Recearch Artide
Ziraat Mühendisliği (378), 67-77
DOI: 10.33724/zm.1264739

Material Analysis of a Sample Airless Wheel That Can Be Used in The Landing Gear of Small UAVs for Smart Agriculture Using the Finite Element Method

Sonlu Elemanlar Yöntemi ile Akıllı Tarıma Yönelik Küçük İHA'ların İniş Takımlarında Kullanılabilecek Örnek Bir Havasız Tekerleğin Materyal Analizinin Yapılması

Abstract

Unmanned Aerial Vehicles (UAV) in categories 1 and 2 are small in size and have a maximum gross take-off weight between 5 - 40 N and 40 - 250 N, with a normal operating altitude of 120 m above ground level. One of the major concerns for UAVs is the weight of aerial vehicles, which is aided primarily by material changes. Tires for UAVs are primarily made of ABS, rubber silicone, and nylon to reduce flight problems. These tires add to the dead weight and drag during flight.

In response to these issues, a rigorous analysis was performed to select the best possible configuration using various materials such as Acrylonitrile Butadiene Styrene (ABS), rubber silicone, and nylon materials. UAV wheel manufacturing is commonly known as the production of high-strength light-weighing parts. It also provides a broader range of design options and favors an iterative design approach, so it is important the method of production. To achieve the best results, the iterative design approach was used in the analysis application. The study incorporated a design for airless tires with 40 spokes, leveraging Autodesk Inventor Pro for modeling. Subsequently, the designs underwent Finite Element Analysis to assess static radial strength. Bending and torsion stresses during landing were deemed negligible owing to the lightweight nature of categories 1 and 2 UAVs and were thus excluded from the analysis.

Sorumlu Yazar
Abdullah BEYAZ[1]
abeyaz@ankara.edu.tr
0000-0002-7329-1318

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[1] Ankara University, Faculty of Agriculture, Department of Agricultural Machinery and Technologies Engineering, Ankara, Türkiye

Gönderilme Tarihi : 02 Ekim 2023
Kabul Tarihi : 04 Aralık 2023

The modeled wheel design in Autodesk Inventor Pro analysis based on Finite Element Analysis of the airless wheels revealed that wheels made of rubber silicone exhibited superior shock absorption, with a deformation of only 2.314 mm at 625 N upon impact during UAV landing maneuvers.

Keywords: Smart farming, UAV wheels, Airless wheel manufacturing, Material analysis, Finite element method

Özet

1. ve 2. kategorideki İnsansız Hava Araçları, küçük boyutlu olup, maksimum brüt kalkış ağırlığı 5 - 40 N ve 40 - 250 N arasındadır, normal çalışma irtifası yerden 120 m yüksekliktedir. İnsansız hava araçların için en önemli endişelerden biri, öncelikle malzeme değişiklikleriyle desteklenen hava araçlarının ağırlığıdır. İHA›lara yönelik lastikler uçuş problemlerini azalmak için öncelikle ABS, kauçuk silikon ve naylondan malzemelerden yapılmaktadır. Bu lastikler ölü ağırlığa eklenir ve uçuş sırasında sürüklenir.

Bu sebeple, ABS, kauçuk silikon ve naylon malzemeler gibi çeşitli malzemeler kullanılarak mümkün olan en iyi konfigürasyonu seçmek için titiz bir analiz gerçekleştirilmiştir. İHA tekerleği imalatı, genellikle yüksek mukavemetli hafif ağırlıklı parçaların üretimi olarak bilinir. Ayrıca, daha geniş bir tasarım seçeneği yelpazesi sunar ve yinelemeli bir tasarım yaklaşımını destekler, bu nedenle üretim yöntemi önemlidir. En iyi sonuçları elde etmek için analiz uygulamasında yinelemeli tasarım yaklaşımı kullanılmıştır. Bu çalışma, 40 bölmeli havasız tekerlekler üzerinde yapılmıştır. Tekerlek tasarımları Autodesk Inventor Pro'da modellenmiş ve kategori 1 ve 2 İHA'ların hafif olması nedeniyle iniş sırasında tekerleklerin bükülmesi ve burulması göz ardı edilerek tekerleğin radyal yöndeki statik dayanımı sonlu eleman analizi kullanılarak incelenmiştir.

