Experimental investigation of a 3D-printed Airless tire for vibration analysis

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***Abstract*—The research presented here looks into the vibration properties of 3D-printed airless tires, which have the potential to revolutionize tire design and transportation efficiency. Through extensive experimentation and vibration research, three distinct tire constructions were investigated. Because of its good damping and deformation qualities, thermoplastic polyurethane (TPU) was chosen as the 3D printing material. The experimental arrangement was designed to simulate real-world road conditions, and an MPU6050 sensor captured tire vibrations in three axes. The vibrational properties of the tire structures were revealed using Fast Fourier Transform (FFT) analysis, allowing for a comparative assessment of their stability. Structure 1 was found to be the most vibration-stable, followed by Structures 3 and 2.**

Keywords—3D Printing, Airless tire, TPU material, FFT analysis, Tire Structure.

I. Introduction

Advances in additive manufacturing technology have resulted in astounding improvements in a variety of industries in recent years. One such discovery is the creation of 3D-printed airless tires, which have the potential to revolutionize transportation and mobility. These tires, which lack the traditional air-filled structure, promise increased durability, lower maintenance, and higher safety. The current study begins with a thorough experimental investigation of the unique 3D-printed

airless tire, focusing on its vibration characteristics, a critical factor that directly affects ride comfort, vehicle stability, and overall performance.

The primary goal of this research is to investigate the vibration qualities of a 3D-printed airless tire in depth. This study seeks to reveal the tire's dynamic behavior under varied operational situations through thorough experimental investigation. Understanding the vibration characteristics in depth can provide useful insights into optimizing the design and performance of these unique tires.

The demand for sustainable and effective transport solutions is driving the selection of this research topic. Traditional air-filled tires are prone to punctures, pressure changes, and deterioration over time, demanding frequent maintenance. The introduction of 3D-printed airless tires have the ability to address these issues and reshape the future of tire technology. This study seeks to help the development of these revolutionary tires by thoroughly investigating the patterns of vibration.

The findings of this study have great promise for both society and industry. For starters, a better understanding of the vibration characteristics of 3D-printed airless tires can lead to the development of tires that provide passengers with a more comfortable ride. Furthermore, because of the reduced maintenance requirements and greater durability of these tires, vehicle owners and fleet operators can save money. Furthermore, the automotive and additive manufacturing industries can profit from the findings, allowing for the improvement of tire designs and manufacturing methods.

This study's overarching goal is to perform a complete and comprehensive experimental analysis of the vibration qualities of a unique 3D-printed airless tire. This goal is pursued through a set of particular objectives designed to provide light on the dynamic behavior of these novel tires under a variety of operational conditions. To begin, the study intends to thoroughly examine the vibration

characteristics of the 3D-printed airless tire, taking into account aspects such as frequency, amplitude, and damping. Second, the study examines how various operational parameters, such as varying speeds and road surfaces, affect the tire's vibration response. This investigation will yield vital data on the tire's adaptability in a variety of usage conditions. Finally, the research aims to transfer the findings into prospective design improvements that can improve the overall performance and riding comfort of the tire. The project intends to contribute significantly to the growing environment of tire technology and its potential impact on transportation efficiency, user experience, and industry improvements through these objectives.

The transformational potential of 3D-printed airless tires motivated the selection of this study topic. The possibility of revolutionizing a critical component of modern transportation is extremely appealing. The opportunity to contribute to the evolution of sustainable and efficient mobility solutions is driving this research.

The research's originality stems from its examination of cutting-edge technology - 3D-printed airless tires - via the lens of vibration analysis. While earlier research has mostly focused on the mechanical and material features of these tires, this study aims to bridge a major knowledge vacuum by shedding light on their dynamic behavior.

Finally, this study aims to give a thorough examination of the vibration characteristics of 3D-printed airless tires. This research intends to contribute to the development of more pleasant, durable, and efficient tire solutions for the future of transportation by better understanding their dynamic behavior.

II. Literature Review

The potential of 3D printing technology to support sustainable manufacturing methods is covered by Embia, G., et al. [1]. The chapter examines the many industrial uses of 3D printing while emphasizing how technology can cut down on waste, energy use, and environmental effects. This reference adds to the continuing conversation on sustainability in the industrial sector by offering insights into the incorporation of 3D printing into contemporary manufacturing processes.

