materials. It is noted that the thermal effects has a considerable effects on mechanical behavior of the tire [15]. However, the effect of temperature on free vibration is not considered in this investigation. All parameters used in numerical model are listed in table 1 and 2. For imposing the boundary effects, the unloaded tire is considered to be fixed on the hub and inflation pressure is applied on internal surfaces of the tire (Fig. 3). The effect of velocity can be investigated by inserting an equivalent centrifugal load to the tire model. The inclusion of this effect requires a detailed knowledge about mass distribution of the tire. Assuming the whole tire is made by the rubber, the mass directly depends on tire overall thickness at different sections of its structure.

Using a special capability of COSMOS known as "shell mesh" [16] each component of the tire complex structure, shown in Fig. 2, can be defined as a shell with specific thickness and mechanical properties. According to Ref. [6], the value of $1100 {kg}/{m^3}$ is used for density of rubber in this work. For the radial tire 185/60R15, the total number of 75362 nodes and 34945 elements are used for meshing the geometry of the tire. All the nodes pass three degree of freedom which is suitable for the current analysis (Fig. 3).

Results and Discussion

The present study is applied to see the effect of various working conditions and design factors on free vibrating response of 185/R6015 radial tire. For inflation pressure of $240kPa$, the first five natural frequencies and mode shapes of the tire are given in Fig. 4 and table 3. Comparing the results with the obtained natural frequencies from experimental studies [18] proves the validity of the analysis. The inflation pressure has a great effect on deformation and stiffness of a pneumatic tire. As result, the natural frequencies of tire are directly influenced by any change in this factor.

Table 1: Material properties of the rubber [17].

	$E(MPa)$	u	Density $\left({kg}/{m^3}\right)$
Rubber	18	0.49	1.15E03

Table 2: Material properties of cord layers [17].

	$E_{xy}(MPa)$	$E_{yz}=E_{xz}(MPa)$	u	$G_{xy}=G_{yz}=G_{xz}(MPa)$	Density $\left({kg}/{m^3}\right)$	Angle(deg)
Nylon belt	809.367	14.75	0.444	4.924	1.15E03	90
Steel belt	27317.78	12.478	0.4632	4.16	2.50E03	70
Carcass	1196.15	13.3	0.4596	4.4375	1.15E03	0

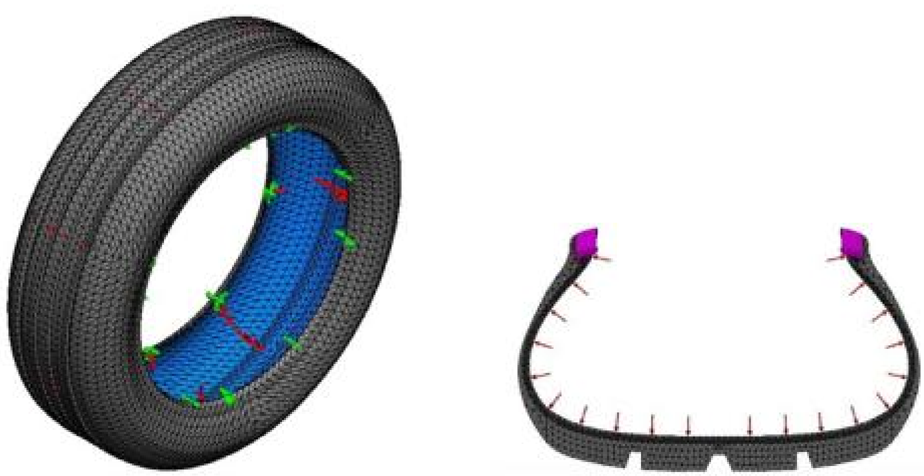

Fig3. Imposing boundary condition and Shell-FEM model used for a whole tire model for numerical analysis

Table 3: Comparing the numerical and experimental results for natural frequency at inflation pressure $240\ kPa$.

