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Design, Analysis and Optimization of an NPT for Light Motor Vehicles

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Abstract: Non-pneumatic tyres (NPTs) have wide application prospects due to their advantages of no run-flat, no need for air pressure maintenance and no risk of tyre explosion. This project compares the behavior of the following spoke designs : hexagonal, radial, angled and triangular. After selection of the optimal design DOE analysis is done on the spoke design to find an optimal spoke shape which has stiffness similar to that of a pneumatic tyre. The paper discusses the effect of uniaxial loading in static conditions and vibrational analysis of various geometric shapes of spokes in NPT. The spoke structures are designed using Solidworks CAD software and analysis is done using ANSYS. The DOE analysis is done using Minitab software. The expected outcome of the project is the identification of optimal spoke structure for NPT to be used in LMVs at high speeds.

Keywords: NPT, spoke structure, CAD, Finite Element Analysis, DOE.

I. INTRODUCTION

Non-Pneumatic Tyres(NPTs) are also known as airless tyres or flat-free tyres. They use various methods like filling the tyre with a material (mostly polymer foams) or using mechanical elastic wheels or by employing a structure made of flexible material which can deform and regain its shape to replace the air in the traditional pneumatic tyre. They are mostly used in small vehicles like lawn mowers or heavy construction vehicles where the risk of punctures is very high. We will be focusing on NPTs. For more than 100 years, vehicles have been rolling along on cushions of air encased in rubber. Pneumatic tyres have been the dominant mobility solution since the release of the first pneumatic tyre for bicycles in 1888 by Dunlop due to its low mass, cheaper price, and low contact pressure. Pneumatic tyres are required to maintain constant specific air pressure for optimal performance. However, pneumatic tyres have an inevitable weakness in maintaining proper air pressure in various situations and this mainly deteriorates the overall safety of pneumatic tyres. Also, they can get flat or punctured or can explode under certain circumstances which is the reason behind the huge number of road accidents happening all over the world. Due to this, efforts are being made since 1920, to deliver a good quality tyre while ensuring safety. Several tyre engineers have attempted to develop non-pneumatic tyres by filling an elastomer into the space for air or by building polygon typed spokes to replace the air of a pneumatic tyre. According to recently disclosed non-pneumatic tyre (NPT) prototypes, the current strategy being employed uses flexible polygon spokes and an elastomer layer having inner and outer rings.

A typical Non-Pneumatic Tyre consists of a hub, several flexible spokes, a shear ring, and a rubber tread. The spokes in NPTs replace the pressurized air in pneumatic tyres. Generally, synthetic rubber is used to make tyre tread and a shear ring is a composite structure composed of a shear band with two circumferential reinforcements (i.e., inner and outer rings). NPTs have several advantages over pneumatic tyres. They are easy to manufacture in comparison with pneumatic tyres. They require low to no maintenance cost hence they prove to be a one-time investment. They have environmental benefits. Since they never go flat and can be retreaded, they will not be thrown away as often as pneumatic tyres. Also, NPTs can be recycled and reused which would save acres of land being used as tyre graveyards worldwide. The recent focus of the research in the development of the NPTs is to use the spokes as the deformable section of the tyre. The current research is being done to develop a structure of the spokes that can be used for LMVs and high-speed applications. The structures currently in use are unsuitable for high-speed applications or use in regular passenger vehicles. There is comprehensive research being done on the material that can be used for the manufacturing of spokes. Recent research suggests that polyurethane is the most acceptable material for the application. Also, research is being done on the use of 3D manufacturing processes to be used in manufacturing NPTs. In 2012 Michelin launched Tweel which is their NPT tyre aimed for heavy construction vehicles. But as this tyre design showed excessive vibration at a speed of greater than 100 Km/hr they are limited to low-speed applications. Recently Michelin and General Motors launched their NPT prototype named Uptis aimed at passenger vehicle cars. Michelin Uptis represents major advancement toward achieving its VISION concept, which includes four pillars of innovation: airless, connected, 3D printed and 100% sustainable. NPTs can go a long time without any maintenance; they are used as the tyres for various rovers launched by various space agencies. Goodyear has been developing non-pneumatic technologies since the 1970s when it participated in the design of tires for NASA’s Apollo lunar roving vehicle, and in recent years in the development of a tire for future missions to Mars.

Non-pneumatic tyres have numerous advantages over traditional pneumatic tyres. But the existing non-pneumatic tyres are used for low-speed applications and for heavy lifting vehicles. With the increase in speed of the vehicle, vibrations in NPT increases. Therefore, the existing version of NPTs can’t be used for LMVs and high-speed applications. Currently, the research done on the structures of NPT spokes is limited. Hence, there is a need for a newer and optimal design of NPT spoke structures for LMVs. As NPT is an emerging technology, it’s yet to be used on a domestic scale. This also means that there is a lot of research to be done in this field. Various spoke structures can be studied for all the loads that are applied to the tyre during its normal use. Various types of applications will have different types of optimal structures. Hence, it is necessary to determine optimal structures for various applications. With the change in the structure, the shape of the contact patch of the tyre also changes. This in turn affects various properties like rolling

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resistance and traction provided by the tyre. With an increase in the speed of rotation of tyres, the heat generated by them is also increased. The current research has shown that heat dissipation is a major issue in NPTs. Hence research can be done in ways to solve the problem of heating tyres. The vibration characteristics of a tyre are very important to determine the maximum operating speeds that the tyre can safely operate under. There is currently a lot of research going on the topic of manufacturing methods of NPTs with an emphasis on 3D printing technology. NPTs are also emerging as a major part of future space missions. Optimizing NPTs for a specific mission can be a huge task and an innovative area of research. Non-pneumatic tyres are emerging advancements in tyre technology. The pressurised air from conventional pneumatic tyres is replaced by flexible spokes in NPTs. The design of these spoke structures varies with its application. This chapter reviews the recent work done in the field of non-pneumatic tyres and the design of its spoke structure.

Z. Hryciow, et. al. [1] have studied the influence of the change of shape of spokes in commercially available NPT. It is observed that an increase in curvature of the spokes resulted in an increase in deformation of the shear beam, whereas it significantly decreased the radial stiffness of the tyre. I.G. Jang, et. al. [2] have used the technique of topology optimization to determine the structure of spokes of NPT with the goal to match the static stiffness to that of the current pneumatic tyres. In [3] Jaehyung Ju, et al, investigates the hexagonal honeycomb spokes for a high fatigue resistance cellular structure design. It finds that a high cell angle causes cellular structures to have flexibility under uniaxial loading. In a study carried out by Kwangwon Kim, et. al. [4], which aims at comparing the contact pressures generated in pneumatic and non-pneumatic tyres having honeycomb spoke structure for varying loads, it is found that vertical stiffness in NPTs decreases with increasing loads. Chihun Lee, et al [5] have studied the dynamic properties of NPT, having a flexible hexagonal honeycomb structure. It found that as rolling speed increases the displacement of the centre of the hub follows a periodic sinusoidal curve. Also with the increase in rolling speed, the effective stiffness of the tyre increases which leads to an increase in the reaction force and high displacement amplitude.