Arya, R.K.K., et al. [2]. (2023) explore how 3D printing technology is revolutionizing the pharmaceutical industry. The chapter looks at how 3D printing is being used in the production of medical devices, personalized medicine, and drug formulation. This source provides insightful information on the changing field of pharmaceutical manufacture by examining the possible advantages and difficulties of using 3D printing.

In the framework of Industry 4.0, Argade, N.U. et al.[2]. (2023) examine the effects of 3D printing on the Micro, Small, and Medium Enterprises (MSME) sector in India. The chapter examines the ways in which 3D printing technology might support industrial development and economic progress by helping Indian MSMEs become more innovative, productive, and competitive. This reference provides insightful information for policymakers, industry players, and researchers interested in promoting technical advancement and entrepreneurship in India's MSME sector by outlining the advantages and disadvantages of adopting 3D printing in the Indian context.

J.M. Jafferson et. al [4] explored a detailed examination of advancements in the area of airless tires in this study, with a special emphasis on the imaginative designs used to engineer energy-absorbing holes in the next generation of non-pneumatic tires. Notably, the incorporation of lattice structures stands out as a transformative strategy, promising structural weight reduction while also improving tire performance. The research involves the development and testing of airless tires with twelve separate Volume lattice structures, sixteen distinct Triple poly minimal surfaces (TPMS) lattices, and hybrid TPMS configurations, all created using NTopology. A detailed investigation was carried out to gather more insights, comparing weight and material cost factors, with a specific focus on the use of TPU material offered by BigRep. This work not only provides a thorough review of alternative design approaches but also acts as a useful guide for users looking for an easy way to design energy-absorbing core structures within airless tires using NTopology.

This study, written by Kim et. al[5], investigates the inherent advantages of non-pneumatic tires (NPTs) over regular pneumatic tires. Notably, NPTs have a flat-proof operation and do not require air-pressure maintenance. The study examines the static contact behavior of NPTs with hexagonal honeycombs and their relevance to vertical loading. The research studies contact pressure and local deformation of cellular spokes in NPTs using a finite element-based numerical simulation in ABAQUS. The results show that, even with equal load-bearing capacity, NPTs have lower contact pressure due to lower spoke stiffness. Furthermore, NPTs with hexagonal lattice spokes with a larger cell angle show lower local cell wall stress, highlighting the benefits of their flexible honeycomb characteristic, especially under uni-axial compression.

The research proposes two unique design approaches for non-pneumatic tires (NPTs) including a compliant cellular solid spoke component in this study undertaken by Fanhao Meng et. al[6]. The research investigates the degrees of freedom (DOFs) and stiffness of NPTs with cellular architectures under identical vertical loading circumstances using ANSYS as the primary finite element analysis tool. A key discovery demonstrates that the tread has only in-plane translational DOF in the radial direction, excluding all other DOFs. Using enhanced and synthetic design approaches founded on compliant processes, the research presents two distinct cellular structures:

(i) cross arcs cell and (ii) rectangle cell. The examination of geometric parameters' influence on NPT performance is a critical aspect of this investigation, paving the way for improved NPT performance by optimization of cellular structure geometries.

This research dives into the critical field of non-pneumatic tire (NPT) development, where honeycomb spokes are widely used. The choice of finite element (FE) modeling approach can drastically affect outcomes and stymie development, according to Otis Wyatt et. al[7]. To fill this information vacuum, the study investigates the best FE type for different dimensions of honeycomb NPT spokes. Compression testing was carried out using 3D-printed NPT segments with varied spoke thickness-to-height ratios. According to the study, 3D shell components are the best choice for ratios of 1/18 or smaller, whereas ratios of 1/12 or greater favor 2D plane elements (quadrilaterals and triangles) for accurate forecasts.

This research, led by T. Prabhuram et. al[8], investigates airless tires, which differ from standard pneumatic tires, which frequently suffer from punctures and flats due to wear and tear. The study intends to do a static analysis of these airless tires utilizing different 3D printing materials and spoke structures such as honeycomb, triangular, and diamond. Acrylonitrile Butadiene Styrene + Polycarbonate (ABS+PC), Polyethylene Terephthalate (PET), and High Impact Polystyrene (HIPS) are among the materials under consideration. The analysis was performed using ANSYS Workbench 19.2, which compares factors such as total deformation, equivalent elastic strain, equivalent von Mises stress, and strain energy between conventional and airless tire models.

