International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 05, May-2021

# Study on The Feasibility of using Non-Pneumatic Tyres with Re-Entrant Type Auxetic Structured Spokes in Cessna 172 Aircraft Tyres

Jayanthi Srivatsa Sharma[1], Y Srinivas[2], R. Sabari Vihar[3], D. Govardhan[4]
Research student[1], Senior Faculty[2], Assistant professor[3], Head of the department[4], Department of CAD/CAM, CITD, Telangana , India; Department of Aeronautical Engineering, Institute of Aeronautical Engineering, Telangana, India

*Abstract*: **Airless tyres or otherwise known as Non-pneumatic tire (NPT), conveniently replaces the air which is present in the conventional tire with flexible spokes. This NPT overcomes the drawbacks of a pneumatic tyre like a flat tire, blowouts, air leakage, and regular maintenance of air pressure. The research of NPT is generally done in Automobiles, where it is proving to fetch good results. We have seen NPT's being used in heavy trucks, Cars, and Military Jeeps among many others. This project explores the feasibility of using NPT's in Aircraft, specifically in Cessna 172, by analyzing the structural behavior of the NPT with Re-Entrant Auxetic Structured spokes. This is done by designing the model in PTC Creo and performing Static and Modal analysis in ANSYS Workbench. The design of NPT is based on the dimensions of a conventional Cessna 172 tyre, but with Re-Entrant Auxetic Structured spokes. The design consists of four main parts namely an aluminum hub, elastic spokes (which support the vertical load), high steel shear band, and tread (made of rubber). The properties of these airless tyres like resistance against rolling, contact pressure, load-bearing potential can generally be altered by changing the designs and we will be analyzing one such design in this paper. The results obtained from Static Structural and Modal analysis like Total deformation, Von-Mises Stress, Von-Mises Strain, and Maximum Principal Stress give us an insight into how well the design functions under loading. The results are presented, analyzed and appropriate conclusions are drawn. The scope for future research is also discussed.**

***Keyword: Non-pneumatic tyre, Re-Entrant Structure, Auxetic Structure, Cessna 172, Total deformation, Von-Mises Stress, Von-Mises Strain, Maximum Principal Stress, Static Structural Analysis, Modal Analysis, PTC Creo, Ansys Workbench.***

## 1. INTRODUCTION

### Brief History

Often known as one the greatest inventions of all time, the wheel, revolutionized history. As a matter of fact, the important innovation was the combination of the wheel and a fixed axle, which enables the wheel to be attached to a steady platform. The wheel's functionality is severely restricted without the fixed axel. Historic research suggests that a potter's wheel, which spins freely and has a wheel and axle mechanism, was the first device to employ the wheel and axle's combination. The first artefacts in fact were discovered in Ur, which date to around 3150 BCE, and evidence of vehicles using wheels may have been discovered by the late 4th millennium BCE. Wheeled vehicles have been part of human civilizations henceforth. The wheels have been developed a lot, to suit the growing technology. It has been a long journey from 3100 BCE to 1888 AD when Dunlop released the first commercial pneumatic bicycle tyre. Pneumatic tyres have been in use ever since.

### Pneumatic Tyre

Pneumatic tyres have advantages such as having low energy loss, low vertical stiffness, low contact pressure and low mass. The major disadvantages include the possibility of a puncture during travel, the tedious requirement for maintaining appropriate air pressure, and to top it off is the intricate manufacturing process. Because of its major impact on passenger comfort, noise, control of vehicle, and damage, contact pressure distribution is an important factor for designers of the industry. Owing to the significant contact stresses, high contact pressure causes faster tread damage. It also has a negative impact on passenger comfort and because of its heavy cyclic shear pressure in the longitudinal and lateral directions, high contact pressure differences cause faster tread damage. Low contact pressures, on the other hand, makes controlling the vehicle difficult. Noise is also said to be produced due to the uneven contact pressure. In short, for obtaining the ideal tyre design, a suitable contact pressure degree in addition a low contact pressure peak is desired. These disadvantages of the pneumatic tyre can be transgressed using Non-Pneumatic Tyres. Non pneumatic tyres are proving to be the next big things in tyre technology.

### Non-Pneumatic Tyre

These have multiple advantages such as eliminating the possibility of a puncture, eliminating the tedious requirement for maintaining appropriate air pressure amongst many other things. The environment also is benefitted by using this NPT.

Since they never get punctured and can be re-treaded, these have a longer durability. Land fill mass will thus be reduced greatly. This type of innovation works well and must be considered by research and development facilities all over the world. Airless tyres have received much interest of researchers from various research institutes all over the world as a watershed moment in the field of vehicle design. At large, most of these non-pneumatic tyres are still under inspection and the experimentation is still due . Despite the fact that TWEEL tyres have been launched, their spokes are based on polymer materials, which implies that they suffer from a shorter lifespan, poor reliability, and harmful for the environment. As a result of this, non-pneumatic tyres made of metals has to be explored and developed.

Researchers find employing metal spokes in chiral structures in order to further our understanding of structural technology and to form the basic theories for solids and the vibrational characteristics is of paramount importance for further development. This however is the beyond the scope of this paper. The filling of an elastomer in place of air has been experimented by many tire researchers who have also tried to replace air by using polygon shaped spokes.

Many of the recent Airless tyres are seen employing a unique flexible polygon shaped spoke. In order to find the optimal tyre performance, there arises a need to explore various other polygon-based geometries. After experimenting and analyzing the various properties of hexagonal honeycombs, including the local and macro cellular properties, some of them were found to perform very well with respect to the in-plane direction. Due to their intriguing optical properties accompanied by mechanical properties, chiral structures have piqued the interest of many scholars lately. There are several research findings that may be used in a variety of design research.

A honeycomb geometry created using a tangential connection of periodic ring nodes accompanied by ligaments is known as chiral structure chiral structure is one in which the ligament joined to ring nodes are on opposite sides of the ligament where as an anti-chiral structure is one in which the ligament joined to ring nodes are on the same side of the ligament. The basis for research is till the fascinating mechanical properties of 2D chiral structure. We have included the Auxetic Re-entrant Structure in our design.