Sonlu eleman analizine dayanarak Autodesk Inventor Pro ile modellenen havasız tekerlek tasarımı, İHA'nın iniş sırasında 625 N yükte 2.314 mm'lik bir esneme sergilediğini ve şok emiliminde kauçuk silikon malzemenin üstün performans gösterdiğini ortaya koymuştur.

Anahtar Kelimeler: Akıllı Tarım, İHA Tekerlekleri, Havasız tekerlek imalatı, Materyal analizi, Sonlu Elemanlar Yöntemi

Introduction

UAVs in agriculture use data in smart agriculture remote sensing and plant monitoring to form the structure detection of diseases and pests in plants based on techniques, water stress detection, yield and maturity estimation, weed flora detection, water resources control, and workers' as passive applications made for surveillance purposes. In recent years, smart agriculture has been adopted in agriculture. It represents the start of a new agricultural production management method (Türkseven et al., 2016).

Multiple typical fields of use, including 'smart agriculture', are rapidly expanding UAV's utility. Today's market features a diverse array of UAVs, each designed with a specific function, wheel geometry, and main gear setup, all reflecting the expanding UAV industry. In smart farming applications, fixed-wing UAV models use landing gears with wheels.

According to the Republic of Türkiye Directorate General of Civil Aviation, categories 1 and 2 Unmanned Aerial Vehicles are medium-sized UAVs, with a Maximum Gross Take-off Weight of 5 (included) – 40 N and 40 (included) – 250 N respectively, and a typical operating altitude of 120 m above ground level (Fidan & Ulvi, 2021). This analysis is specifically focused on the wheel components of these UAVs.

While the plane is on the ground, its landing gear prevents it from tipping over. The gear is designed to withstand the aircraft's momentum and weight upon touchdown, serving as a critical buffer between the airplane and potential disaster. It is essentially a one-dimensional structure that experiences thermal shocks, high friction, skidding, and non-linear elongation from the beginning to the end of the landing (Krüger et al, 1997). Landing gear and wheels represent structural components that are frequently modified to meet project-specific requirements, as examined by de Souza et al. (2013). Utilizing software that incorporates the Finite Element Method (FEM) for these studies is crucial for optimizing design. Such tools ensure that components are engineered to tolerate minor displacements and strains while maintaining their essential properties.

Airless tires, as emphasized by Suhag et al. (2013), eliminate the need for a separate wheel and tire assembly. They are engineered as an integral unit, replacing the multiple components traditionally required. It consists of a rigid hub connected by flexible, deformable polyurethane spokes to a shear band and a tread band. In 2015, Shafabakhsh et al. examined the impact of wheel load and configuration on runway damage. They concluded that wheels bearing substantial weight contribute significantly to this damage, which is intricately linked to the way an aircraft disperses its total weight through its landing gear system. UGVs can use the airless wheels studied by Lizuka et al. (2020) to move over hard and sloppy terrain. They imply that vehicles in disaster zones are vulnerable to punctures when driving over debris and can be stacked easily when driving over loose soil. For their 2021 study, Kinoshita et al. focused on the design and analysis of lightweight permanent magnetic wheels tailored for inspection drones. Their goal was to enhance the versatility of UAVs, making them more suitable for a variety of applications. A comprehensive analysis of the design, production methods, and structural dimensions of airless tires is presented by Askarjon et al. (2022) in the literature, along with a discussion of the potential applications in the field of mechanical engineering. The airless tire model presented by Sanjeev Kumar (2021) swapped out the Polyethylene as engineered elastic for common elastic materials. Quattrocchi et al. (2022) investigated the stress and strain performance of an airless wheel prototype by employing a synergistic approach of 2D digital image correlation and thermoelastic stress analysis. Samples of the novel airless wheels were 3D printed using fused deposition modeling and stereolithography with polylactic acid and photopolymer resin, respectively. These non-contact methods are used to analyze the static mechanical behavior of various wheel-ground contact configurations.