This study, led by Kim et. al[9], investigates the advantages of non-pneumatic tires (NPTs) as a flat-proof, maintenance-free alternative to traditional pneumatic tires. The study compares the static contact pressure of NPTs with hexagonal honeycomb spokes to pneumatic tires under varied vertical loads. Using ABAQUS finite element numerical simulations, the researchers discovered that NPTs have lower contact pressures due to their higher lateral spoke stiffness when built for similar load-bearing capacity. Furthermore, some spoke designs, such as Type A, exhibit

extremely low contact pressures, whilst Type C spokes exhibit reduced local stress within the spoke cell struts, demonstrating the structural flexibility of NPTs under uni-axial compression.

Tweel-2 and Saddle, two new non-pneumatic tire designs inspired by the commercial Tweel model, are introduced in this paper by Liu et. al[10]. Four tire samples were evaluated via 3D printing, yielding amazing results. With the relative density being the same, Tweel-2 displayed 1.4 times the vertical bearing capacity of the Tweel model. While the Saddle tire exceeded the vertical bearing capacities four times that of the Tweel model and 2.4 times that of honeycomb tires. Finite element simulations revealed that the Tweel-2's circumferential unit improves spoke coordination, thereby optimizing energy absorption, whereas the Saddle tire's hyperbolic paraboloid configuration optimizes stress distribution, allowing more material to contribute to energy absorption, thereby improving overall strain energy levels in the spokes.

A unique approach for characterizing the deformation process of regularly organized cellular materials created using Fused Deposition Modelling with ABSplus material is provided in this paper by Kucewicz et. al[11]. The study investigates two separate topologies with identical relative densities that are compressed at different deformation velocities ranging from quasi-static to dynamic settings. Notably, the study delves into these topologies' energy absorption capabilities. Prior to that, the mechanical properties of 3D printed material samples were rigorously evaluated and mathematically connected with experimental data at various strain rates. The study successfully obtained strong alignment between experimental and numerical findings across all loading conditions by using an elastic-viscoplastic constitutive model with Cowper-Symonds hardening parameters computed by a MATLAB authorial script.

A detailed approach for characterizing the deformation of regular cellular structures under static stresses is outlined in Kucewicz et. al[12] paper. Fused Deposition Modelling with ABSplus material was utilized to create three topologies with equal relative densities. The investigation begins with analyzing material properties and numerically connecting them with experimental results. The findings of experimental compression testing were closely aligned with finite element analyses, comprising deformation, failure, and force characteristics. Mesh sensitivity and various discrete model aspects were taken into account. Notably, the work focuses on energy-absorption properties, investigating them both with and without the erosion criterion for modeling material failure.

The research of Daman Pak et. al[13] focuses on the mechanical properties of 3D-printed lattice-based airless tires, particularly during significant deformations. These hexagonal lattice-patterned tires are subjected to experimental tests to determine the effect of geometric factors and lattice kinds on radial reactions. A finite-strain beam element is also created to model their behavior under various loading circumstances. This study gives useful information for optimizing and constructing complicated lattice-based airless tires.

Montanini et. al[14] paper addresses the present goal of researching the structural response of lattice components made using additive manufacturing (AM). The goal is to make 3D-printed items more competitive with traditional methods of production. The researchers used digital image correlation (DIC) and thermoelastic stress analysis (TSA) to assess full-field strain and stress on 3D-printed airless wheel prototypes. These prototypes are made with a variety of printing processes (FDM and SLA) and materials (photopolymer resin and PLA). In addition, a parametric finite element model is created to compare numerical findings with experimental results, establishing the framework for lattice morphology topological optimization.

The research of Rugsaj et. al[15] focuses on the spokes of airless tires, which are normally made of highly elastic thermoplastic polyurethane (TPU) to replace traditional inflation. Due to restrictions in traditional production processes, developing complicated spoke shapes is a difficulty. However, advances in 3D printing provide a solution, allowing for intricate constructions made of a variety of materials. This study investigates the mechanical properties of TPU under various 3D printing circumstances. Tensile tests compare specimens from actual NPT spokes to 3D printed counterparts, allowing researchers to investigate the effect of strain rate on

mechanical qualities. The findings show that 3D printing can be used to create NPT spokes, particularly with materials like TPU.

