DESIGN AND EXPERIMENTAL INVESTIGATION OF THE RIGIDITY OF A NEW GENERATION, NON-PNEUMATIC TIRE FOR AIRCRAFTS[1]

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Abstract: Conventional pneumatic tires (PT) involve several operational limitations including maintenance requirements, bursting, and sudden pressure loss due to their dependence on internal air pressure. To overcome these limitations, a new-generation non-pneumatic tire (NPT) for use in aircraft nose landing gear was designed, manufactured and its mechanical performance was evaluated experimentally in this study. In addition to, a conventional PT was subjected to test as well. An NPT concept was investigated adopting a biomimetic design approach. The spoke structure of the tire was parametrically designed based on Fibonacci curves, which provide geometric continuity and efficient load transfer characteristics. The geometry was specifically designed to control deformation behavior under vertical loading conditions and enhance structural rigidity. The designed NPT was manufactured using a 3D printer from TPU material due to its advanced elastic properties, energy damping capacity, and suitability for additive manufacturing. Prior to experimental testing, a reference aircraft was selected and vertical loads acting on the nose landing gear during taxiing and landing were calculated. These calculated loads were applied in a controlled manner during the vertical stiffness test, and load–displacement data were obtained. For comparative evaluation, the same experimental procedure and test conditions were applied to a conventional PT commonly used in aviation, which has same external geometrical dimensions and material properties. As a result of the experiments, the NPT exhibited the vertical displacement of 24.5 mm under a 2500 kg load, while the PT exhibited the displacement of 32.4 mm under the same load. This outcome indicates improved load-carrying capability, enhanced structural stability, and potential operational reliability advantages. Overall, the findings confirm that NPTs represent a feasible alternative for future aircraft landing gear.

Keywords: Non-Pneumatic Tire, Fibonacci Curve, Aircraft Nose Landing Gear, Additive Manufacturing, Vertical Stiffness, Experiment

INTRODUCTION

Aircraft landing gear systems as one of the critical subsystems of an aircraft are responsible for safely supporting and attenuating the loads acting on the aircraft during take-off, landing, and taxiing phases. Since the wheel has direct contact with both the road and the vehicle systems, it is one of the most important components of the landing gear system. Wheels have a direct impact on flight safety and operational performance, as they perform essential functions such as load carrying, energy absorption, providing road grip, and preventing vibrations caused by surface irregularities (Delprete et al., 2023).

Today, pneumatic tires are widely used in various industries due to the distinct advantages that they offer when used with solid rims. These advantages include increased energy efficiency on uneven surfaces, improved driving comfort, reduced minimum ground contact pressure, and a relatively lightweight structural design. However, pneumatic tires exhibit distinct structural characteristics as a result of complex and high-precision manufacturing processes. These structural characteristics of traditional pneumatic tires can lead to safety risks such as bursting or sudden air loss, especially under heavy and demanding operational conditions; this situation can significantly limit the vehicle's mobility and reliability (Sardinha et al., 2023). Statistical data shows that approximately 70% of road traffic accidents are caused by tire pressure loss. It has been reported that, especially when vehicle speeds exceed 160 km/h, the fatality rate of

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accidents caused by tire air loss reaches nearly 100% (Martin & Laumon, 2005). Similarly, the research conducted in the aviation sector reveals that at least 20% of accidents that occur each year are caused by tire bursts (Wang et al., 2021).

As expectations for safety, driving stability, and comfort increase today, the requirements for tire performance are also constantly increasing. Therefore, the development of tires that are resistant to high speeds, safe, and long-lasting is among the primary goals of both scientific research and industrial production processes. In recent years, research on non-pneumatic tires (NPTs) has increased in order to overcome the limitations of traditional pneumatic tires. NPTs minimize safety issues such as blowouts or sudden air loss due to their structural design, which eliminates risks associated with air pressure. Additionally, these tires offer environmental and operational advantages such as low maintenance requirements, long service life, use of recyclable materials, and energy efficiency. These features are driving increasing interest in NPTs as an alternative solution in both the road transportation and aviation sectors (Sun et al., 2024).

The development of non-pneumatic tires began with the flexible tire design patented by Papadopoulos in 1914. In this design, springs were used instead of air inside the rubber tire to develop an alternative load-bearing mechanism (Papadopoulos, 1914). Following this initiative, research on airless tire systems that did not require internal pressure has gradually increased.

