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Modal Analysis of Tyre for Station Wagon

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Abstract- This paper presents the modal analysis of car's tyre under the value of speed 100km/h. The model of tyre is drawn by using SolidWorks 2014 and analysed by ANSYS 14.5. The material of tyre is rubber. The investigation is made on tyre model of station wagon, Toyota's Kluger. The tyre sidewall marking is P205/75R*15. There are many forces acting on the wheel. Inflation pressure acts on the tyre with magnitude of 241kPa. Principal stress theory, von- Mises stress theory, deformation and natural frequency equations are applied by theoretically and numerically. The results from theoretical and numerical approaches of frequency of tyre are compared. Working frequency of tyre is 4.495Hz. Working frequency does not match with natural frequencies of car's tyre at tenth mode shapes. Therefore, the car's tyre has no tendency of resonance.

Indexed Terms- Car's Tyre, Speed, Stress, Deformation, Frequency

I. INTRODUCTION

Tires are utilized in many types of vehicles, such as bicycles, motorcycles, cars, trucks and aircrafts. It enhances vehicle performance by providing traction, braking, steering, and load support. The vehicle tyre has many functions which include supporting the load of the vehicle, providing load carrying capacity, transmission of the forces which drive brake and guide the vehicle. The structure of the tyre is very complex. It consists of several layers of synthetic polymer, many flexible filaments of high modulus cord, and glass fiber, which are bonded to a matrix of low modulus polymeric material. A tyre acts as a spring between the rim and the road. This spring characteristic is very important to the vehicle's ride [2].

Tyre sidewall markings are obvious. They are tyre type, tyre width, aspect ratio, wheel's diameter, speed rating, tyre construction and load index. The tyre is P 205/70 R 15 95 S. The type of tyre "P" is used for passenger. Section width is 205 and its unit is in millimeter. 70 is aspect ratio. Aspect ratio is the ratio of section height per section width. There are three construction of tyre. They are (i) radial, (ii) bias-belted and (iii) diagonal bias. The symbol "R" is radial type of construction. Rim diameter is 15 and its unit is in inches. The symbol "95" is load index. Its means that car's maximum load is 700kg/tire. The speed symbol "S" means that car's maximum speed is 180km/h. [2]
One of the most obvious signs of problem is shakiness and vibration. Shakiness in the front such as the steering column is a sign that front rim is bending. While vibration in seat or behind vehicle may indicate that rear rim is bending. Vibration can be reduced by aligning the wheel, balancing the wheel, correctly inflated the tyre, managing the speed, not overloading the vehicle. [3]

Figure 1 shows type of Kluger's tyre. Figure 2 illustrates Aluminum wheel is fastened to the rear hub with steel studs and lug nuts. Figure 3 shows components of tyre. Components of tyre are bead, filler, liner, nylon belt, steel belt, tread, piles, sidewall and chamfer.

Fig 1. Type of Kluger's Tyre

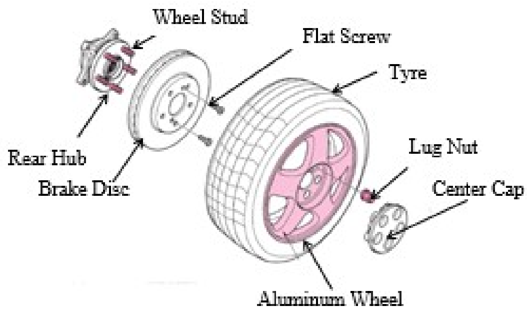

Fig 2. Aluminum Wheel is fastened to the Rear Hub with Steel Studs and Lug Nuts [16]

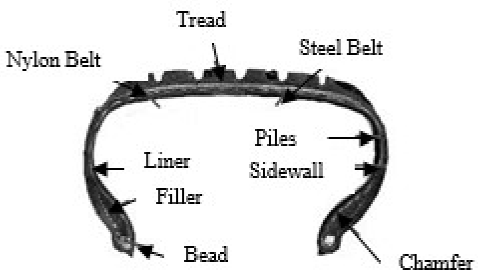

Fig.3. Components of Tyre [9]