Dennise Mathew et. al[16] work on smart industry technology using AI techniques. In this research Neural Networks, Deep Learning, and Reinforcement Learning were used as tools to design intelligent machines. It was found that using the above tool in the paradigm of Industry 4.0 may enhance man-machine interaction with more automation, which results in enhancement in the economy. To continue the study of Industry 4.0 Deepak Kumar et. al[17] did a study on the pharmaceutical sector. In this study, 3D printing is used as a smart tool to enhance manufacturing in the pharmaceutical industry. It was found that introducing 3D printing technology in this sector can help manufacture prosthetics, implants, artificial tissue, and organs. This boosts the economy and reduces manufacturing costs. To explore more about 3D printing in manufacturing Nidhi U. Argade et. al[18], studied the MSME sector. The different sectors for the study were considered, which are Public, automotive, electronics, etc. In this study, a theoretical background of 3D Prinitng was created by considering parameters like material, and process at the time of COVID-19. It was found that zero effect and zero defect goals can be achieved using Additive manufacturing.

III. Methodology

Thermoplastic Polyurethane (TPU) was chosen as the 3D printing material because of its good damping and deformation capabilities. The benefits of TPU, like flexibility and wear resistance, make it an excellent choice. Following that, three distinct tire structures are thoroughly modeled using Fusion 360 software, based on the study literature. To enable 3D printing, these 3D models are transformed into Stereolithography (SLA) file format. The three selected tire structures are individually produced into physical prototypes using Fused Deposition Additive (FDA) 3D printing technology. These 3D-printed airless tire prototypes, depicted in Figure 1 are the topic of extensive experimental testing, which includes vibration analysis.

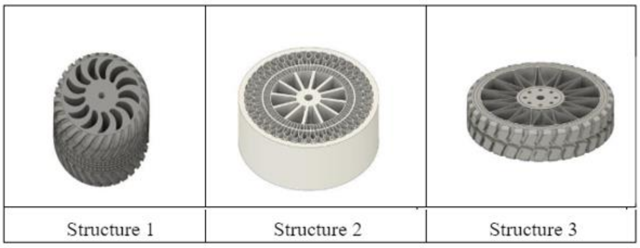

Figure 1 shows Various types of Airless tire Structure

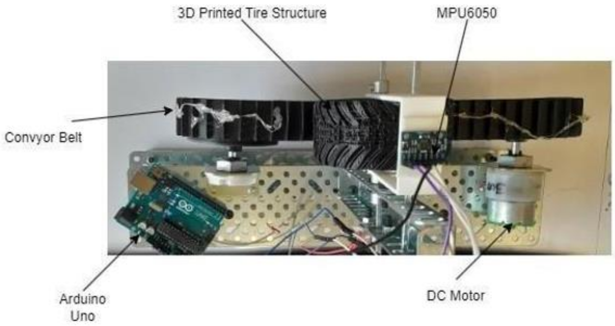

Figure 2 shows an Experimental Setup for Airless tire testing

The testing approach for the 3D-printed airless tire is based on a meticulously planned setup, as shown in Figure 2. This setup seeks to imitate real-world road conditions for thorough study. It has a sturdy steel chassis attached to a conveyor belt, which is connected to a DC motor. The operation begins by turning on the DC motor, moving the conveyor belt, and starting the tire rotation. When attached to a vehicle's chassis and propelled, this system roughly resembles the behavior of an airless tire. A smaller chassis is put atop this tire configuration, housing an MPU 6050 sensor that is tightly coupled to an Arduino Uno microcontroller.

The Arduino Uno is designed to continually record and store acceleration data in three axes relative to time: x, y, and z. This data records the intricate movements and vibrations felt by the tire setup during its rotation cycle. As the motor turns on the conveyor belt, the tire begins to rotate, causing movements that the MPU 6050 sensor detects and records. These movements are measured in terms of acceleration and provide important information for further investigation.

Following that, the collected acceleration data is thoroughly analyzed. This study aims to assess the vibration characteristics of various 3D-printed tire structures. This methodology provides a robust framework for analyzing and comparing the vibration resistance characteristics of various 3D-printed tire designs by simulating real-world road conditions and obtaining the corresponding acceleration data.