In 1973, Dunlop developed a puncture-resistant wheel/tire system that allows the vehicle to move safely even in the event of air pressure loss, producing the first commercially available run-flat tire (Dunlop Tires, n.d.). Led by this innovative design, research into non-pneumatic tires gained momentum in areas with demanding operational conditions, such as industrial, agricultural, construction, military, medical, space, and exploration technologies, and today they are used effectively and reliably in these sectors.

For NPTs, vertical stiffness behavior is the main characteristic. When they are designing, the vertical stiffness value should be defined. High vertical stiffness value means high load carrying capacity of tire. With this concern, some researches focus on vertical stiffness characteristics of NPTs.

Rugsaj & Suvanjumrat (2020) examined the vertical stiffness value of the Michelin Tweel non-pneumatic tire using a tire testing machine. During the experiment, loads of 4, 16, 18, 20, and 22 kN were applied to the tire in five different positions. As a result of the test, the vertical stiffness value obtained using force-displacement data remained constant under different loads and was calculated as 869.93 N/mm. Additionally, the vertical stiffness values of pneumatic tires of the same size were calculated using the Rhyne equation given in (1). The comparative results obtained revealed that non-pneumatic tires exhibited higher vertical stiffness compared to pneumatic tires (Rugsaj & Suvanjumrat, 2020).

$$K = 0.00028P\sqrt{WxOD} + 3.45 \quad (1)$$

where, K = the vertical stiffness; P = the inflation pressure; W = footprint width; and OD = the overall diameter.

Sim et al. (2021) designed an alternative model based on a commercial NPT reference with three different spoke configurations: the fillet-applied model, the asymmetric-spoke division model, and the symmetric-spoke division model. These models were analyzed under vertical load using ANSYS finite element software. The analysis results showed that the fillet-applied model had the least deformation and the highest vertical stiffness. Furthermore, it was reported that adding a minimum fillet to the spokes increased the vertical stiffness performance of the NPTs (Sim et al., 2021).

Rugsaj & Suvanjumrat (2023) designed a non-pneumatic tire with an X-shaped rim spoke structure for harsh construction site conditions. In the study, analyses using a finite element

model investigated the effects of spoke number and thickness on the tire's vertical stiffness and stress distribution. The results showed that increasing the number of spokes increased stiffness and improved load distribution, while a low number of spokes increased local stress and reduced load capacity. Furthermore, a decrease in spoke thickness caused deformation and bending, leading to high stress values applications (Rugsaj & Suvanjumrat, 2023).

Vashi et al. (2021) developed non-pneumatic wheels using PLA material to reduce weight in Category 1 and 2 unmanned aerial vehicles. In the study, three different configurations with 4, 5, and 6 spokes were designed using PLA material, and static and dynamic strength analyses in the radial direction were performed using Ansys software. The analysis showed that the 4-spoke design exhibited the highest deformation and stress values, while the 6-spoke design exhibited the lowest deformation and stress values. As a result, the 6-spoke model was determined to be the most suitable configuration (Vashi et al., 2021).

Sharma et al. (2021) designed NPT with re-entrant type auxetic structured spokes of the same size as the Cessna 172 tire to investigate the applicability of non-pneumatic tires in aircraft. The wheel consisted of four components: an aluminum hub, polyurethane spokes, a steel cutting band, and a rubber tread. Static analyses were performed by applying the maximum load capacity of the Cessna 172 tire as the vertical load and the aircraft's nominal speed as the rotational speed. Additionally, modal analysis was conducted to determine the tire's natural frequency values and associated mode shapes. The static analysis results showed that the maximum stress values of the design remained below the yield limit (Sharma et al., 2021).

Zhang et al. (2021) developed a flexible-arm bionic NPT model in 195/50R16 dimensions, inspired by the lower leg structure of a kangaroo, to establish a reference for research methods and improvement strategies in NPT design. After the created radial stiffness model was tested and validated, the radial, lateral, and longitudinal stiffness values obtained under different loads in the analysis, along with ground pressure values, were compared to those of a pneumatic tire of the same size. The results obtained demonstrate that NPT exhibits superior performance compared to traditional pneumatic tires (Zhang et al., 2021).