Though there have been studies on multiple designs and their analysis, there has been little research on Non-Pneumatic tyres with Re-entrant type auxetic structured spokes. Apart from this, the feasibility of Non-pneumatic tyres in aircrafts, has not been studied before. Our research explores the possibility of using non-pneumatic tyres with Re-entrant type auxetic structure in small Aircraft, specifically the Cessna 172. We have conducted Static and Modal analysis in Ansys 19.2 on a model designed in PTC Creo parametric 7.0.2.0. The design is based on dimensions of the Cessna 172 tyre 6.00-6 whose values were collected from the Michelin tyres website. The dimensions of the designed parts, materials used, force and displacements applied, etc. have been mentioned in the Methodology. The results of the study have been shared in the Results and Discussion section of this paper.

## 2. LITERATURE REVIEW

The NPT’s have been under research for quite some time now. Experimentation of NPT’s has been done using different configurations with an aim to improve their characteristics.

Jaehyung Jua, Doo-Man Kimb and Kwangwon Kimb Kwangwon Kim b (2012) [1] conducted research and reported their outcomes . Airless tyres (NPT) with an appropriate solid spoke part that effectively substitutes the usage of air in a pneumatic tyre had been presented in here. In this work, researchers examined various hexagonal spokes in honeycomb shape for a configuration with higher resistance against fatigue , aiming for obtaining reliable hexagonal structures with minimal local stresses . Two hexagonal honeycombs were proposed using the mechanics involved in honeycombs, an identical thickness of cellular wall and an identical load bearing potential. The elastic limits of the structures were drawn using the ABAQUS , which took into account the nonlinearity of the structures resulting from bending and buckling. For approving the structure, required cell structures with relatively lower stress values were applied to the spokes of the NPT, and the local stresses were investigated under identical loading scenarios. Under similar vertical load bearing capabilities, hexagonal honeycombs with a high positive cell angle exhibit relatively lower stresses and bulking (the Type C spoke in honeycomb shape in this investigation). The NPT's cellular spoke designs were evaluated using regular and auxetic spoke in honeycomb shapes and the related cell designs. The notable discoveries are as follows: The in-plane feasibility of hexagonal honeycombs is dependent on the ratio of l to X1.The flexibility of the spokes in the form of a honeycomb increases as the cell's angle increases, reducing the normal force of an NPT. The structures C and F spokes have a greater cell angle magnitude, which results in reduced local stresses, which is beneficial for a fatigue-resistant spoke design. In whichever way, the spoke in honeycomb shapes of Type C were superior in terms of resistance to fatigue and the relatively smaller mass structure. The work presented in my paper is an expansion of the structures D, E, and F. We have also included a multi-layered spoke design with a hope to obtain better results.

Mohammad Fazelpour, Joshua D. Summers(2014)[4] discussed the advancement of meso-structures with respect to the shear band of Michelin's non-pneumatic tyre, the Tweel. Research scholars of the Clemson University partnered with Michelin to aid NIST's efforts in enhancing the fuel efficacy and in NASA's efforts to develop human exploration technologies. The goal of each was to supplant the shear band's elastomeric material with materials that can tolerate high temperatures and shear pressures, or to use linear low-hysteretic loss materials. The ideas generated by the ideation approach were prototyped for experimental analysis testing. A contextual investigation analyzing

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 05, May-2021

the documentation reports for each task was directed to give an intelligent comprehension of how the development in the ventures happened.

The objective of fostering this review was to attempt to distinguish rules and approaches that could be incorporated into a deliberate methodology for designing meso-structures. The development of meso-structure enhancement for the shear band of non-pneumatic tyres was investigated by engineers at Clemson University between 2007 and 2010. The structural analysis of a shear band in a non-pneumatic tyre with meso-structure was performed. The process started with an ideation technique, then moved on to honeycombs, and finally presented novel designs like the S-type meso-structure. Further research was done for three years by a few analysts at Clemson University who added to this progress. The study work focused on modelling and optimization, with no specific instructions for creating new meso-structures. The idea to implement an auxetic structure in our design draws inspiration from this research. A structural analysis of airless tyres with spokes in the form of hexagonal honeycomb structure with the same thickness of cellular wall were examined and findings were reported by Aravind Mohan, C Ajith Johny, A Tamilarasu, J Pradeep Bhasker and K Ravi [3]. The NPT with spokes shaped in honeycomb structure had a higher magnitude of cell angle demonstrated concentration of less stress, which is important for resistance against fatigue. The ratio of cell height to inclined angle of each cell was said to be a major determinant in the construction of honeycomb especially with respect to its feasibility under axial stress loading scenarios. Greater flexibility and of course feasibility are a byproduct of ratios of higher magnitude. NPTs with spokes having hexagonal geometries have reduced contact pressures due to decreasing vertical rigidity with increasing load.

There are many more research paper which have influenced our paper and are presented in the references. The references presented support us by providing information about nonpneumatic tyres and the research which has been done till now. The papers present the different ways in which the research has been done on NPT with regards to their applications in the Automobile Industry. We have tried to explore into the possibility of using NPT's in Aircrafts which has not been studied at large till date. Though the regular tyres of aircraft support the load and function well, the possibility of getting deflated due to an obstacle on the runway remains , which poses great danger. If for any reason under inflating or over-inflating a tyre is done, this could lead to an increase in the shear forces which can lead to faster damage of an aircraft tyre. The pressure differences between various tyres can probably lead to aircrafts deviating from the runway, separation of the shoulder of the tyre, breaking of lower sidewall due to compression, separation of treads and casting's damage. Our research tries to overcome these issues by inculcating the NPT in aircrafts The above research has shed light as to which spoke designs prove to be fruitful under loading conditions which has helped us to decide upon the design configuration of our NPT.