II. FORCES ACTING ON THE CAR'S TYRE

Braking force, aerodynamic drag force, centrifugal force, friction force and tangential force act as x direction of car's wheel. Bump force, aerodynamic lift force and radial force act in the vertical direction as y of car's wheel. Lateral force and axial force act in the direction as z of car's wheel.

i) Vertical Weight, W_V

The total vertical weight is determined by the sum of the vehicle weight, passenger weight and extra weight. Vertical weight=vehicle weight+ passenger weight+ extra weight

ii) Lateral Force, F_L

Lateral force acts upon the wheel when steering or when there is a crosswind. They cause the vehicle to change direction.

$$F_L= [(C_f+C_r)\ \beta] + \frac{1}{v}(aC_f-bC_r)\omega-(C_f\delta) \qquad (1)$$

iii) Braking Force, F_B

While the car is running with a constant speed, brake can be used to stop suddenly. Braking force appears at the time of one second and final speed is zero.The braking time is the total time required to stop the vehicle absolutely.

$$F_B = ma = m\left(\frac{v_f - v_0}{t}\right) \qquad (2)$$

iv) Friction Force, F_R

When braking force is applied to the wheel, frictional force is generated between the tire and the road surface. Coefficient of friction value depends upon the road condition and the weather conditions.

$$F_R=\mu F_N \qquad (3)$$

v) Aerodynamic Drag Force, F_D

The aerodynamic drag force is the product of the density of air, the drag coefficient, frontal cross-sectional area of car and the car's speed. The value of lift coefficient (C_L) and drag coefficient (C_D) depend upon styles of car such as sedan, coupe, fastback and station wagon. The value of C_L and C_D is chosen for station wagon.

$$F_D=\frac{1}{2}\rho AC_Dv^2 \qquad (4)$$

vi) Aerodynamic Lift Force, F_L

The aerodynamic lift force is the product of the density of air, the lift coefficient, bottom cross-sectional area of car and the car's speed.

$$F_L=\frac{1}{2}\rho AC_Lv^2 \qquad (5)$$

vii) Radial Force, F_R

When the car is in motion, the radial load becomes cyclic in nature with a continuous rotation of the wheel. Radial load depends upon rim's radius, the width of the bead seat, the angle of loading and the inflation pressure in tire.

$$F_R=8br_{rim}\theta_0 \qquad (6)$$

viii) Axial Force, F_a

The air pressure, acting against the sidewall of the Kluger'stire, generates a load, which is in the axial direction.

$$F_a = (r_t^{\ 2} - r_{rim}^{\ 2})\frac{P_0}{4\, r_{rim}} \quad (7)$$

ix) Bump Force, F_m

Bump force is the force between the passenger and passenger's seat of car.

$$F_m = \frac{mv^2}{r_{rim}} + mg \quad (8)$$

x) Tangential Force, F_T

Tangential force is a force that acts on a moving body in the direction of a tangent to the curved path of the body.

$$F_T = \frac{mv^2}{r}\sin\theta \quad (9)$$

xi) Centrifugal Force, F_c

A centrifugal force is a force, arising from the body's inertia, which appears to act on a body moving in a circular path and is directed away from the center around which the body is moving. Table 1 shows the specification data for the tyre of P205/75R*15.Table 2 shows properties of rubber.

$$F_c = \frac{mv^2}{r_{rim}} \quad (10)$$

Table 1

Table1: Specification Data of Tyre

Design Parameter	symbol	value	Unit
Aspect Ratio	AR	75	mm
Diameter of rim	D_{rim}	381	mm
Tyre Diameter	D_t	688.5	mm
Overall width	w	80	mm
Inflation Pressure	P_o	241	kPa

Table 1 shows the specification data for the wheel rim of P205/75R*15.

TABLE 2

Properties of Rubber [1]

Properties	Value	Unit
Density	1.1	mg/m^3
Young Modulus	0.05	GPa
Poisson Ratio	0.49	
Yield Stress	5.5	MPa

Table 1 shows the specification data for the tyre of P205/75R*15. Table 2 shows properties of rubber.