Arvind Mohan, et al in report [6] it is observed that in NPT with larger cell angle, the stress concentration is minimum, which is required for fatigue resistant designs. It could be concluded from this study that a larger cell angle exhibits the least stress, maximum deformation and minimum contact pressure and delivers the best performance under static conditions. K. Tarakaram, et al [7] have discussed different spoke structures such as honeycomb, triangle, plate, curved spoke structures for non-pneumatic tyres.This report concludes that honeycomb structure can provide uniform traction, good strength, fatigue life and reliability. NPT based on gradient anti-tetrachiral structure is proposed and the deformation pattern and mechanical properties of the grounded part of the NPT are studied in Taoyu Wu, et al. [9]. Its result shows that the gradient anti-tetrachiral structures can bear more load and have relatively consistent deformation patterns demonstrating its application potential in the NPT industry. This paper deals with the design and analysis of different spoke structures for vertical forces, steady-state vibrations and dynamic deformations, determination of the most optimum structure of the spokes for Light Motor Vehicle (LMVs).

II. METHODOLOGY

This project focuses on finding an optimum design of the spoke structure from various structure designs such as hexagonal, radial, angled and triangular. Modelling of these structures was done using SOLIDWORKS 2018 CAD software. Analysis of these structures, using FEA software was carried out for vertical loading (static and dynamic) and structural vibrations. The analysis was done using ANSYS WORKBENCH 20. Doe optimization data analysis is carried out using Minitab Software. The results obtained in the analysis of the structures were compared and an optimum design was selected.

A. Material Selection:

An NPT tyre has 4 main parts: inner ring, spokes, outer ring and tread. Fig. 2.1 shows the basic structure and components of NPT. The inner ring is made of an aluminium alloy and acts as a rigid hub. It has a thickness of 3mm. The spokes are required to have in-plane flexibility and are used as the replacement of air in the pneumatic tyres. The spokes are made of Polyurethane which is a hyperelastic material It's uniaxial test results [8] are used as inputs to model the hyperelastic material in Ansys FEA software. The outer ring is made of high strength steel cord (ANSI 4340) and it has a thickness of 0.5mm. The outer ring forces the tread to deform in shear. Also, without the outer ring, the spokes above the contact zone between the tread and road would buckle. The tread is made of styrene-butadiene rubber. It has a thickness of 15mm. Table 2.1 shows the considered properties of the materials considered. It is the part that comes in contact with the road surface. The wheel designation selected for the NPT is 185/65 R15.

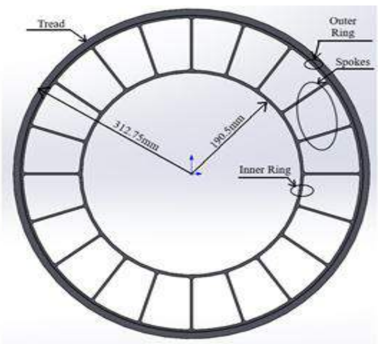

Fig 2.1 : Various components of NPT

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Table 2.1: Properties of materials

Material	Density (kg/m^2)	Yield Strength(MPa)	Young's Modulus(GPa)	Poisson's Ratio
Steel	7800	710	210	0.33
Aluminium	2800	503	72	0.29
Polyurethane	1200	145	32*	0.49*
Rubber	1043	16	11.9*	0.49*
*Properties are approximated				

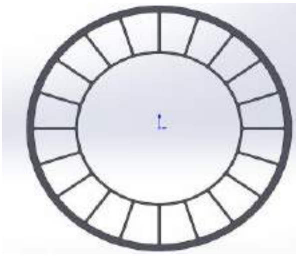

Fig 2.2 : NPT with Radial Spokes

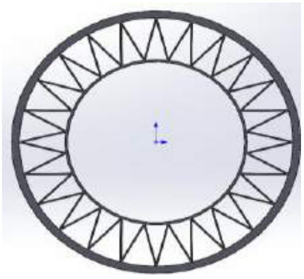

Fig 2.3 : NPT with Triangular spokes

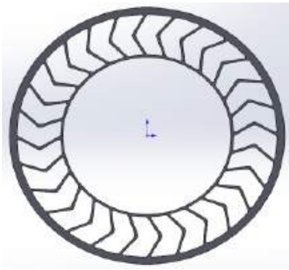

Fig 2.4 : NPT with Angled spokes

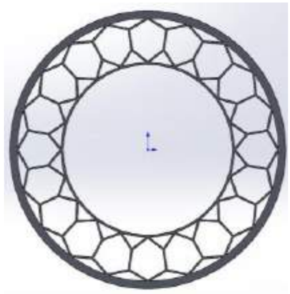

Fig 2.5 : NPT with Hexagonal spokes

B. Modelling: For Radial spoke structure model, The spokes in this design are simple radial beam-like structures as seen in fig 2.2. There are in total 20 equally spaced radial spokes. The spokes in triangular spoke structure model, resemble a triangle with total 24 triangles as seen in Fig. 2.3. The angle(θ) made by the edge of the triangle with the vertical plane is 21°. For Angled spoke structure model the spokes are angled with the horizontal at an angle of 60°. They resemble the shape of an arrowhead. There are in total 28 angled spokes as in Fig.2.4. As these spokes are directional they are pointed in the opposite direction to that of the rotation of the wheel. This is done so that the tyre can provide higher tractive stiffness. The point where the two angled spokes meet is in between the two. This model contains a hexagonal arrangement as seen in Fig 2.5. The dimension of the hexagons are as follows: l = 48.5mm, h = 46.5mm and θ = 135° with reference to Fig 2.6. There are 20 such hexagons.