In this study, a new generation non-pneumatic tire was designed based on the Fibonacci curve for aircraft applications. The designed structure was produced using 3D printing technology with TPU (Thermoplastic Polyurethane) material. The mechanical behavior of the non-pneumatic tire was experimentally investigated performing compression test. For comparison purposes, the same test procedure was applied to a pneumatic tire having the same geometrical dimensions which is currently used in aircrafts.

DESIGN METHODOLOGY

The non-pneumatic wheel designed in this study was sized based on the 11×4.00-5 pneumatic wheel (Figure 1(a)) commonly used in unmanned aerial vehicles, in line with the comparable performance target. This ensured mounting compatibility and functional comparability. The reference wheel has an outer diameter of 280 mm, an inner diameter of 127 mm, and a thickness of 100 mm. The design process was carried out using Siemens NX software, and effective dimensional optimization was achieved through controlled design changes using a parametric modeling approach.

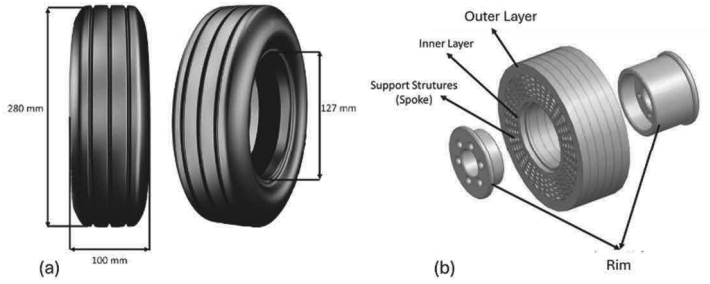

Figure 1. (a) 11×4.00-5 Pneumatic Tire, and (b) the Components of Non-Pneumatic Tire

The non-pneumatic wheel shown in Figure 1(b) consists of four basic components: the rim, the inner layer, the support structure, and the outer layer.

The rim is designed to be compatible with existing pneumatic tire sizes and to provide the necessary rigidity; it is modeled in two parts for ease of assembly. The size and position of the mounting holes are determined to be compatible with the test rig.

The inner layer is the structure that enables load transfer between the rim and the support structure. This layer ensures both structural integrity and balances the overall deformation behavior of the tire.

The support structure (Spoke), which is the most distinctive component of the non-pneumatic tire, has been designed based on the Fibonacci spiral geometry shown in Figure 2(a), instead of the air pressure found in traditional pneumatic tires. This spiral form provides a more homogeneous load distribution in the radial direction, reducing stress concentrations and improving the tire's flexibility performance. The CAD-modeled spoke geometry is shown in Figure 2(b).

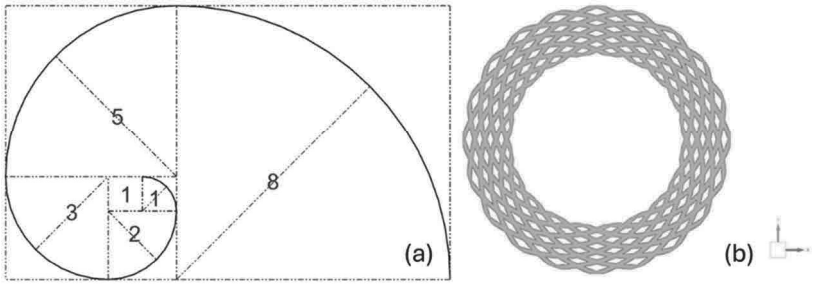

Figure 2. (a) Fibonnacci Spiral, (b) Support Structure of the NPT Based on Fibonacci Spiral

The outer layer in contact with the road is designed according to the base width and outer diameter of the reference pneumatic tire. Since the outer layer is in contact with the road, its structure determines friction, road grip, and wear performance. However, due to the prototype considered in this work, the tire has been designed as flat without a tire tread pattern. This has simplified the production and analysis processes and allowed for a focus on the mechanical behavior of the non-pneumatic tire.