## 3. METHODOLOGY

**Design**

Creo is a computer-aided design (CAD) software patented by PTC. This suite has many applications, which ease the designing process for the designer. Creo operates on Microsoft Windows and has apps for 3D CAD parametric, visualization, solid modeling, technical illustrations, 3D direct modeling, FEA , schematic design, 2D orthographic views, and simulation. Creo Parametric and Creo Elements go head on with CATIA, SolidWorks and Siemens Solid Edge. The Creo software forms as the successor for the format Pro engineering software. Creo has been in development since 2009.In October 2010, PTC declared that Creo would replace the former name which was Project lightning. PTC launched Creo 1.0 in June 2011. It creates an ecology or an interface where it can connect to or collaborate with other softwares like Solidworks, Siemens Nx, Windchill for Product Lifecycle Management (PLM), Mathcad, Arbortext, etc. Thus, for its simplicity and user-friendly interface, we had selected the Creo to perform the design. The design is based on the dimensions of a Cessna 172 aircraft which has an outer diameter of about 440 mm. The four main parts of the NPT design are :-

- ALUMINIUM HUB
- POLYURETHANE SPOKES
- HIGH STEEL OUTER RING / SHEAR BAND
- RUBBER TREAD BAND

**ALUMINIUM HUB**

The Hub can be fabricated by the Casting process using (AL7075-T6) Aluminum alloy. The hub remains stationary during the motion. The hub is associated directly with the vehicle. This has the longest life in comparison to other parts. The spokes of the design are bonded very strongly with the hub to ensure that these do not separate easily. Our hub is shown in the figure below.

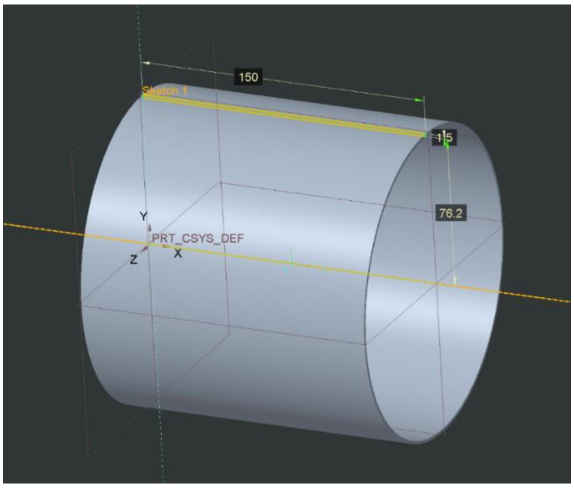


*Figure 3. 1 Hub*

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 05, May-2021

**Dimensions**

Section Width :- 0.15 m (150 mm)
Thickness :- 0.0015 m (1.5 mm)
Radius :- 0.0777 m (77.7 mm)

**POLYURETHANE SPOKES**

Polyurethane, the material our spokes are made of, was discovered in 1937 by Otto Bayer in Germany. Polyurethane has seen immense development from being a flexible foam. to a rigid foam known as PMDI. These rigid foams show excellent resistance towards heat conduction and applaudable retardance towards flame. This material is being used in many types of research related to NPT. It effectively replaces the air in pneumatic tyres. Polyurethane can tolerate heavy uni-axial loads and can still regain its original shape after deformation, which is a desired quality, especially in structurally auxetic spokes.