III. THEORETICAL MODAL ANALYSIS OF WHEEL'S RIM

The x-axis is the intersection of the wheel plane and the road plane with positive direction forward. The y-axis perpendicular to the road plane with positive direction upward. The z-axis in the road plane, its direction being chosen to make the axis system orthogonal and right hand.

There are vertical component acting in the y direction, longitudinal component acting in the x direction, and lateral component acting in the z direction.The force exerted in the x direction is the sum of friction force, braking force, aerodynamic drag force and tangential force. The force exerted in the y direction is the sum of bump force, lift force and radial force. The force exerted in the z direction is the sum of lateral force, axial force and centrifugal force.

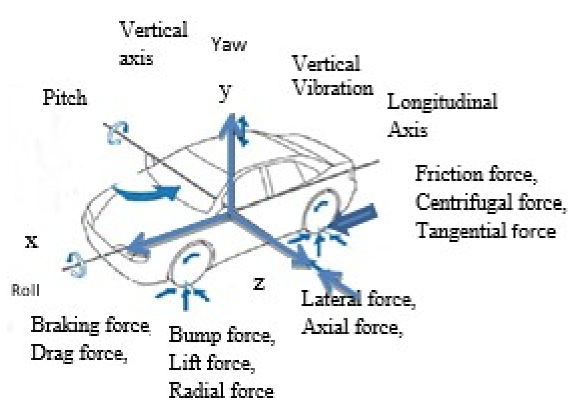

Fig 4. Forces Acting on the Car [1]

Figure 4 shows the forces acting on car direction of x, y and z.

Stress in x direction, $\sigma_x = \frac{F_x}{A_x}$ (11)

Stress in y direction, $\sigma_y = \frac{F_y}{A_y}$ (12)

Stress in z direction, $\sigma_z = \frac{F_z}{A_z}$ (13)

By using von-Mises Criterion equation,

$$\overline{\sigma} = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{\frac{1}{2}} \quad (14)$$

$$\text{Deformation}, \delta = \frac{Pl}{AE} = \frac{\sigma l}{E} \quad (15)$$

$$\text{Natural Frequency}, F(Hz) = \frac{1}{2\pi}\sqrt{\frac{g}{\delta}} \quad (16)$$

Effective stress, deformation and frequency can be calculated by using the equation 14, 15 and 16.

IV. MODAL ANALYSIS OF WHEEL'S RIM

In modal analysis of car's tyre, only fixed support is provided at the bolt hole circle location of car's wheel as shown in figure 5. ANSYS software is used to analyze the ten mode shapes of car's tyre.

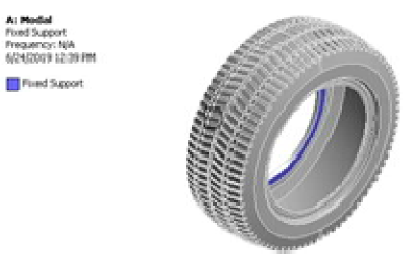

Fig 5. Fixed Support

Fig 6. Meshing of Tyre

This geometry model was meshed with high smoothing of 11230 nodes and 1512 elements as shown in Figure 6. This meshed model was imported to static structural analysis.

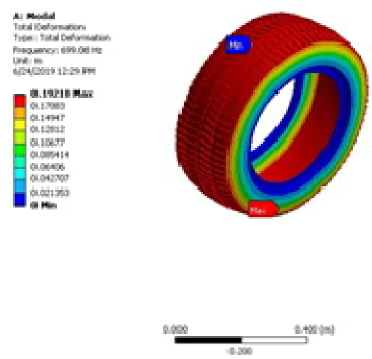

Fig 7. First Mode Shape of Tyre

The first mode shape of tyre is shown in Figure 7. Total deformation of first mode shape is 0.19218m at frequency 699.08 Hz.

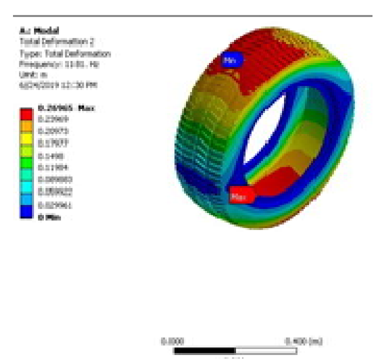

Fig 8. Second Mode Shape of Tyre

The second mode shape of tyre is shown in Figure 8. Total deformation of second mode shape is 0.269m at frequency 1181.1 Hz.