IV. RESULTS AND DISCUSSION

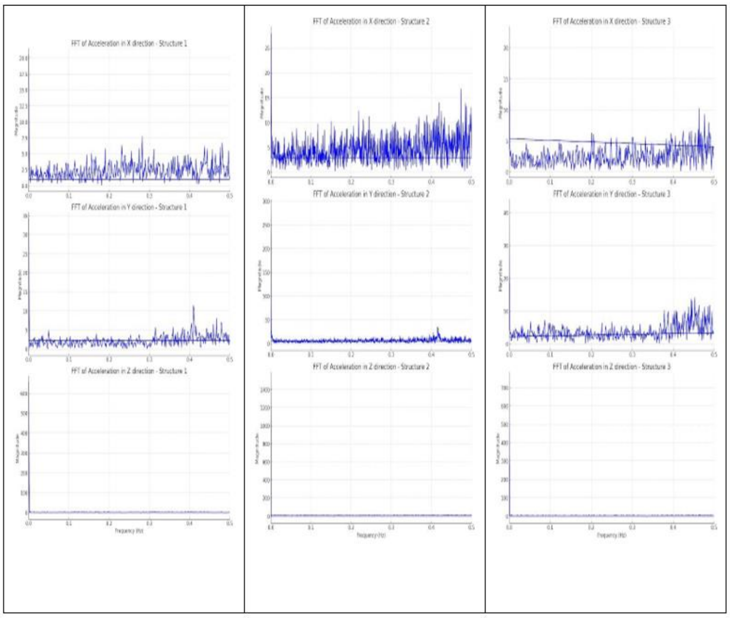

Figure 3 shows FFT plot of various types of 3D-printed airless tires

The MPU6050 sensor provided invaluable data in the form of x, y, and z-axis acceleration readings over time. We used Fast Fourier Transform (FFT) analysis on this dataset to acquire a better understanding of the vibrational properties of the various 3D-printed airless tire structures. FFT is a mathematical approach that deconstructs complex signals into their constituent frequencies, allowing for a better understanding of delicate vibrations in time-domain data.

Figure 3 depicts a series of FFT graphs matching various 3D-printed airless tire structures. These charts show the frequency components of the recorded acceleration data. Peaks in these figures show prominent vibration frequencies, with peak height representing the magnitude of vibrations at those frequencies. We discover specific frequencies linked with severe vibrations by analyzing peak positions on the frequency axis. This vital information aids in comprehending how each tire structure reacts to changing road conditions. We may analyze the relative performance of tire structures in terms of vibration dampening by comparing FFT charts. Structures with fewer and smaller magnitude peaks may be more vibration resistant, making them possibly more suitable for specific real-world applications.

Based on the above FFT plot shown in the figure.3, The vibration stability of each 3D printed airless tyre structure was carefully assessed using numerous critical parameters. We looked at the size of dominating frequencies as well as their proximity to critical resonance or operational frequencies to assess overall stability.

To begin, we calculated the total vibration energy for each structure, which offers a comprehensive estimate of vibration intensity. Notably, Structure 1 had the lowest overall vibration energy, indicating improved dampening stability. Structure 2, on the other hand, had the highest overall vibration energy, making it the least stable of the three, while Structure 3 was in the middle. We also took into account the number of dominant frequencies in each structure's vibrational signature. Fewer dominant frequencies, assuming magnitudes remain within tolerable boundaries, are often indicative of improved stability. Finally, the magnitude at dominant frequencies was critical in our judgment. Lower magnitudes at dominant frequencies indicate less pronounced vibrations, which helps to maintain overall stability.

The full examination of these metrics resulted in a clear ranking of stability: Structure 1 was the most stable, followed by Structure 3, and Structure 2 was the least stable. It should be noted that this ranking is limited to the vibration performance of these structures under the testing conditions.

V. Conclusion

The study of 3D-printed airless tires and their vibration characteristics has important implications for tire technology and transportation in the future. Further research can be conducted to optimize the design characteristics of Structure 1, which was found as the most vibration-stable choice in this study. Exploring alternative 3D printing materials and processes to improve overall tire performance and durability is also a viable path. Real-world road testing and simulation in a variety of scenarios can provide useful information. Furthermore, the environmental impact of 3D-printed airless tires, particularly their recyclability and sustainability, calls for further research. Collaborations between the automotive and additive manufacturing industries can help speed up the transition from research to practical implementation, ultimately changing how we see and use tires in the transportation sector.

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