Order	Shell-FEM Natural frequency (Hz)	Experiments [18]. Natural frequency (Hz)
1	94.49	95.5
2	122.02	119.5
3	138.82	134
4	161.65	155
5	182.55	185

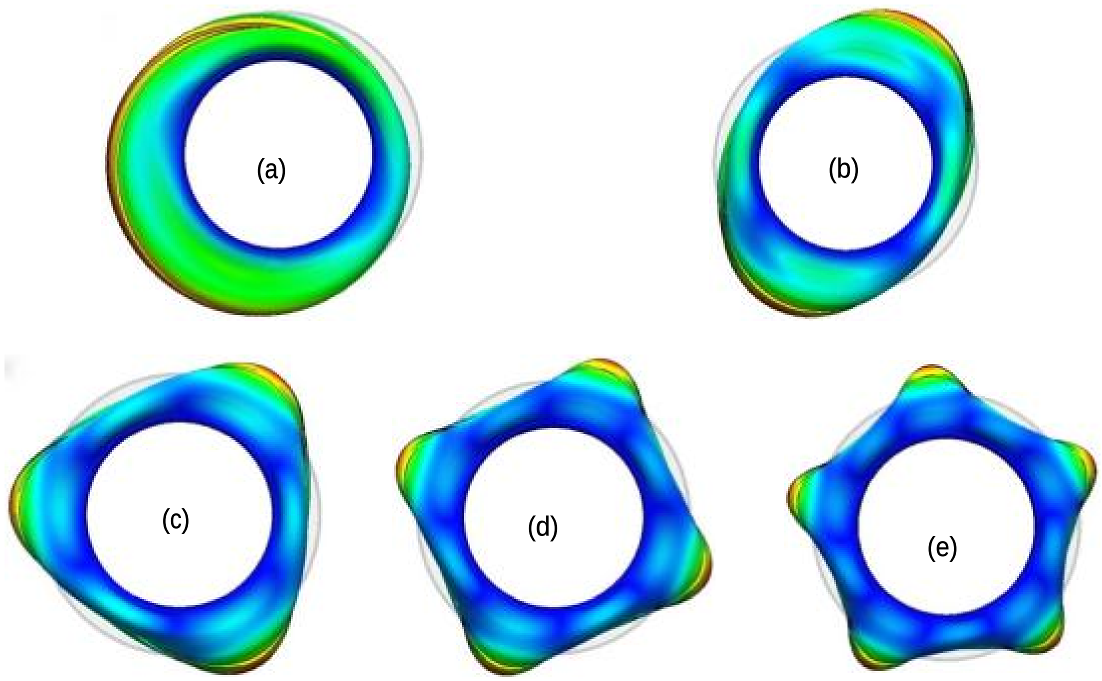

Fig4. The first five mode shapes of radial tire 185/60R15 under the pressure of $240\ kPa$ (a) at natural frequency 94.49 Hz; (b) at natural frequency 122.02 Hz; (c) at natural frequency 138.82 Hz; (d) at natural frequency 161.65 Hz; (e) at natural frequency 182.55 Hz.

Variation of natural frequencies with a range of inflation pressures illustrated in Fig. 5 for better interpretation. It can be seen that as inflation pressure increases, the natural frequencies of the tire increase. However, for the pressures above $240kPa$ a negligible amount of variation can be observed for natural frequencies. So, an optimum value is found for stiffness of the tire.

As mentioned earlier, using "shell element" option, the thickness of tire components and angle of cord layers can be readily selected for design purposes. For same inflation pressure, the effect of ply angle of steel belts on natural frequencies is first studied in this section. It is noted from table 4 that no significant change in frequency is occurred by varying the angle of embedded steel belts.

It is noted that the tire as a composite structure is made by several layers, namely rubber belts, steel belts, carcass and tread layer. The effect of each layer thickness on tire natural frequencies is also investigated in this section. Five following cases are considered and the results are given in table 5.