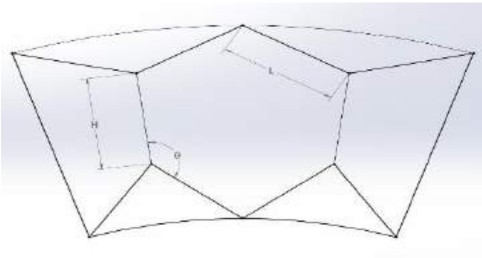

Fig 2.6 : Sectional view of the hexagonal structure

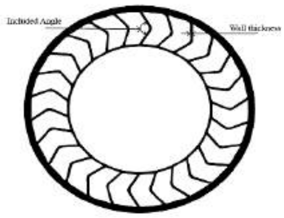

Fig. 2.7: NPT with Angled Spokes

C. Static Analysis:

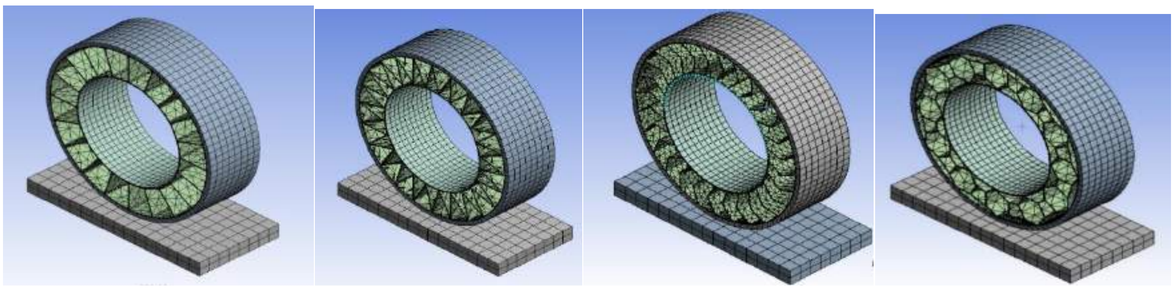

Fig. 2.8 : Meshing for selected NPTs

Static Analysis for all the 4 spoke structures is done using the Static Structural Analysis System in ANSYS Workbench. Aluminium Alloy for inner ring, Polyurethane for spokes, Structural Steel for outer ring and Rubber for tread are the materials specifications during analysis. A load of 3500N is applied to the centre of the tyre and the displacement of the centre in x and z direction is fixed. The bottom part of the road is given as fixed support. Fig 2.8 shows the mesh for radial spoke tyre model, triangular spoke tyre model, Angled spoke tyre model, Hexagonal spokes model

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D. Design of Experiments:

From the data gained previously by analysing different spoke structures, we concluded that NPT with angled spoke structure had similar deformation characteristics as that of pneumatic tyres. To further get the optimal results, Design of Experiments (DOE) is used. The optimization for DOE is done using Box-Behnken method with 3 Levels 15 runs orthogonal array and executed using Minitab Statistical data Analysis Software. Different sets of parameters like number of spokes, spoke included angle and spoke thickness are considered to get different designs for angular spoke structure of NPT. For this, 26, 28, 30 spokes are considered with thicknesses of 3mm, 4mm, and 5mm for the included angles of 100°, 120° and 140°. From the combination of all these different design parameters, 27 different NPT are designed. There are three parameters and three levels as seen in table 2.2. They can be controlled to obtain a desired output.

Table 2.2: Range of Process Parameters

Sr. no.	Process parameter	Levels		
1	Number of spokes	26	28	30
2	Included angle	100°	120°	140°
3	Spoke Thickness	3mm	4mm	5mm

In the Box-Behnken method,15 runs orthogonal arrays considered. For a 3 factor-3 level setup the total number of experiments to be conducted is given by 3^3 from which 15 experiments are considered as seen in table 2.3.

Table 2.3: OA table of experiments

Trial Run	Spoke Thickness	Included Angle	No. of spokes
1	3	100	28
2	5	100	28
3	3	140	28
4	5	140	28
5	3	120	26
6	5	120	26
7	3	120	30
8	5	120	30
9	4	100	26
10	4	140	26
11	4	100	30
12	4	140	30
13	4	120	28
14	4	120	28
15	4	120	28

For the 15spoke structures, the static structural analysis feature of ANSYS workbench is used. A load of 3500N is applied to the centre of the tyre and the displacement of the centre in x and z direction is fixed. The bottom part of the road is given as fixed support. Modal Analysis is performed to evaluate the natural frequencies and mode shapes of a component. A mode shape is the deformation that the component would show when vibrating at the natural frequency. The modal analysis is carried out for all the 15 angled spokes structures at five different modes. The following table 2.4 shows the results of static and modal analysis performed on all the 15 models which are considered during optimization.

Table 2.4 Static Analysis result for DOE parameters

Trial Run	Spoke Thickness	Included Angle	No. of spokes	Tyre centre Deformation (mm)	Max. Stress (MPa)	1st mode frequency (Hz)	2nd and 3rd mode frequency (Hz)	4th and 5th mode frequency (Hz)
1	3	100	28	27.1	96.295	4.33	11	61.85
2	5	100	28	18.664	62.169	8.96	22	77.81
3	3	140	28	10.513	59.31	4.89	22.68	71
4	5	140	28	6.77	44.31	9.85	43.3	86.85
5	3	120	26	21.84	94.4	4.37	14.28	63.7
6	5	120	26	12.117	77.737	9.32	29.2	80.55
7	3	120	30	13.99	86.233	4.66	15.1	67.7
8	5	120	30	11.06	66.671	9.69	30.45	82.1
9	4	100	26	25.004	89.659	6.37	15.95	68.2
10	4	140	26	10.9	65.738	6.95	32.1	76
11	4	100	30	19.312	77.111	6.74	16.87	72.64
12	4	140	30	8.45	51.867	7.42	33.35	81
13	4	120	28	15.5	71.346	5.39	17.15	68.95
14	4	120	28	15.5	71.346	5.39	17.15	68.95
15	4	120	28	15.5	71.346	5.39	17.15	68.95

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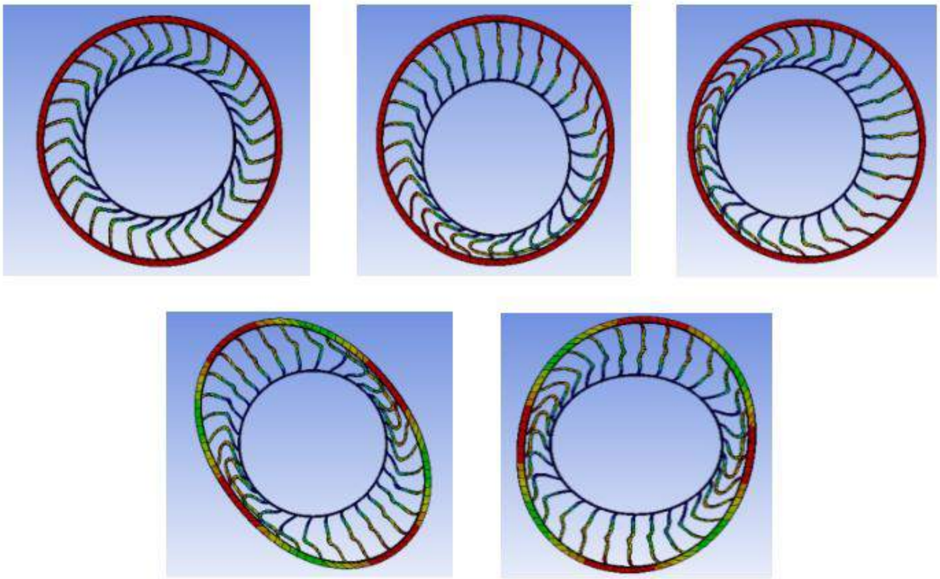

Fig 2.9 Mode Shapes

Fig 2.9 show the mode shapes from mode shape 1 to 5 that were obtained from the modal analysis of the samples. These mode shapes and their respective frequencies can be used to determine if the resonance will occur or not depending on the real time vibrational data.