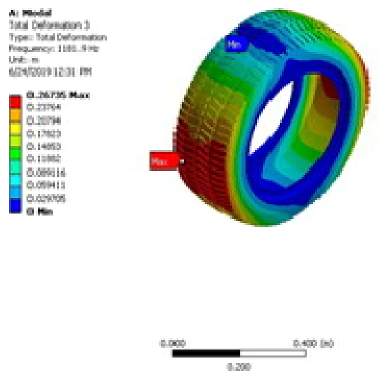

Fig 9. Third Mode Shape of Tyre

The third mode shape of tyre is shown in Figure 9. Total deformation of third mode shape is 0.267m at frequency 1181.9 Hz.

The fourth mode shape of tyre is shown in Figure 10. Total deformation of fourth mode shape is 0.54561m at frequency 1975 Hz.

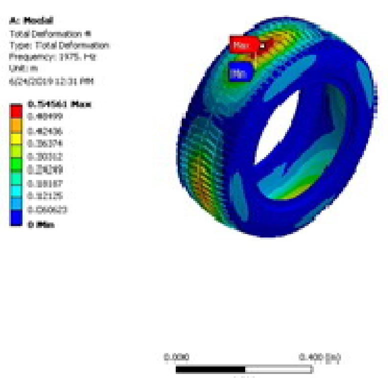

Fig 10. Fourth Mode Shape of Tyre

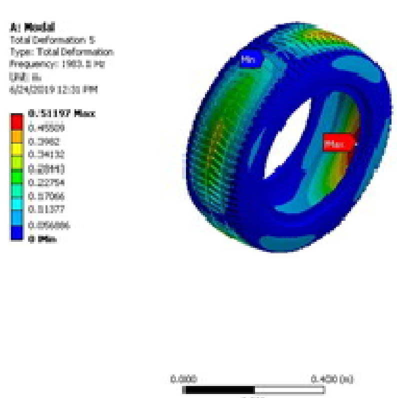

Fig 11. Fifth Mode Shape of Tyre

The fifth mode shape of tyre is shown in Figure 11. Total deformation of fifth mode shape is 0.51197m at frequency 1983.1 Hz.

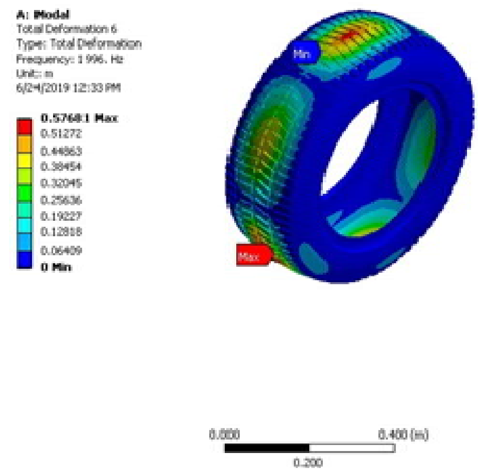

Fig 12. Sixth Mode Shape of Tyre

The sixth mode shape of tyre is shown in Figure 12. Total deformation of sixth mode shape is 0.57681m at frequency 1996 Hz.

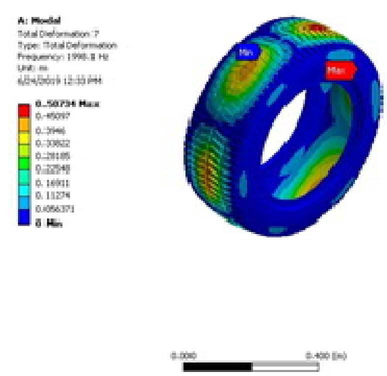

Fig 13. Seventh Mode Shape of Tyre

The seventh mode shape of tyre is shown in Figure 13. Total deformation of seventh mode shape is 0.50734m at frequency 1998.1 Hz.