The design industry uses a straightforward strategy by standardizing the design process for the parts on every side of the usage environment. The procedure utilizes elementary geometry and previous data to derive the crucial dimensions of the landing gear. There is a growing need to shift focus from traditional rubber tires to more lightweight wheels, as the thickness of rubber tires not only contributes to increased drag but also becomes superfluous weight during flight.

One of the main concerns is the need to reduce the weight of aerial vehicles by using airless tires, and this is something that has been helped along by the introduction of new materials. There is cause for alarm because the rubber used in UAV tires is relatively hefty. These rubber tires not only increase the UAV's overall weight but also its resistance to forward motion. Using the finalized airless wheel layout, a finite element analysis of the aforementioned substances was carried out. ABS, rubber silicone, and nylon materials were tested for their relative strengths in airless wheel designs with 40 spokes that were produced for UAV airless wheel manufacturing for lightweight UAV wheels.

Material and Method

Material

The primary objective of this research was to achieve a reduction in the weight of UAV wheels. To identify the most effective material for this purpose, comprehensive calculations were undertaken to evaluate various potential materials. The candidates included Acrylonitrile Butadiene Styrene (ABS), rubber silicone, and nylon, all of which were assessed for their suitability based on their general properties.

Table 1. General properties of ABS Material

Information	
Name	Acrylonitrile Butadiene Styrene
Description	Acrylonitrile Butadiene Styrene, Molded
Keywords	ABS, structural, Plastic

Type	Plastic
Subclass	Thermoplastic
Source	Autodesk
Basic Thermal	
Thermal Conductivity	1.600E-01 W/(m-K)
Specific Heat	1.500 J/(g-°C)
Thermal Expansion Coefficient	85.700 μ m/(m-°C)
Mechanical	
Behavior	Isotropic
Young's Modulus	2.240 GPa
Poisson's Ratio	0.38
Shear Modulus	805.000 MPa
Density	1.060 g/cm^3
Strength	
Yield Strength	20.000 MPa
Tensile Strength	29.600 MPa

Table 2. General Properties of Rubber Silicone Material

Information	
Name	Silicone
Description	Silicone Rubber
Keywords	SI, structural, Plastic
Type	Plastic
Subclass	Elastomer
Source	Autodesk
Basic Thermal	
Thermal Conductivity	2.275E-01 W/(m-K)
Specific Heat	1.880 J/(g-°C)
Thermal Exp. Coefficient	8.100 μm/(m-°C)
Mechanical	
Behavior	Isotropic
Young's Modulus	0.003 GPa
Poisson's Ratio	0.49
Shear Modulus	1.007 MPa

Density	1.250 g/cm^3
Strength	
Yield Strength	10.340 MPa
Tensile Strength	6.500 MPa

Table 3. General properties of Nylon Material

Information	
Name	Nylon 6/6 Composite
Description	Molybdenum disulfide filled nylon
Keywords	PA, Polyamide, lubricated, structural, Plastic
Type	Plastic
Subclass	Thermoplastic
Source	Autodesk
Basic Thermal	
Thermal Conductivity	2.400E-01 W/(m-K)
Specific Heat	1.340 J/(g-°C)
Thermal Expansion Coefficient	55.800 µm/(m-°C)
Mechanical	
Behavior	Isotropic
Young's Modulus	2.930 GPa
Poisson's Ratio	0.35
Shear Modulus	1000.000 MPa
Density	1.130 g/cm^3
Strength	
Yield Strength	82.750 MPa
Tensile Strength	82.680 MPa

The analysis application took into account wheel dimensions with 60 mm diameter for the center circle, 90 mm diameter for the total wheel, and 8 mm thickness, also 40 spokes for light weight UAV wheel design with the best shock absorbance material. A tread height of 1 mm was selected for the airless wheel to maintain the material properties and achieve optimal displacement outcomes. The wheel designs were modeled and analyzed in Autodesk Inventor Pro (under an educational license). The static strength of the wheel in the radial direction was then evaluated using FEA for Category 1 and 2 UAVs, as illustrated in Figure 1.