E. Analysis for the Predicted Model

From the data gained from results Design of Experiments, the tyre with spoke structure having 30 spokes with thickness of 5mm and included angle of 100° is selected for the further analysis. Static Analysis for all the Selected tyre is done using the Static Structural Analysis System in ANSYS Workbench. Aluminium Alloy for inner ring, Polyurethane for spokes, Structural Steel for outer ring and Rubber for tread are the materials specifications during analysis. A load of 3500N is applied to the centre of the tyre and the displacement of the centre in x and z direction is fixed. The bottom part of the road is given as fixed support. To study the dynamic characteristics of the selected tyre, its explicit dynamic analysis is carried out using ANSYS Workbench. Aluminium Alloy for inner ring, Polyurethane for spokes, Structural Steel for outer ring and Rubber for tread are the materials specifications during analysis. The linear deformation of the wheel rim is fixed in y and z directions while it's linear deformation in x-direction and rotational deformation in all x, y and z directions are free. The initial velocity is given as 100 km/h in x direction and 833 angular velocity is given in rotational z direction. The bottom of the road is defined as fixed support. The simulation was run for a total time of 3 millisec.

III.RESULT AND DISCUSSION

Fig 3.1 shows the deformation of the NPT with spokes of 4mm thickness and fig 3.2 shows the deformation of the NPT with spokes of 5mm thickness.

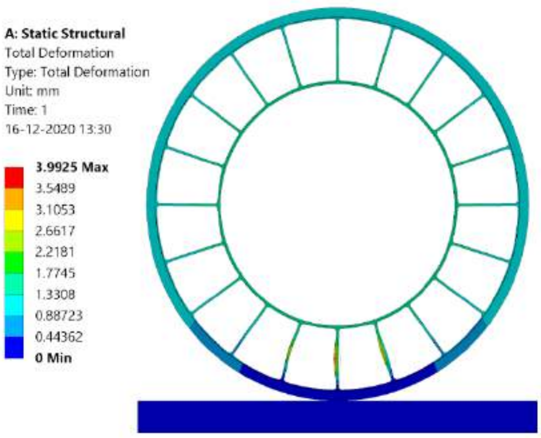

Fig 3.1 : Total deformation of radial spoke

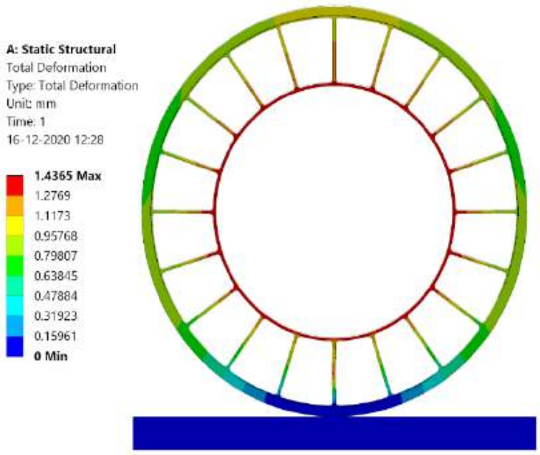

Fig 3.2 : Total deformation of radial spoke

The graph in fig 3.3 shows the trend of deformation of the spokes with respect to the angular position of the spoke. The point of contact is taken as the reference plane and counter-clockwise direction is taken as +ve. From the graph, it is clear that the deformation is symmetric about the vertical axis. The deformation is maximum (3.9 mm for 4mm spoke thickness and 1.4mm for 5mm spoke

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thickness) at the spoke at 0°. This is due to the fact that this spoke experiences only compressive load and goes in buckling, while the spoke exactly opposite to it experiences tensile load. Fig 3.4 and fig 3.5 shows the stress developed on the tyre for 4mm and 5mm spoke thickness respectively. The maximum stress developed is on the steel rim. The stress is under safe permissible limit according to material properties.

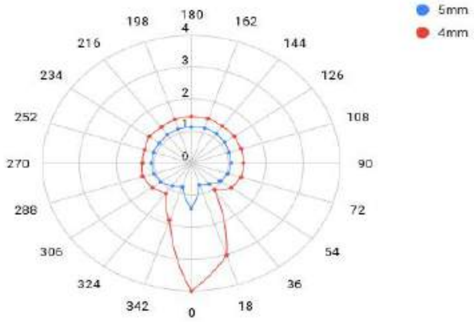

Fig 3.3 : Deformation of radial spokes with respect to their angular position with 4 mm wall thickness with 5 mm thickness

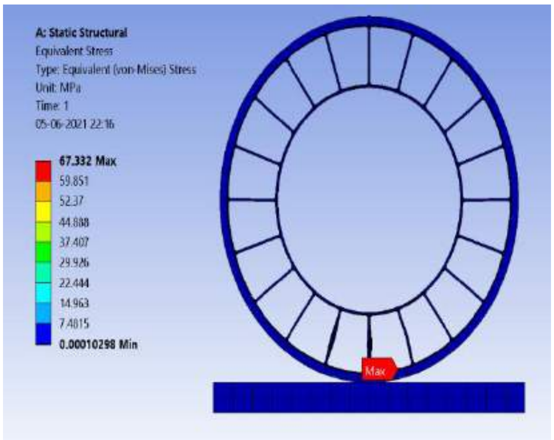

Fig.3.4: Equivalent Stress for radial spokes with 4 mm wall thickness

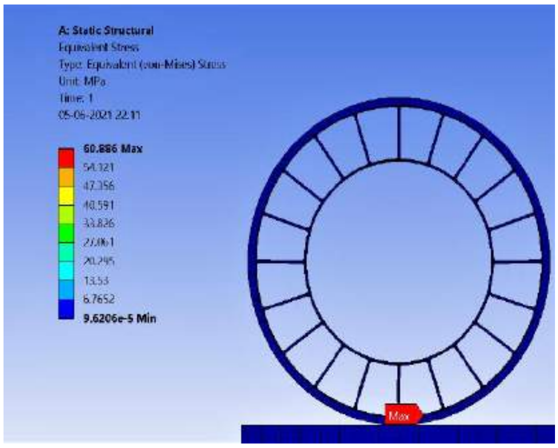

Fig.3.5: Equivalent Stress for radial spokes with 5 mm wall thickness

Fig 3.6 shows the deformation of the NPT with spokes of 4mm thickness and fig 3.7 shows the deformation of the NPT with spokes of 5mm thickness. The graph in fig 3.8 shows the trend of deformation of the spokes with respect to the angular position of the spoke. As triangles are known to be one of the stiffest shapes this structure gives us the least deformation of all the models. The deformation of spokes for the given load has almost the same value for each and every spoke. Fig 3.9 and fig 3.10 shows the stress developed on the tyre for 4mm and 5mm spoke thickness respectively. The maximum stress developed is on the steel rim. The stress is under safe permissible limit according to material properties.