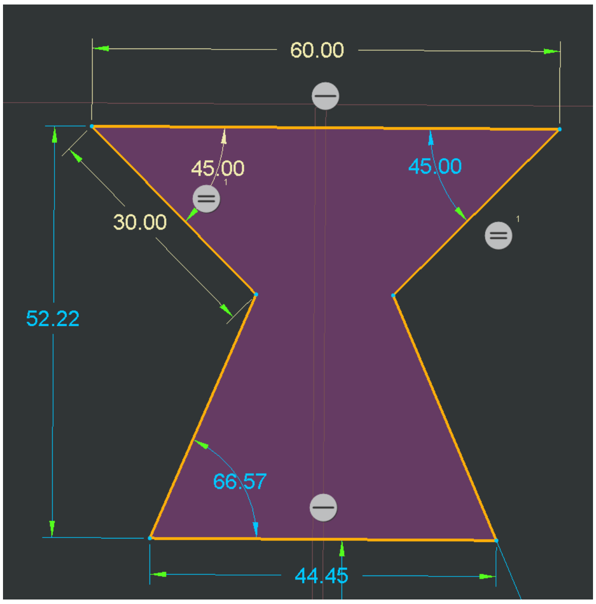


*Figure 3. 3 Base design for First Layer*

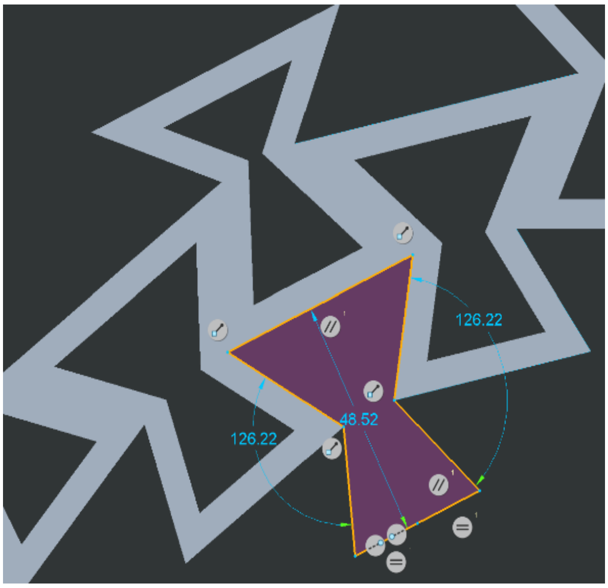


*Figure 3. 6 Base design for Third Layer*

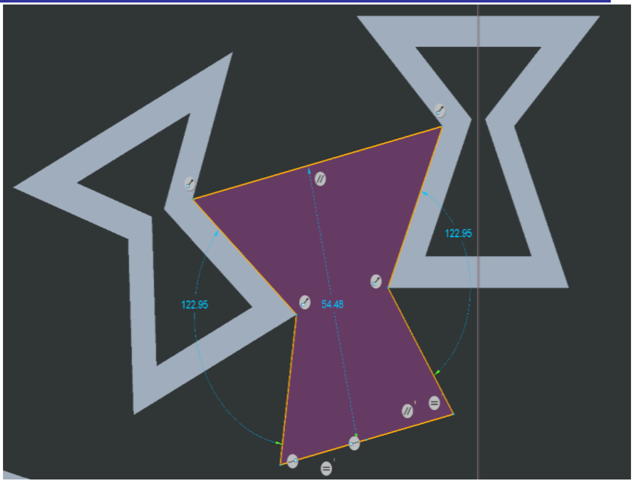


*Figure 3. 2 Base design of Second Layer*

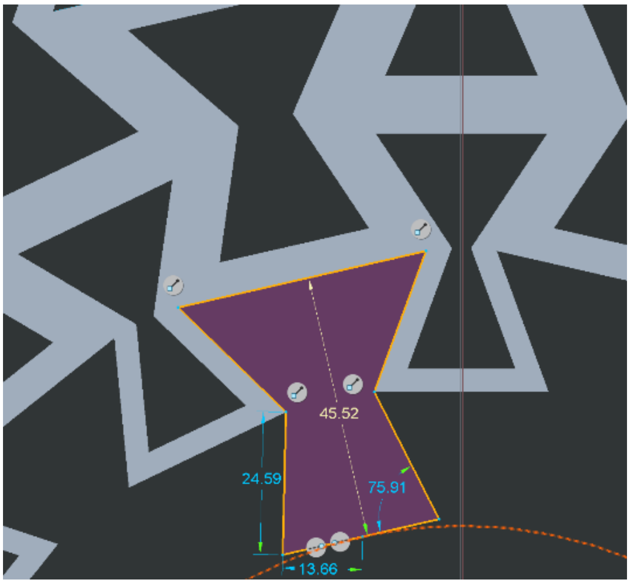


*Figure 3. 5 Base design for Fourth Layer*

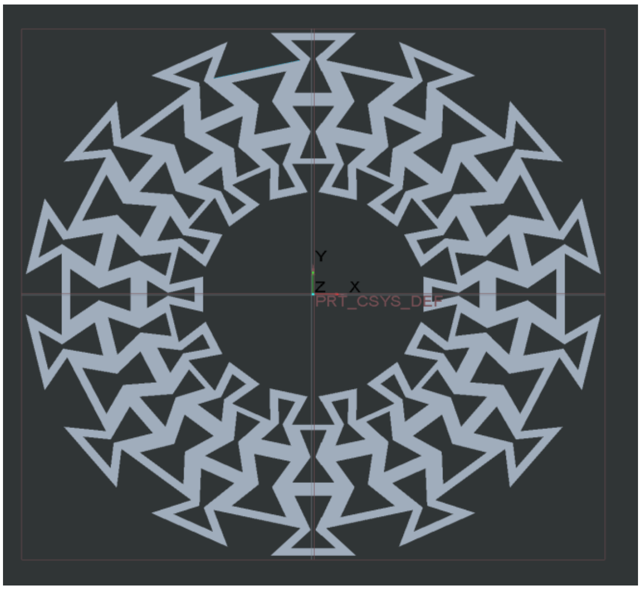


*Figure 3. 4 Four Layered Spoke*

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 05, May-2021

### Outer Ring / Shear Band

It is a component situated between the tread and the spokes. It is generally comprised of high steel wires wound in a circular fashion. It Bolsters the tread from shearing off during the motion. Its along with the tread band to facilitate the strong bond between them and to provide great cornering stiffness. The shear band is made by wrapping high steel chords over the top of a drum for as long as the desired base thickness is not obtained. The shear band is made of high steel.

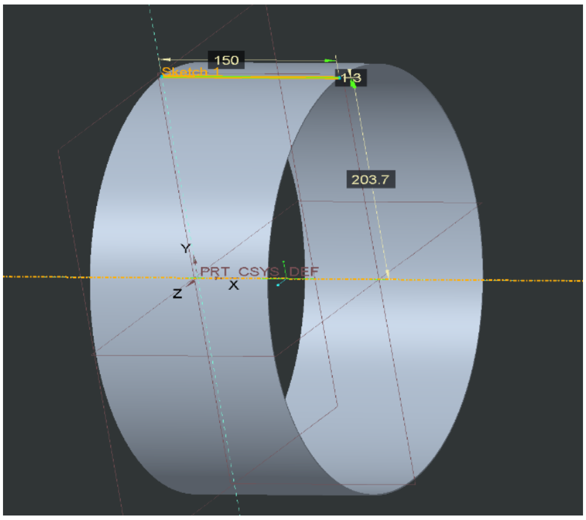


*Figure 3. 7 Outer Ring*

**Dimensions**

Section Width :- 0.15 m (150 mm)
Thickness :- 0.0013 m (1.3 mm)
Radius :- 0.205 m (205 mm)

### TREAD BAND

Tread band directly encounters the runway. It is desired to provide optimal amount of traction and optimal resistance against rolling is desired. The terrain decides the design of the tread. Tread band is manufactured using the Extrusion process. In order to add strength and durability the entire assembly is Vulcanized. The process in which rubber is treated with sulphur is generally known as Vulcanization.