3D PRINTING PROCESS AND PARAMETERS

The wheel rim is manufactured from Al 7075-T6 block material using a machining method on a lathe. The non-pneumatic wheel designed for this project was manufactured from TPU (thermoplastic polyurethane) material using the fused deposition modeling (FDM) technique, one of the additive manufacturing methods. TPU was preferred due to its properties suitable for NPT, such as flexibility, impact resistance, and compatibility with additive manufacturing. The FDM method based on the principle of melting thermoplastic filaments and depositing them in layers, was preferred for its accessibility, low cost, rapid prototyping, and ability to produce complex geometries.

The FLSUN V400 model FDM-type 3D printer, shown in Figure 3, was used in the production process. This 3D printer has a print volume of 300 mm in diameter and 410 mm in height. It can also print with a layer thickness range of 0.05–0.30 mm and a nozzle diameter of 0.4 mm. The device has the capability to produce with various thermoplastic materials, including TPU.



Figure 3. FLSUN V400 3D Printer

The prints were made using eSUN brand TPU filament with a diameter of 1.75 mm. The print temperature was optimized according to the manufacturer's recommendations, and the best results were obtained at 230 °C. The bed temperature was tested in the range of 45–60 °C, and optimal adhesion was observed at 60 °C. Additional adhesive was applied to the bed surface during the printing process. All print parameters were adjusted using Ultimaker Cura software, and production was carried out under these conditions.

To minimize the use of supports and to easily remove the supports from the structure after production, the printing direction was selected as the XY axis with the wheel width as the Z axis. A 45/-45 raster angle, 0.2-layer height, and 100% infill density were used in prototype production.

To eliminate the risk of high material loss due to potential errors caused by the long printing time, the NPT was manufactured from six interlocking parts, like Lego pieces, and then assembled as shown in Figure 4.



Figure 4. The Printed Parts of NPT

EXPERIMENTAL METHODS

Load Calculation

Prior to testing, the loads acting on the nose landing gear during the operation of the aircraft have been calculated. Zenair STOLL CH 701 whose weight data is given in Table 1, have been used as a reference for the load calculation due to the availability of its flight manual.

Table 1. The Weights for the ZENAIR STOL CH 701 (Zenair, 1999)

Type	Weight (kg)
Empty Weight	260
Maximum Take-off Weight	450
Maximum Landing Weight	450

The loads acting on the nose landing gear have been calculated using formulas provided in CS-23(European Union Aviation Safety Agency, 2018). The results of the landing gear load calculations performed for the requirements defined in CS-23 are given in Table 2.

Table 2. The Force Values Calculated by Formulas in CS 23

Conditions	Type	Force (kg)	Force (1.5) (kg)
Level Landing (CS 23.1)	Vertical Force	425.74	638.61
	Drag Force	136.84	205.26
Spin Up (D23.1)	Vertical Force	662.8	994.2
	Horizontal Force	289.93	434.895
Braked Roll (CS 23.493)	Nose	308.04	462.06
	Drag Force	230.54	345.81
Supplementary (CS 23.499)	(a)(1) Vertical Force	221.11	331.665
	(a)(2) Drag Force	176.89	265.335
	(b)(1) Vertical Force	221.11	331.665
	(b)(2) Forward Force	88.44	132.66
	(c)(1) Vertical Force	221.11	331.665
	(c)(2) Side Force	154.78	232.17
Towing Loads (CS 23.509)	(5), (6)	187.64	281.46
	(9), (10)	141.98	212.97

Vertical Stiffness Test

The test rig used for the vertical stiffness test of the tire is shown in Figure 5. This test rig structure consists of (1) carcass structure, (2) hydraulic unit, (3) concrete block, (4) slide frame, (5) fork frame, (6) radial load piston, (7) lateral load piston, (8) radial linear scale, and (8) lateral linear scale. The maximum capacity of the test mechanism's radial piston is 20,000 kg, and the total error rate is ±0.2%.

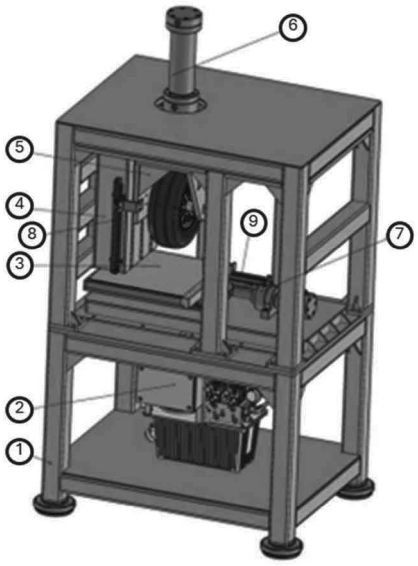

Figure 5. Static Test Unit Structure Diagram

First, it was mounted on the developed non-pneumatic tire test device. Then, force was gradually applied to the tire in the vertical direction. Displacement values were also obtained using a radial linear scale and reported.