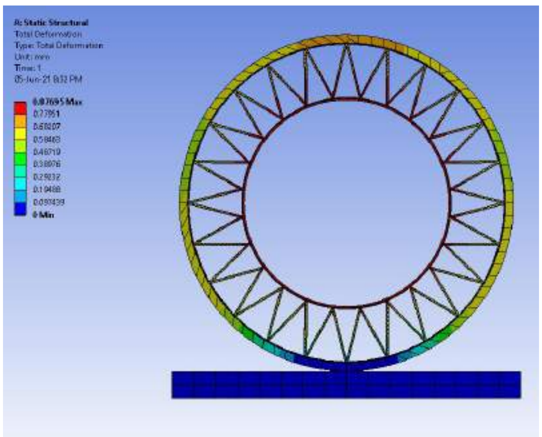

Fig 3.6 : Total deformation of triangular

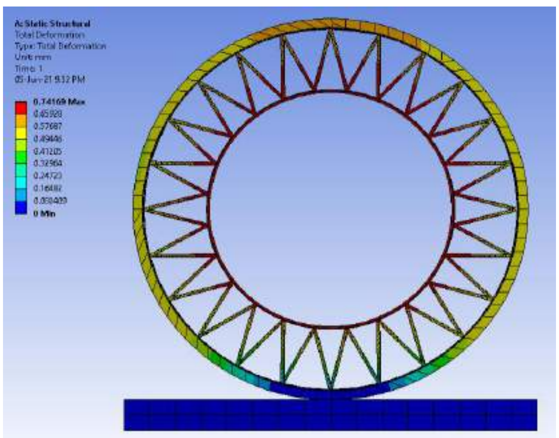

Fig 3.7 : Total deformation of triangular

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spoke with 4 mm wall thickness | spoke with 5 mm wall thickness

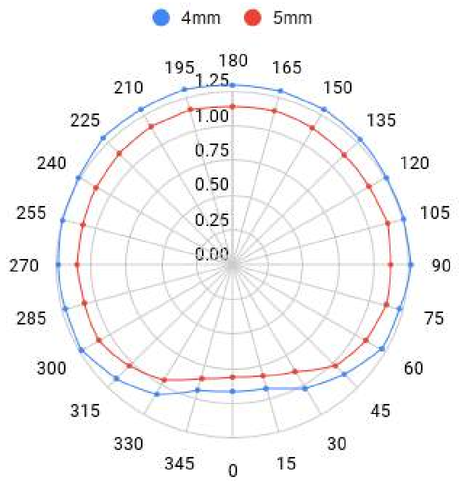
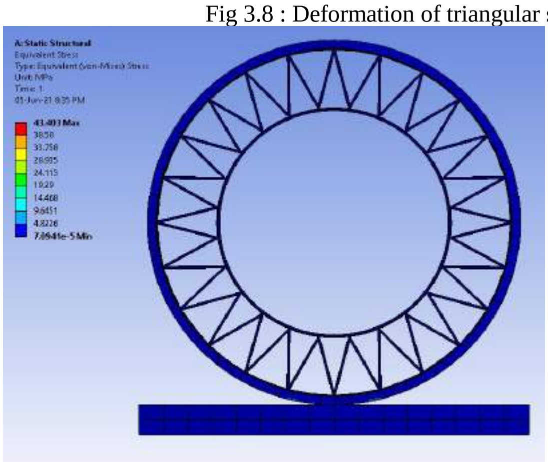


Fig 3.8 : Deformation of triangular spokes with respect to their angular position



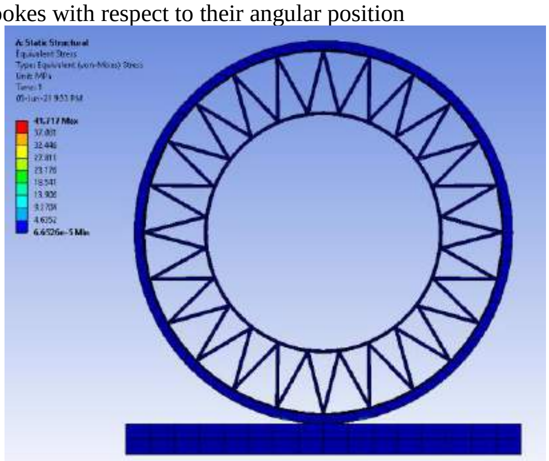
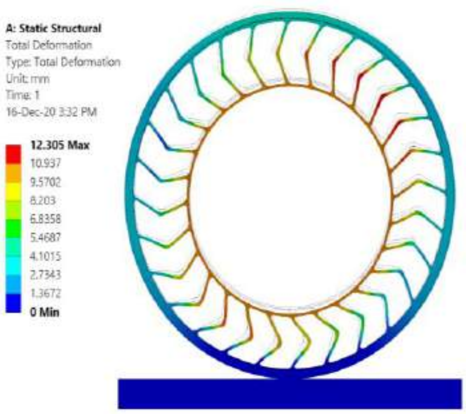


Fig. 3.9: Equivalent Stress for triangular spoke with 4 mm

Fig. 3.10 : Equivalent Stress for triangular spoke with 5 mm

Fig 3.11 shows the deformation of the NPT with spokes of 4mm thickness and fig 3.12 shows the deformation of the NPT with spokes of 5mm thickness. The graph in fig 3.13 shows the trend of deformation of the spokes with respect to the angular position of the spoke. From the graph, we can see that the direction of deformation of the tyre is not vertically downward. This is due to the fact that this structure is not symmetric about the vertical axis. As a result, the deformation of the spokes is also not symmetric about the vertical axis. Fig 3.14 and fig 3.15 shows the stress developed on the tyre for 4mm and 5mm spoke thickness respectively. The maximum stress developed is on the steel rim. The stress is under safe permissible limit according to material properties.