Case1; Thickness of each layer: Rubber= 1mm, Nylon Belt= 1mm, Steel Belt= 0.5mm, Rubber= 1mm, Steel Belt= 0.5mm, Caracas= 3mm, Rubber Tread= 9mm.

Case2; Thickness of each layer: Rubber= 1mm, Nylon Belt= 1mm, Rubber= 1mm, Steel Belt= 1mm, Caracas= 3mm, Rubber Tread= 9mm.

Case3; Thickness of each layer: Rubber= 1mm, Nylon Belt= 1mm, Steel Belt= 1mm, Rubber= 1mm, Steel Belt= 1mm, Caracas= 1mm, Rubber Tread= 9mm.

Case4; Thickness of each layer: Rubber= 1mm, Nylon Belt= 1mm, Steel Belt= 1mm, Rubber= 1mm, Steel Belt= 1mm, Caracas= 3mm, Rubber Tread= 5mm.

Case5; Thickness of each layer: Rubber= 1mm, Nylon Belt= 2mm, Steel Belt= 0.5mm, Rubber= 1mm, Steel Belt= 1mm, Caracas= 3mm, Rubber Tread= 9mm.

It can be found that the natural frequencies do not effected by any variation in thickness of different tire layers. The effect of different transitional velocity on variation of first five natural frequencies of radial vibrations of the tire is investigated and the results are given in table 6. It can be seen that no significant change in vibrating behavior of tire is observed as speed increases from $V = 40\,{}^{km}\!/_{h}$ to $V = 140\,{}^{km}\!/_{h}$.

The pattern of tread blocks has a considerable effect on driving and braking characteristics of vehicles. Furthermore, the dynamic motion of tires can also be improved by using suitable tread pattern. A smooth tire and tires with three different tread are modeled in this section for vibrational analysis. It is clear from table 7 that a slight increase in natural frequencies is obtained for more elaborate tread designs.

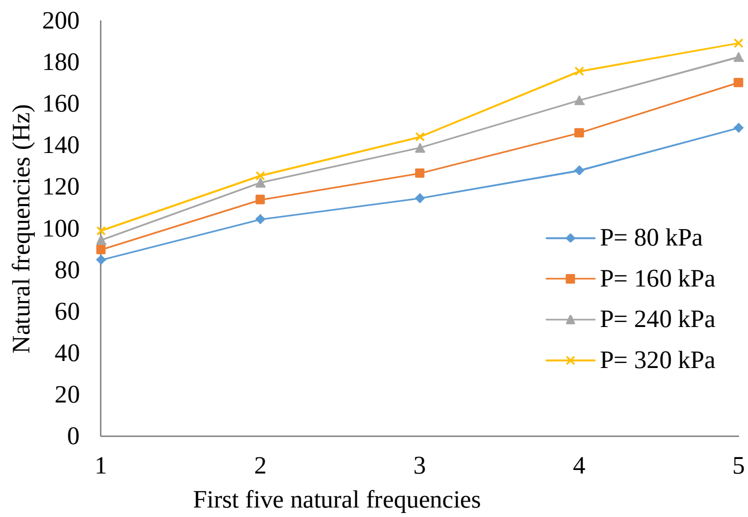

Fig5.. Variation of inflation pressure and natural Frequency.

Table 4: Influence of angle of steel belt on natural frequencies of radial vibrations of the tire

Ply angles of steel belts	±60	±62	±64	±66	±68	±70
1st natural frequencies (Hz)	90.47	91.34	92.68	93.12	93.88	94.49

Table 5: Influence of layers thickness on natural frequencies of the tire.

	Natural frequencies (Hz)				
	1(*Hz*)	2(*Hz*)	3(*Hz*)	4(*Hz*)	5(*Hz*)
Case1	95.21	119.53	137.11	166.55	182.89
Case2	94.168	117.8	134.55	165.4	180.12
Case3	95.46	117.04	135.05	155.92	162.99
Case4	101.13	126.98	144.93	170.28	191.93
Case5	99.28	123.49	138.37	160.02	186.64

Table 6: Influence of translational velocity on natural frequencies of the tire.