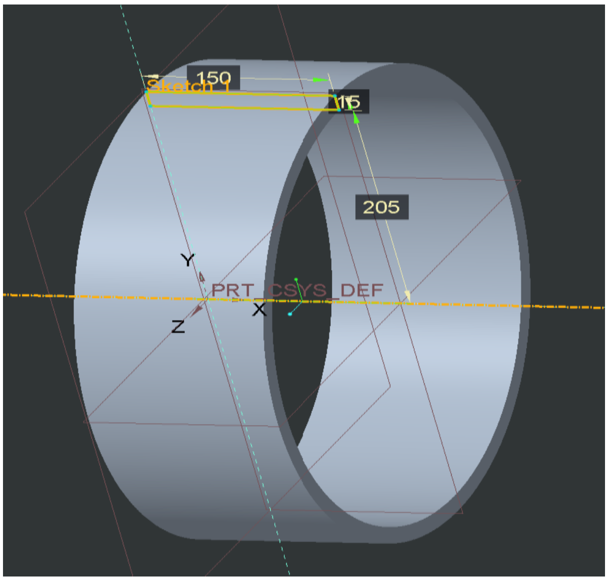


*Figure 3. 9 Tread Band*

**Dimensions**

Section Width :- 0.15 m (150 mm)
Thickness :- 0.015 m (15 mm)
Radius :- 0.22

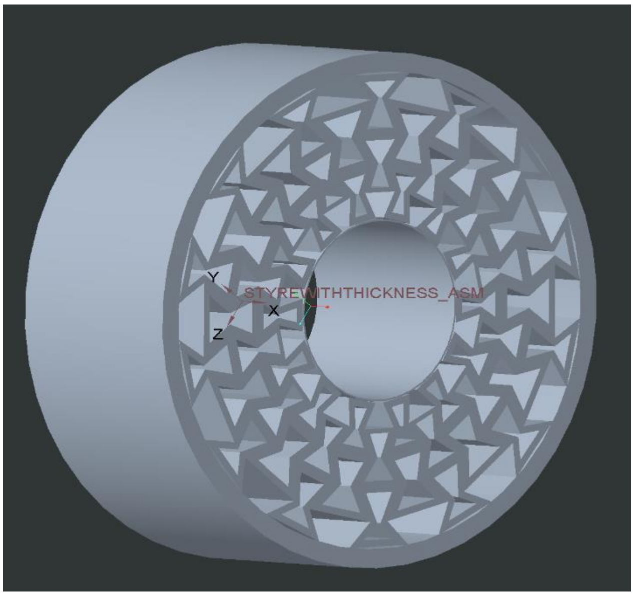

*Figure 3. 8 Assembled Spoke.*

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 10 Issue 05, May-2021

## Analysis

Ansys is a Finite element analysis (FEA) software used all over the world. FEA involves discretizing the body into small components called elements. The software has numerical algorithms which govern the characteristics of these elements and thus predict the nature of these elements under multiple constraints and loading conditions. The analysis can be done from simple objects to complex structures without any complications. Ansys is useful in Electrical and Chemistry departments as well. This creates simulations in a virtual environment which can be adjusted as per our requirements. This is known as Virtual Prototyping. Virtual prototyping helps us to create various testing scenarios so as to achieve the best possible outcome without having to create a physical prototype and waste money.

### Modelling

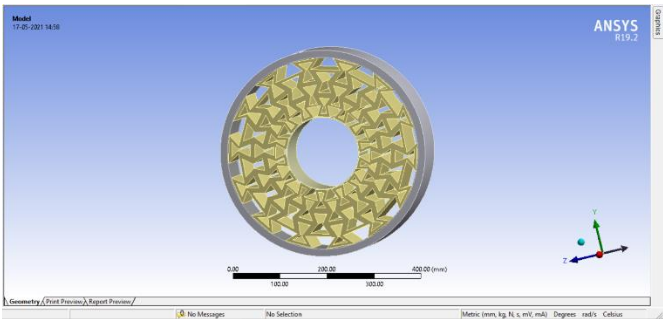


*Figure 3. 10 Modelling*

Modelling is the phase which occurs following the entry of data into the Engineering Data sources and importing the geometry into the workspace. Our model appears like this after the importing into Ansys Workbench.

### Assigning Materials

Table -Material properties of non-pneumatic tyres

| part | Hub | Spoke | Outer Ring | Tread |
|---|---|---|---|---|
| **Material** | AL-7075-T6 | Polyurathane | AISI 4340 | Rubber |
| Density in kg/m3 | 2800 | 1200 | 7800 | 1043 |
| Youngs modulus E (Mpa) | 72000 | 32 | 210000 | 11.9 |
| Poisson's Ratio v | 0.33 | 0.49 | 0.29 | 0.49 |
| Yield Strength Mpa | 500 | 140 | 470 | 16 |

*Figure 3. 11 Material Properties*

The above materials have been assigned respectively to the model imported into the workspace.

### Meshing the model

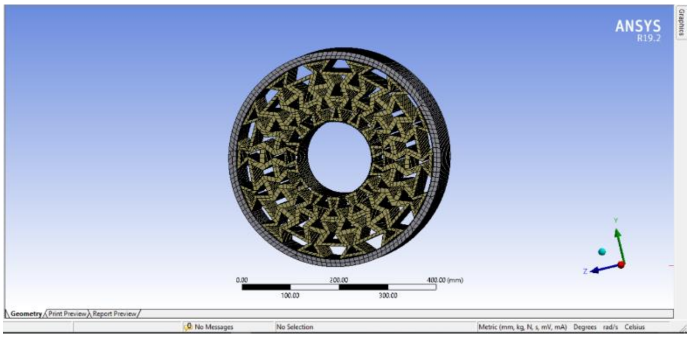


*Figure 3. 12 Meshed Model.*

The next step is to mesh the body. Meshing can be done either using the default settings or by changing some settings in the mesh settings.

Element size used : 0.01 m (10 mm)
Number of Nodes : 1,67,613
Number of Elements : 27150

### Constraints

Fixed support: Fixed support is applied at the hub our body.