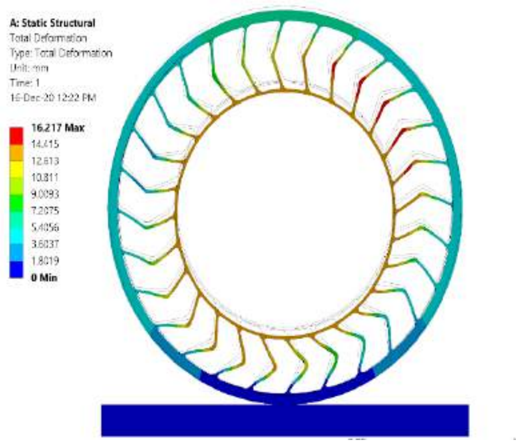


Fig 3.11 : Total deformation of angled

Fig 3.12 : Total deformation of angled

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spoke with 4 mm wall thickness spoke with 5 mm wall thickness

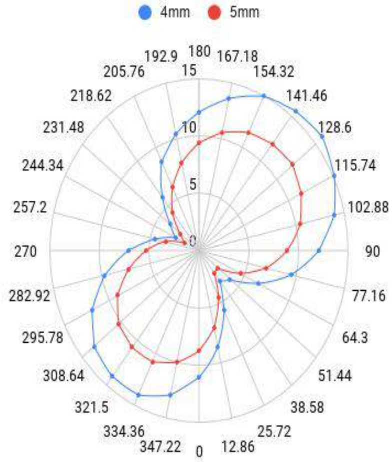


Fig 3.13 : Deformation of angled spokes with respect to their angular position

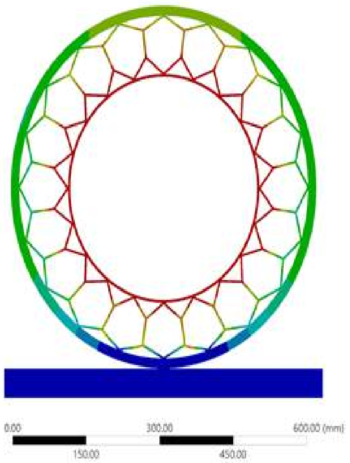


Fig.3.14 : Equivalent Stress for angled spoke with 4 mm

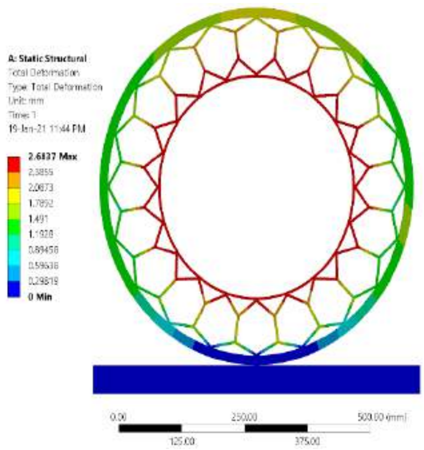
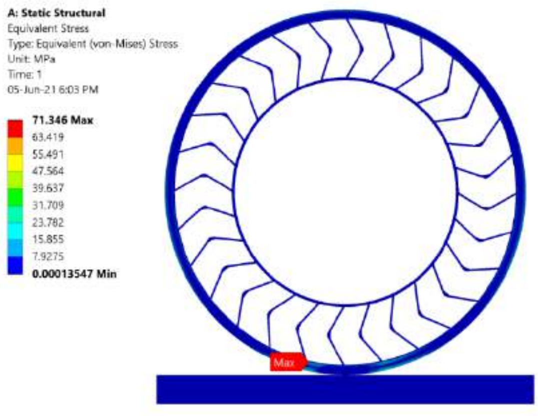


Fig. 3.15 : Equivalent Stress for angled spoke with 5 mm

Fig 3.16 shows the deformation of the NPT with spokes of 4mm thickness and fig 3.17 shows the deformation of the NPT with spokes of 5mm thickness. The graph in fig 3.18 shows the deformation of the hexagonal spokes with respect to the angular position of the spoke. From the graph we can see that deformation is symmetric about the vertical plane as the structure is also symmetric about the vertical plane. Fig 3.19 and fig 3.20 shows the stress developed on the tyre for 4mm and 5mm spoke thickness respectively. The maximum stress developed is on the steel rim. The stress is under safe permissible limit according to material properties.



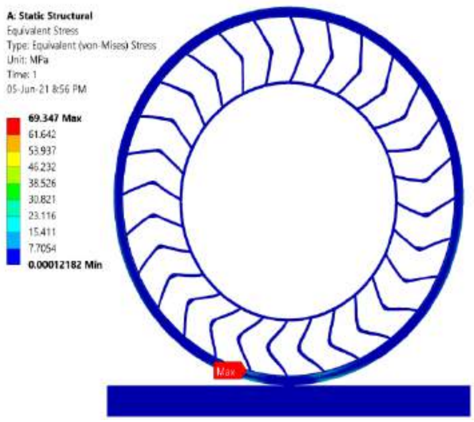


Fig 3.16 : Total deformation of hexagonal Fig 3.17 : Total deformation of hexagonal

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spoke with 4 mm spoke with 5 mm

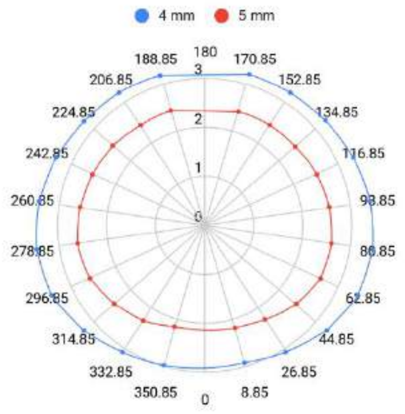
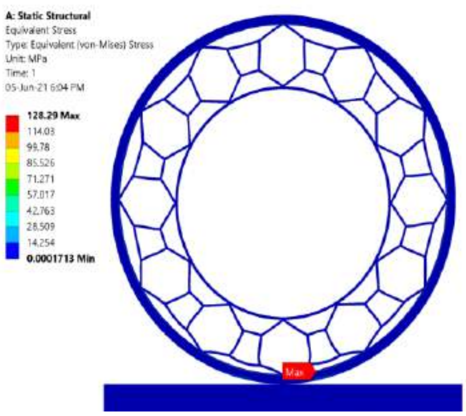


Fig 3.18 : Deformation of hexagonal spokes with respect to their angular position



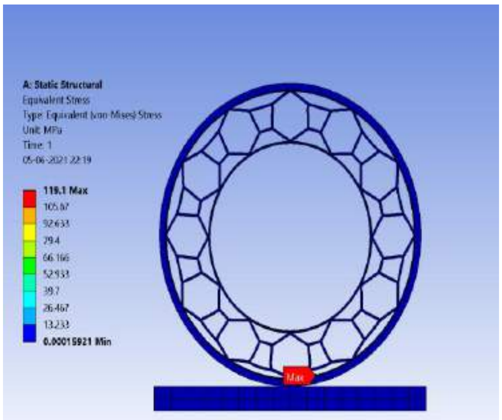


Fig. 3.19 : Equivalent Stress for angled spoke with 4 mm

Fig. 3.20 : Equivalent Stress for angled spoke with 5 mm

Fig 3.21 shows the amount of deflection of the tyre centre from its original position. The Angled spokes with 4mm thickness have the highest deflection of 14mm while the Triangular spokes with 5mm thickness have the least deflection of 1.2mm