	Natural frequencies (Hz)					
Order	$V = 40\,{}^{km}\!/_{h}$	$V = 60\,{}^{km}\!/_{h}$	$V = 80\,{}^{km}\!/_{h}$	$V = 100\,{}^{km}\!/_{h}$	$V = 120\,{}^{km}\!/_{h}$	$V = 140\,{}^{km}\!/_{h}$
1	95.105	95.858	96.892	98.19	99.726	101.47
2	123.19	123.92	124.83	125.77	126.44	126.89
3	139.77	140.74	142.08	143.66	145.65	147.9
4	163.59	165.94	169.09	172.89	177.04	180.92
5	183.64	184.95	186.73	188.95	191.46	194.23

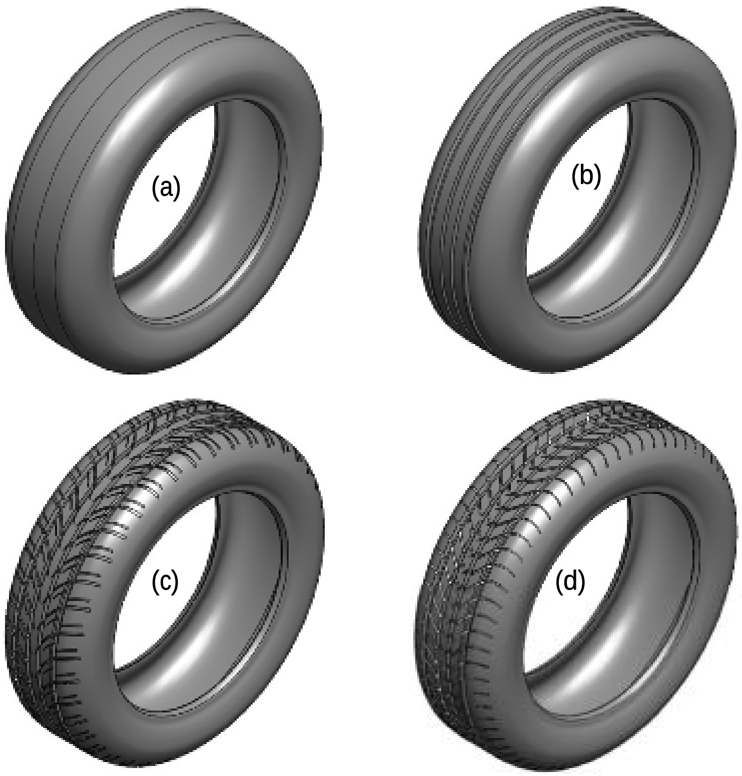

Fig6. Different tread pattern used for numerical analysis of whole tire model.

Table 8. Influence of pattern on the natural frequencies of radial vibrations of the 185/60R15 tire.

	Natural frequencies (Hz)				
	1	2	3	4	5
Without patterns (a)	83.27	103.83	125.71	149.75	168.23
Tread pattern (b)	94.49	122.02	138.82	161.65	182.55
Tread pattern (c)	101.50	117.69	143.10	173.00	205.28
Tread pattern (d)	101.53	122.93	149.47	176.64	205.70

Conclusion

In this work, using "shell mesh" capability for modeling the components of radial tire 185/R6015, the modal analysis is performed for evaluating the natural frequencies and mode shapes of the tire. The effects of various parameters such as the inflation pressure, tread pattern, thickness of belts and ply angles vibrating behavior of tires are also investigated. Due to direct influence on deformation and stiffness, by any raise in inflation pressure the natural frequencies of the tire increase. However, for the pressures above $240kPa$ a negligible amount of variation can be observed for natural frequencies. The results also show that the tread blocks pattern, the layers thickness and their cord ply angles does not have a significant effect on the natural frequencies of the tire.

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