The eighth mode shape of tyre is shown in Figure 14. Total deformation of eighth mode shape is 0.66047m at frequency 2038.7 Hz.

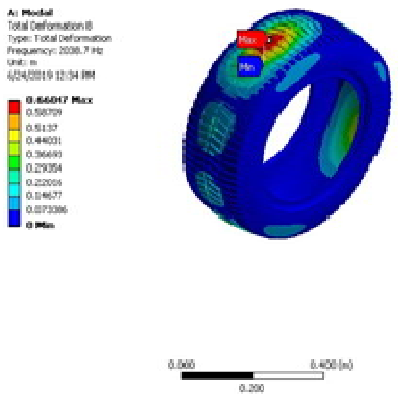

Fig 14. Eighth Mode Shape of Tyre

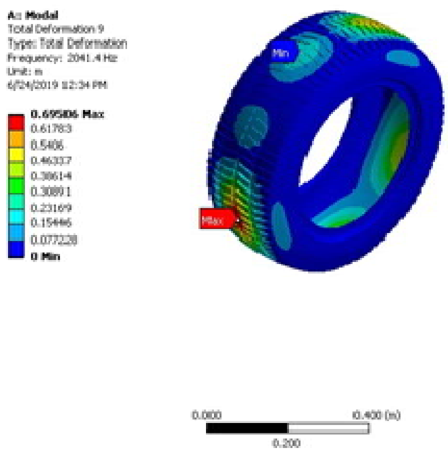

Fig 15. Ninth Mode Shape of Tyre

The ninth mode shape of tyre is shown in Figure 15. Total deformation of ninth mode shape is 0.695m at frequency 2041.4Hz.

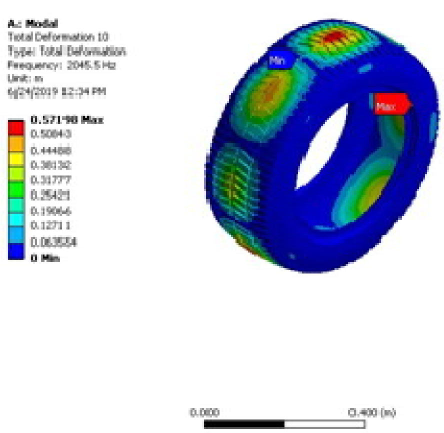

Fig 16. Tenth Mode Shape of Tyre

The tenth mode shape of tyre is shown in Figure 16. Total deformation of tenth mode shape is 0.57198m at frequency 2045.5Hz.

The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. The numerical results of natural frequencies for global mode shapes were compared with working frequency of wheel's rim. The natural frequencies at tenth mode shapes of tyre are shown in Table.

Table 3. Natural frequencies of tenth mode shapes of car' tyre

Mode	1	2	3	4	5
Frequencies (Hz)	699	1181	1182	1975	1983
Mode	6	7	8	9	10
Frequencies (Hz)	1996	1998	2034	2041	2046

Table 3 shows natural frequencies of tenth mode shapes of wheel's rim. Working frequency of car's tyre is 4.495Hz. Working frequency does not match with natural frequencies of wheel's rim at tenth mode shapes. Therefore, the wheel's rim has no tendency of resonance.

V. CONCLUSION

In this research, forces acting on the rim are calculated in the direction of x,y and z. Then, the stresses, deformation and natural frequency of the rim are calculated for materials rubber at speed 100km/h. The natural frequency is analyzed by Ansys 14.5 at different speeds 100km/h. And theoretical results and numerical results of natural frequency are compared. From result, working frequency of wheel's rim is 4.495 Hz. Working frequency does not match with natural frequencies of wheel's rim at tenth mode shapes. Therefore, the wheel's rim has no tendency of resonance.

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NOMENCLATURE

v -speed of car
β -slip angle of car
δ -steering angle
μ -coefficient of friction
C_D , C_L-Drag Coefficient and Lift Coefficient
r_{rim} -the radius of rim
r_t -radius of tire
P_0 -inflation pressure in tire
$\bar{\sigma}$ -Von-Mises stress
$\bar{\varepsilon}$ -equivalent elastic strain
δ -deformation
E - Modulus of elasticity

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