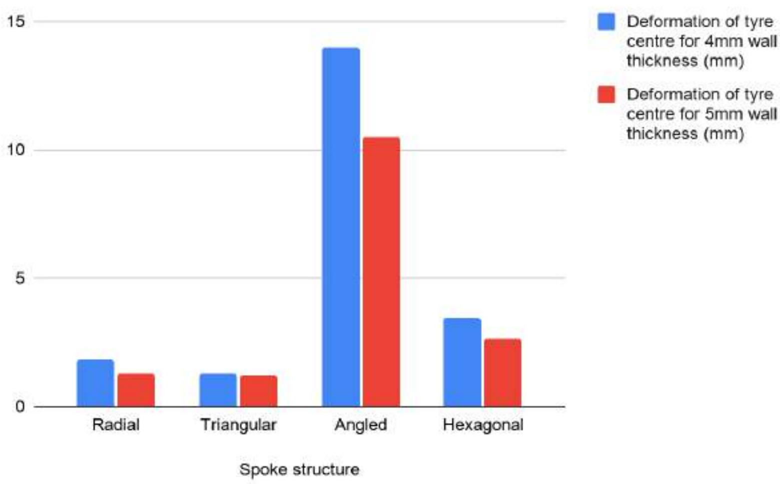


Fig 3.21 :Deformation of the centre of the wheel for all spoke structures

DOE Optimization was carried out using Box Behnken orthogonal array method in Minitab Software. Box Behnken analysis was used to determine the most influential factors and to study the interaction plots of various factors.

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Table 3.1 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	493.357	54.817	166.55	0.000
Linear	3	470.485	156.828	476.50	0.000
Spoke Thickness(A)	1	77.079	77.079	234.19	0.000
Included Angle(B)	1	357.073	357.073	1084.90	0.000
No. of spokes(C)	1	36.334	36.334	110.39	0.000
Square	3	3.202	1.067	3.24	0.119
Spoke Thickness*Spoke Thickness(A*A)	1	0.753	0.753	2.29	0.191
Included Angle*Included Angle(B*B)	1	1.878	1.878	5.71	0.062
No. of spokes*No. of spokes(C*C)	1	0.325	0.325	0.99	0.366
2-Way Interaction	3	19.670	6.557	19.92	0.003
Spoke Thickness*Included Angle(A*B)	1	5.506	5.506	16.73	0.009
Spoke Thickness*No. of spokes(A*C)	1	11.536	11.536	35.05	0.002
Included Angle*No. of spokes(B*C)	1	2.628	2.628	7.98	0.037
Error	5	1.646	0.329		
Lack-of-Fit	3	1.646	0.549	*	*
Pure Error	2	0.000	0.000		
Total	14	495.003			

From table 3.1, we can see that P values for all the three Linear parameters is less than 0.05. An experimental relationship stated by a second-order polynomial equation with interaction terms was fitted between the obtained results and the input variables. The final Regression Equation(Equation (1)) obtained in terms of coded factors is given below,

$$Tyre\ centre\ Deformation\ (mm) = 249.5 - 30.31*A - 1.564*B - 2.74*C - 0.451*A*A + 0.001783*B*B - 0.0742*C*C + 0.0587*A*B + 0.849*A*C + 0.02026*B*C \quad (1)$$

This signifies that all the three parameters have significant variance about the mean. The higher the value of significance, the better the degree of correlation between the values observed and predicted. From Sequential Sum Squares(Seq SS) and Perito chart 3.22 we can say that spoke thickness is the most influential factor followed by included angle and then followed by number of spokes. Fig 3.23 shows the plot for a single factor vs the centre deformation. The value for the centre deformation is the mean value of deformation for every instance where that particular factor is represented. This plot helps us to understand the relation between how the centre deformation varies when the value of a particular factor is changed. Response surface box-behnken Method is used to find the optimal NPT which gives a deformation of 17mm, which is same as that of the pneumatic tyre, and minimizes the maximum stress developed in the tyre which is same as that of the pneumatic tyre. Fig 3.24 shows the response surface interaction showing the effects of a set of two parameters on Tyre center deformation.

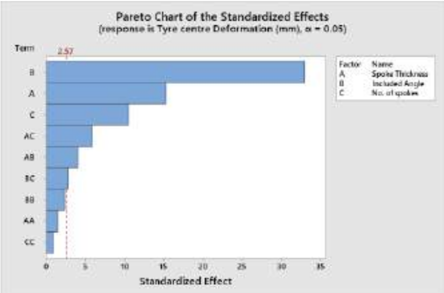

Fig 3.22 Perito chart for tyre center deformation

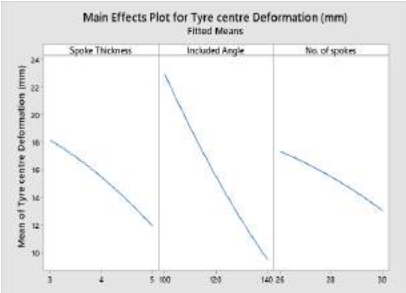

Fig 3.23 Main effects plot for Tyre center deformation

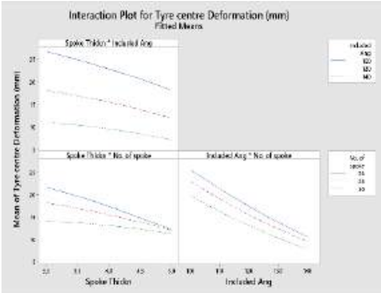

Fig 3.24 Interaction plot for Tyre center deformation

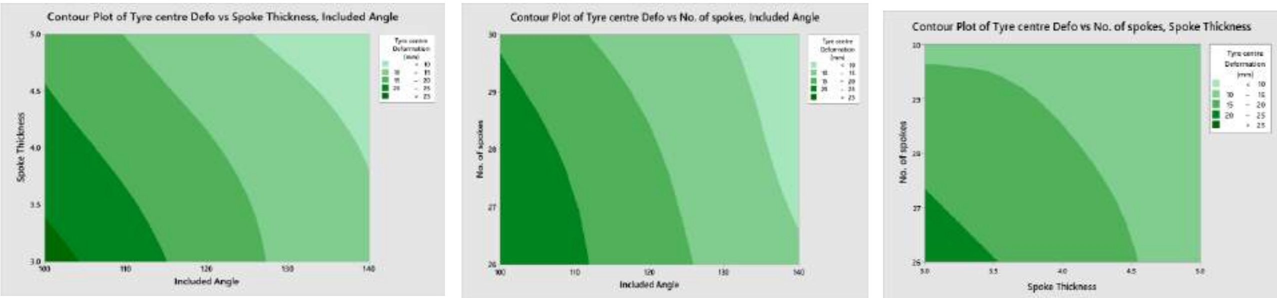

Fig 3.25 Contour Plots

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Fig 3.25 shows the contour plots for the interaction of different parameters on tyre center deformation. The Higher colour intensity shows the higher values for the parameters. It is seen that for the deformation to be 17 mm the range of the colour with third highest intensity of green can be selected. So, for 17 mm deformation, included angle should be between 115° to around 128°, and spoke thickness should be between 4.5 mm and 5 mm as per the 1st graph. From the 2nd graph included angle should be between 112° to around 125°, and number of spokes greater than 29 which can be considered as 30. From the 3rd graph spoke thickness should be between 3.5 mm and 4.5 mm, and number of spokes greater than 27 which can be considered as 30.