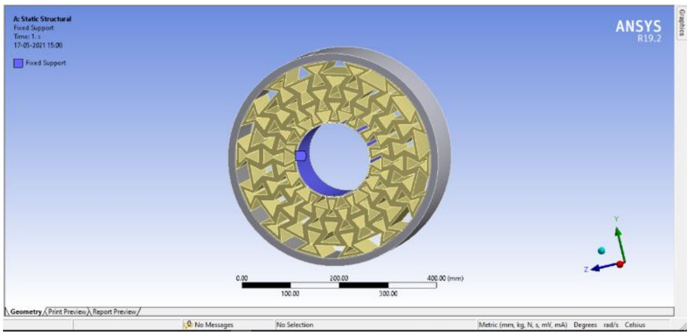


*Figure 3. 13 Fixed Support*

Displacement: The entire body is constrained to arrest the movement of the body in the x and y directions.

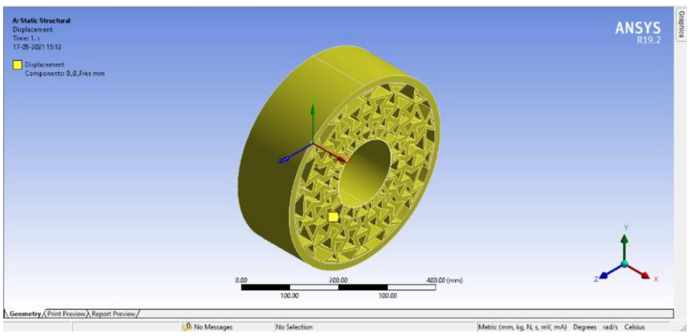


*Figure 3. 14 Displacement*

Force: Force of the magnitude of 7428 N is applied on the Tread of our body which is the maximum bearable load of the Cessna 172 tyre. This Information has been obtained from the Michelin's aviation tyre data for the Cessna 172 tyre. The data suggests that the maximum bearable load of this tyre in the pneumatic form is 757.5 kg (1670 pounds), which translates to 7428 N. We have experimented our design with the same loading conditions to check the performance of our design.

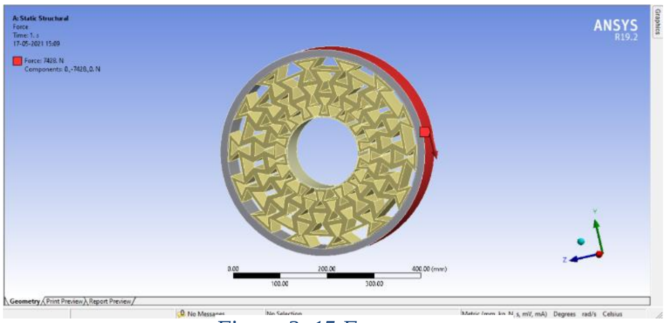


*Figure 3. 15 Force*

Rotational Velocity: Rotational velocity of 280 rad/s was given which is the designated velocity of the Cessna 172.

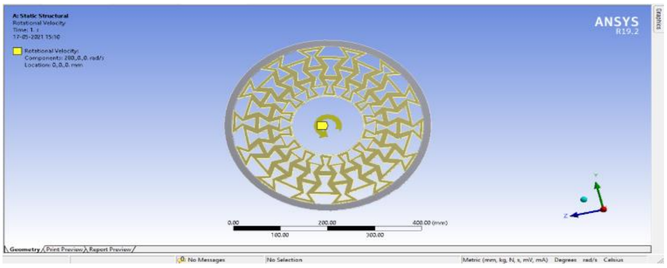


*Figure 3. 16 Rotational Velocity*

Thus, our design has been modelled in PTC Creo and analyzed in Ansys Workbench. All the materials used, forces applied, constraints given etc. have been mentioned. It is. worth noting that the dimensions of the design are based on the Cessna 172 Aircraft's tyre. The dimensions of the tyres were obtained from Michelin's Official Manual of Aircraft tyres. As shown above the Re-entrant Auxetic Structured Spokes were imbibed into the design successfully. The results of the analysis will be discussed in consequent chapters.

## 4. RESULTS AND DISCUSSION

### Static Analysis

The results obtained from our analysis are presented here. The results in Static Analysis include Total Deformation, Equivalent Stress or Von-mises Equivalent Stress, Equivalent Strain or Von-mises Equivalent Strain and Maximum Principal Stress.

### TOTAL DEFORMATION

As seen in the figure below, the maximum deformation produced in the body, as per the forces and constraints mentioned in Methodology, is 0.00178 m (1.78 mm).

This result proves that the deformation is negligible. This also indicates that the design is statically performing well.

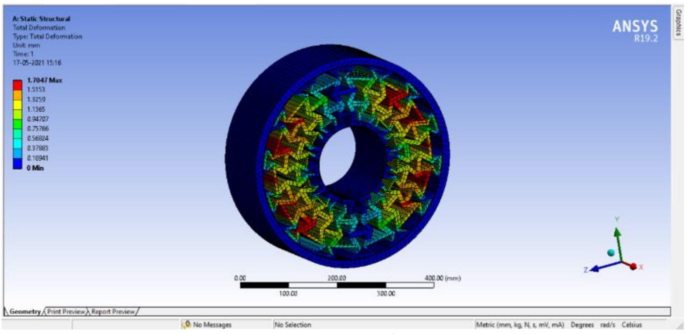


*Figure 4. 1 Total Deformation*

### VON-MISES EQUIVALENT STRESS

Equivalent Stress or Von-Mises Equivalent Stress indicates the overall average stress being produced in the Structure due to uni-axial loading. The maximum result obtained as seen in the figure below is 108.75 mpa. This is well below the yield point of polyurethane which is 140 mpa and thus we can conclude safely that the result obtained is satisfactory. This proves that the structure will not get damaged under the Loading conditions. Thus, we can conclude from this result also that the design is statically performing well.