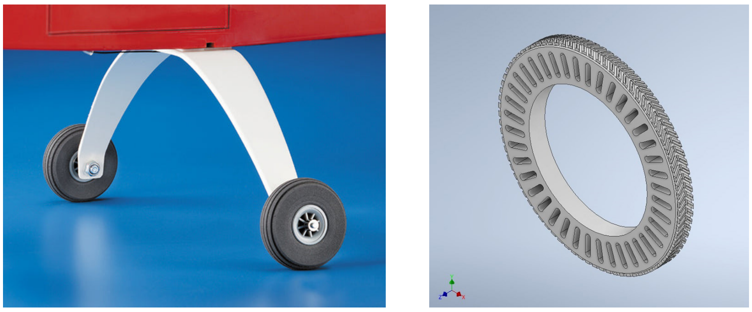

Figure 1. A sample of a basic drone landing gear with wheels (on the left) (Anonymous, 2023a) and an airless wheel modeled in Autodesk Inventor Pro

Method

Design and finite element modeling

The use of the FEM proves to be a useful calculational tool for analyzing the behavior of the materials used in structural projects, such as the one assessing the mechanical performance of the structures. Interpolating displacements, efforts, tensions, and deformations along the element's domain are possible thanks to the FEM, which can be considered a method for generating approach functions. Direct application of the form functions to the FEM's differential equation or too energetic principles like the Virtual Works Principle allows for approximative resolution of structural problems.

The deformation of the wheel was investigated through design and finite element modeling. Figure 1 depicts the Autodesk Inventor Professional model of the wheel, conveniently assembled on a base for the simulation. The design was analyzed using the Autodesk Inventor Pro stress analysis solver, where it was subjected to radial forces distributed across the entire wheel. Material-based manufacturing is best known for its ability to create lightweight, high-strength components. It was chosen as the method of production because it provides more options in terms of design and encourages an iterative design process. The best outcomes were achieved by using an iterative design process. The modeled wheel design in Autodesk Inventor Pro analysis is based on the FEM of the airless wheels and the 375 N, 500 N, and 625 N loads as 1.5, 2, 2.5 times safety factor loads of 250 N in the whole radial direction of the UAV airless wheel (Figure 2). Because category 2 UAVs' weight limit is 250 N. Also, normally three wheels are used in a UAV fuselage but this application is focused on safe and resistant wheels, for this aim maximum loads are applied with 1.5, 2, and 2.5 times safety to the wheel, additionally since every point of the wheels has the possibility of contact when landing, the load was applied spread around it. Additinally, the models were fixed from their insides because of this reason a tire rim was not added to the model for the analysis.

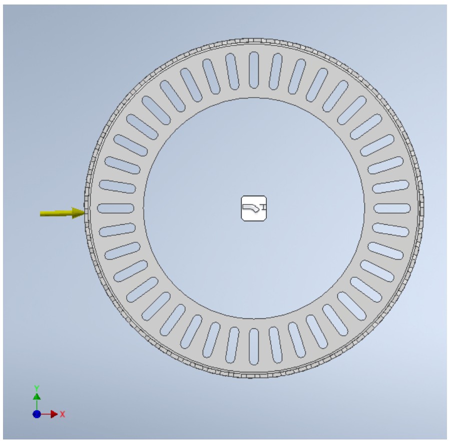

Figure 2. The radial load of UAV airless wheel

Results and Discussion

Despite the potential for bending and torsion experienced by wheels during landing, the analysis was confined to radial forces, as demonstrated in the wheel design modeled in Autodesk Inventor Professional, employing FEA. This focus enabled a comprehensive and fundamental evaluation of the airless wheels, with results detailed in Figures 3 to 11. In the results, the Von Mises Stress, displacement, and safety factors were presented because Von Mises Stress is a good predictor of failure, particularly for ductile materials, displacement shows the deformation of the wheel, and the safety factor shows the ratio yield strength / Von Mises Stress (Anonymous, 2023b).