Solution	Spoke Thickness	Included Angle	No. of spokes	Max. Stress (MPa) Fit	Tyre centre Deformation (mm) Fit	Composite Desirability
1	5	100	29.5152	62.8943	17.0531	0.799454

Fig 3.26 Solution of Optimization

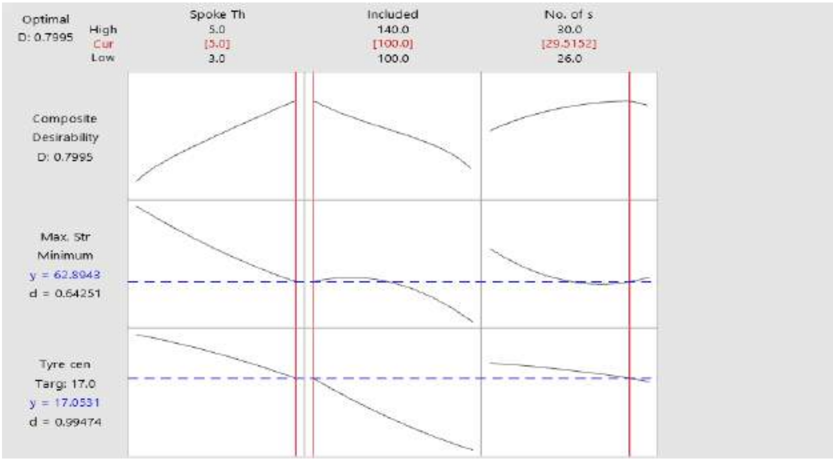

Fig 3.27 Response surface interaction

Optimum Solution was predicted using the Response Optimizer keeping the goal of 17 mm thickness as that of pneumatic tyres and maximum stress generated in the tyre to be minimum. Fig 3.26 shows the Solution of the prediction and Fig 3.27 shows the Response surface Interactions for each variable. The solution concluded that the tyre with 5mm thickness, 100° included angle and 30(~29.5152) Spokes is the optimum Tyre under above constraints.

This result was confirmed by doing static analysis on the model predicted by Box-Behnken Analysis. Fig 3.28 shows the tyre centre deformation which is 17.85 mm and Fig 3.29 shows the maximum stress in the tyre which was 60.9 MPa.

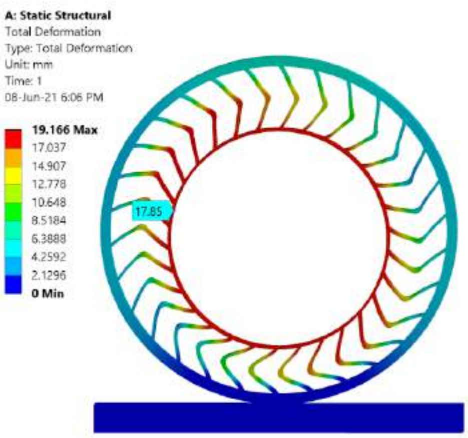

Fig 3.28 Deformation of tyre centre

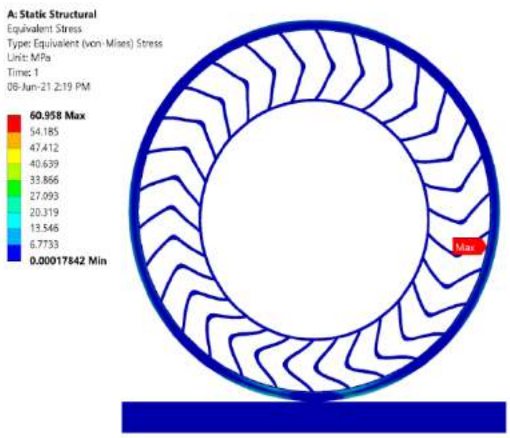

Fig 3.29 Max.Stress generated in the

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for the predicted model tyre for the predicted model tyre

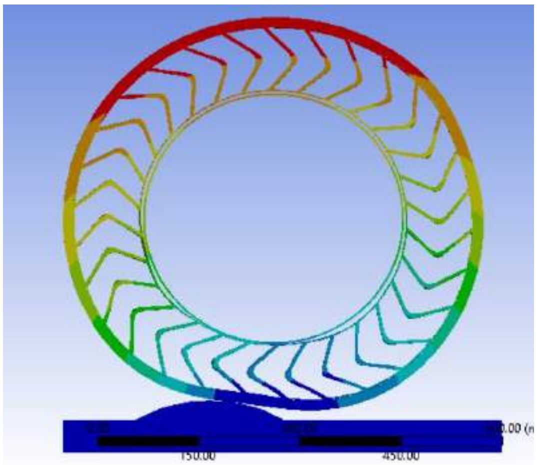

Fig. 3.30 Deformation of the wheel over a bump

Fig 3.30 shows the deformation in the tyre when it hits a bump at the speed of 100km/hr. The maximum stress developed is on the steel ring with a value of 103 MPa, the stress on the entire body was under the permissible limits according to the material properties and the deformation was as expected.

IV. CONCLUSION

In this project, four different geometric spokes structures are modelled for 2 different spoke thicknesses and analysed from which one structure is selected. The selected structure is undergoes Design of experiments from which an optimal structure is predicted. The optimal structure is analysed under static and dynamic Conditions. The conclusions of which are:

- From the comparative FEA analysis of for various spoke designs it was determined that, of the selected designs angled spoke structure can be used to replace conventional pneumatic tyres for LMVs
- From Box Behnken Statistical Analysis it was determined that, for the deformation of tyre centre, all the three considered factors are significant with included angle being the most influential factor followed by spoke thickness & then followed by number of spokes.
- It also showed that the deformation of tyre centre decreases with the increase in either the spoke thickness or the included angle or the no. of spokes in the NPT.
- From the results of Box-Behnken Design analysis among all the studied designs, the NPT with spoke thickness of 5mm, included angle of 100° with 30 spokes is selected as the optimal tyre for 17 mm center deformation and minimum value of maximum stress acting on the tyre.
- The dynamic results show that the Stress is under the permissible limits of the material properties, the tyre is safe when it hits a bump at the speed of 100km/hr.
- The static and dynamic analysis conclude that the selected tyre has the most potential to replace the pneumatic tyre for use in LMVs.

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