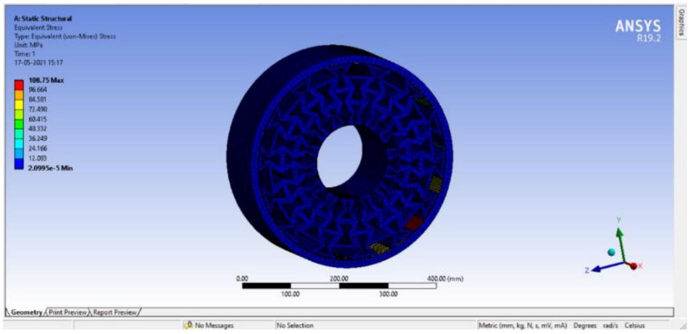


*Figure 4. 2 Von-Mises Equivalent Stress*

### VON-MISES EQUIVALENT STRAIN

Equivalent Strain or Von-Mises Equivalent Strain indicates the overall average strain being produced in the Structure due to uni-axial loading. The maximum strain obtained as seen in the figure below is 0.11192. This is quite negligible and goes onto prove that the structure is performing well under loading conditions.

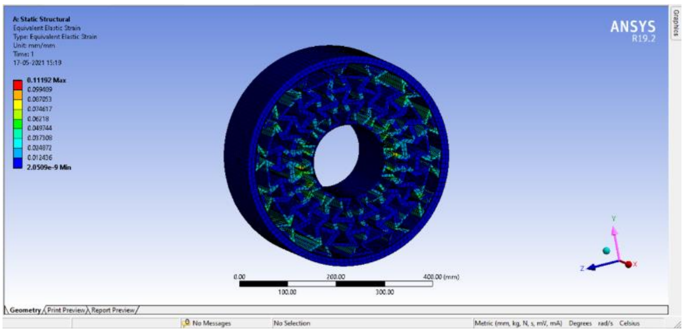


*Figure 4. 3 Von-Mises Equivalent Strain*

## MAXIMUM PRINCIPAL STRESS

MAXIMUM PRINCIPAL STRESS indicates the maximum stress being produced in the Structure due to uni-axial loading. The maximum result obtained as seen in the figure below is 115.54 mpa. This is well below the yield point of polyurethane which is 140 mpa and thus we can conclude safely that the result obtained is satisfactory. This proves that the structure will not get damaged under the Loading conditions. Thus, we can conclude from this result also that the design is statically performing well.

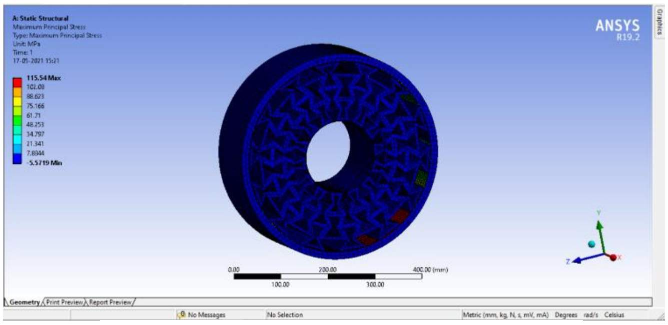


*Figure 4. 4 Maximum Principal Stress*

The Static Analysis results end here. From the results obtained, we can conclude that the design is safe and is performing well under the uni axial loading conditions.

## MODAL ANALYSIS

This analysis can be used to obtain the natural frequency and its corresponding mode shape. Our aim is to make sure that the operating frequencies do not fall in the natural frequency of the body in order to avoid resonance. Thus, various operating frequencies and mode shapes have been obtained from this analysis. The various operating frequencies and mode shapes are presented below:

## TOTAL DEFORMATION FOR MODE SHAPE 1 :

The maximum deformation here is 0.011389 m.
The operating frequency of first mode shape is 22.848 hz.
This is well below the Natural frequency of our model.

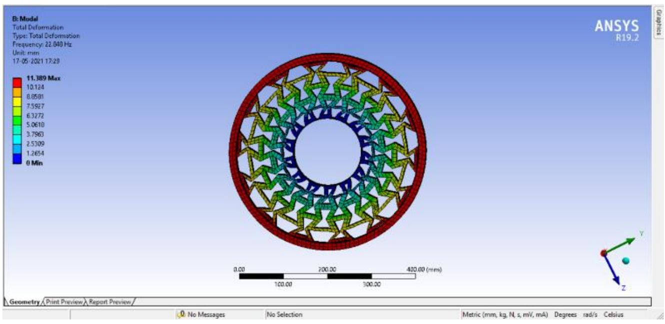


*Figure 4. 5 Mode Shape 1*

## TOTAL DEFORMATION FOR MODE SHAPE 2:

The maximum deformation here is 0.016633 m.
The operating frequency of second mode shape is 58.48 hz.
This is well below the Natural frequency of our model.

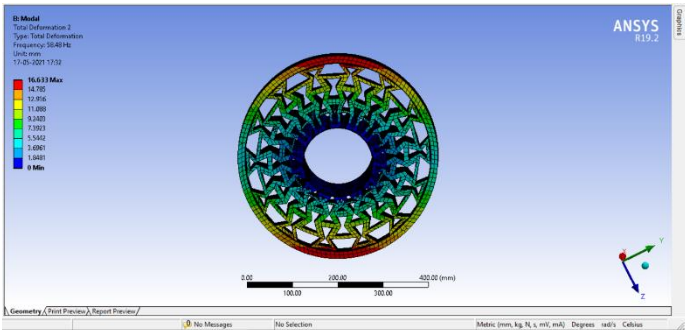


*Figure 4. 6 Mode Shape 2*

## TOTAL DEFORMATION FOR MODE SHAPE 3:

The maximum deformation here is 0.016623 m.
The operating frequency of third mode shape is 58.589 hz.
This is well below the Natural frequency of our model.

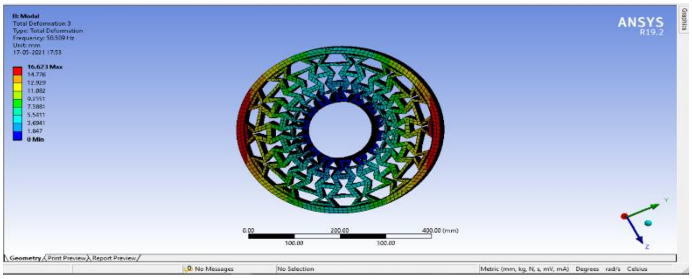


*Figure 4. 7 Mode Shape 3*

## TOTAL DEFORMATION FOR MODE SHAPE 4:

The maximum deformation here is 0.010567 m.
The operating frequency of fourth mode shape is 72.922 hz.
This is well below the Natural frequency of our model.