Next, a pneumatic tire with 180 psi air pressure and the same dimensions as the NPT was mounted on the test rig. During the test, the same procedure was applied to the pneumatic tire as to the non-pneumatic tire.

The final condition of the tires after the test is shown in Figure 6, and the force-displacement curves are shown in Figure 8.

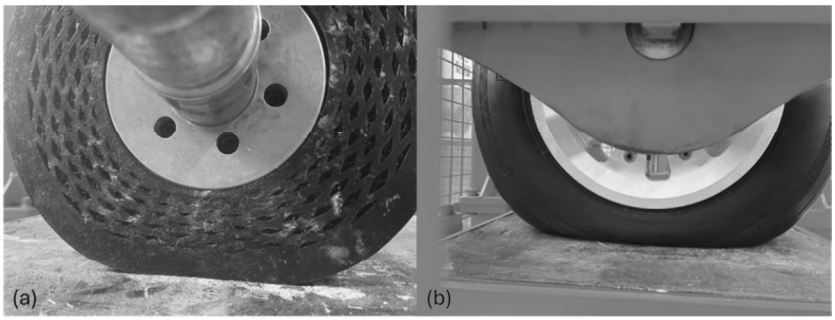

Figure 6. The Final State of (a) Non-Pneumatic Tire and (b) Pneumatic Tire in the Test

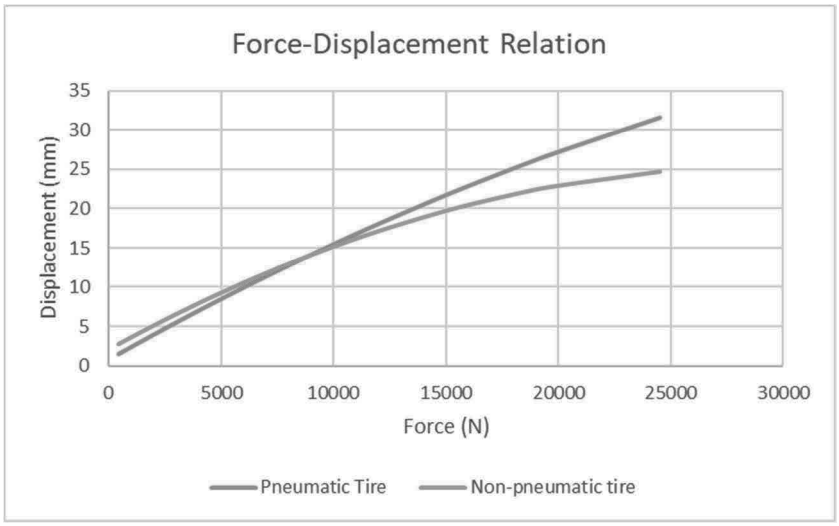

Figure 7. Force-Displacement Results

CONCLUSION

In this study, a non-pneumatic tire was designed to eliminate the periodic maintenance requirements and various operational limitations of traditional pneumatic tires, such as bursting and sudden pressure loss. The non-pneumatic aircraft tire, designed based on Fibonacci curves, was manufactured using the FDM method with TPU material, and its vertical stiffness behavior was experimentally investigated. Comparative vertical load tests conducted with a traditional pneumatic wheel of the same external dimensions revealed that under a 2500 kg load, the non-pneumatic wheel exhibited 24.5 mm vertical displacement, while the pneumatic wheel exhibited 32.4 mm. The test results obtained reveal that the designed non-pneumatic tire exhibited lower vertical deformation and higher vertical stiffness under the same test conditions. These findings indicate that the proposed design could serve as a reference for evaluating vertical load-carrying behavior in aircraft tire applications. In future studies, a numerical analysis model will be developed for the non-pneumatic tire, and lateral and longitudinal loading conditions as well as hard landing scenarios will be investigated.

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