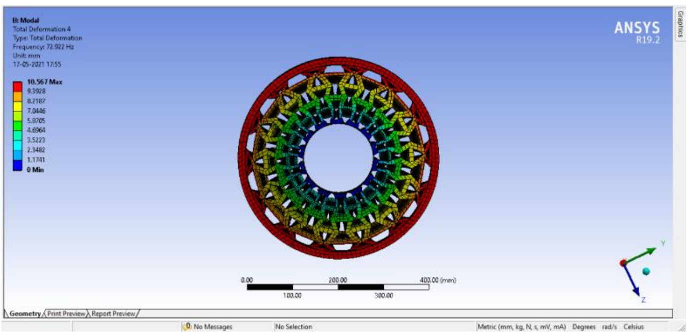


*Figure 4. 8 Mode Shape 4*

| S.no | Type | Result |
|---|---|---|
| **1** | Total Deformation | 0.00178 m |
| **2** | Von-Mises Stress | 108750000 pa |
| **3** | Von-mises Strain | 0.11192 |
| **4** | Maximum Principal Stress | 115540000 pa |

*Table 4. 1 Results*

We can observe from the results above that even in the dynamic analysis the model is performing quite well. The operating frequencies are well below the natural frequency of the body which indicates that resonance will not occur. In the absence of resonance, the product will not be damaged and thus the design is satisfactory. Thus, we can conclude that even under Dynamic Loading the model performs well and hence the product's design is satisfactory.

## 5. CONCLUSIONS

The following can be concluded from the examinations done above:

1. From the results obtained in Static Analysis , we can observe that the Maximum Principal Stress is way below the Yield point of Polyurethane used in the spokes, which implies that the structure will not undergo damage or permanent deformation. Thus, we can safely conclude that the Structure functions well, as it has produced satisfactory results. Similarly, the Modal analysis also indicates that the model performs well as the results obtained are satisfactory.

2. Thus, we can conclude that, from the standpoint of Static and Modal Analysis, this Non-Pneumatic Tyre with Re-entrant type Auxetic Structured spokes can be utilized in Cessna 172 aircraft.

3. However, further testing, including the fatigue analysis among many, and the experimentation with the prototype is essential.

## 6. RFERENCES

[1] Jaehyung Jua, Doo-Man Kimb and Kwangwon Kimb , " Flexible cellular solid spokes of a non-pneumatic tire Compo Struct," 94 2285–2295, 2012.

[2] Xiaochao Jin, Cheng Hou, Xueling Fan, Yongle Sun, Jinan Lv and Chunsheng Lu, " Investigation on the static and dynamic behaviors of non-pneumatic tires with honeycomb spokes," Composite Structures,2019.

[3] Aravind Mohan, C Ajith Johny, A Tamilarasu, J Pradeep Bhasker and K Ravi, " Design and analysis of non-pneumatic tyre," : Materials Science and Engineering 263 (2017)

[4] Mohammad Fazelpour and Joshua D. Summers, "EVOLUTION OF MESO-STRUCTURES FOR NON-PNEUMATIC TIRE DEVELOPMENT,": A CASE STUDY ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2014 August 17-20, 2014.

[5] Taoyu Wu, Mingxuan Li, Xiaolei Zhu & Xiaofeng Lu, " Research on non-pneumatic tire with gradient anti-tetrachiral structures," 2020.

[6] A.M. Aboul-Yazid1 , M.A.A. Emam1 , S. Shaaban1 and M.A. El-Nashar1, "EFFECT OF SPOKES STRUCTURES ON CHARACTERISTICS PERFORMANCE OF NON-PNEUMATIC TIRES, "International Journal of Automotive and Mechanical Engineering (IJAME), ; Volume 11, pp. 2212-2223, June- 2015

[7] Kim K, Ju J and Kim D., "Static contact behaviors of a non-pneumatic tire with hexagonal lattice spokes," SAE Int J Passing Cars - Mech Syst 2013; 6(3):1518−1527.

[8] Raj Abhishek, Anoop Kumar , Non-Pneumatic Tyre design with Honeycomb spoke structure, IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 7 Issue 6, June 2020

[9] Libin Rajan, Shobith Nambiar, C. Ayyanar, Akash Verma and S. Subhash Raj, "Design and Comparative Analysis of Non-Pneumatic Tires for a Tractor", International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-8 Issue-7 May 2019.

[10] Pranav A. Rangdale , Kumar R. Chandak , Prof. Ganesh M. Bagade, "NON-PNEUMATIC TYRE ,"International Journal of Engineering Sciences & Research Technology, ISSN: 2277-9655.

[11] Umesh G C , Amith Kumar S N, " Design and Analysis of Non-Pneumatic Tyre (NPT) With Honeycomb Spokes Structure" IJESC, ISSN: 2321 3361 , Volume 6 , Issue 9

[12] Kwark BM, Yoo EJ, Sung YH, Jang IG. Pattern design of non-pneumatic tire for stiffness using topology optimization. In: Proceedings of the ASME international design engineering technical conferences, DETC2009-86068, San Diego, CA; 2009.

[13] Rhyne T, Cron SM, "Development of a non-pneumatic wheel, "Tire Sci Technol 2006; 34:150–169.

[14] Modeling and analysis of non-pneumatic tyres with different design structures using fem method by K. TARAKARAM, Dr. K. RAMBABU, D. PHANINDRA VARMA, IJSDR, ISSN: 2455-2631, Volume 4, Issue 1, January 2019

[15] Kanyanta V, Ivankovic A. Mechanical characterization of polyurethane elastomer for biomedical applications. J Mech Behav Biomed Mater 2010;3: 51–62.