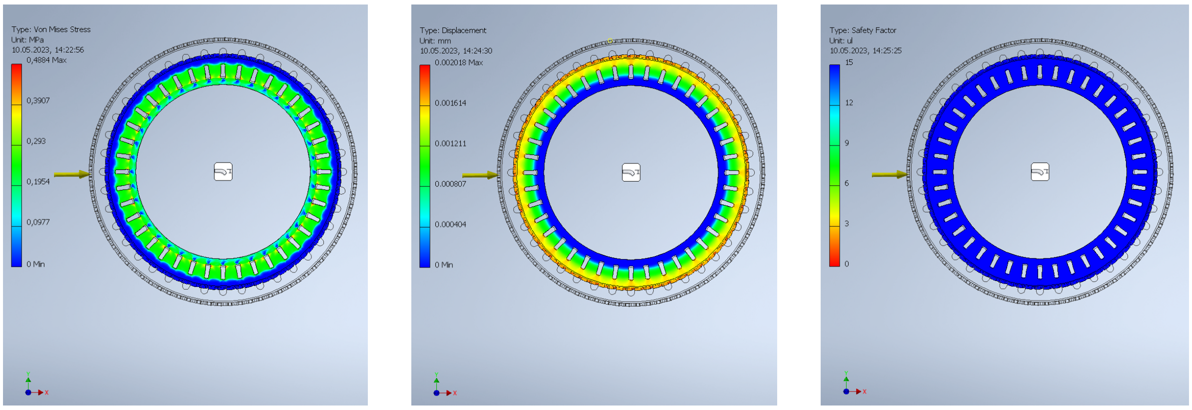

Figure 3. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of ABS material airless UAV wheel under 375 N

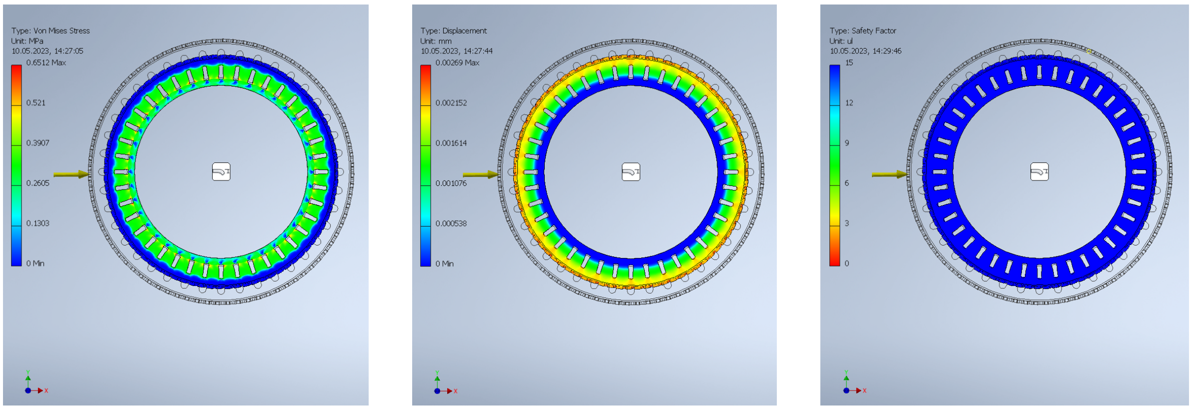

Figure 4. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of ABS material airless UAV wheel under 500 N.

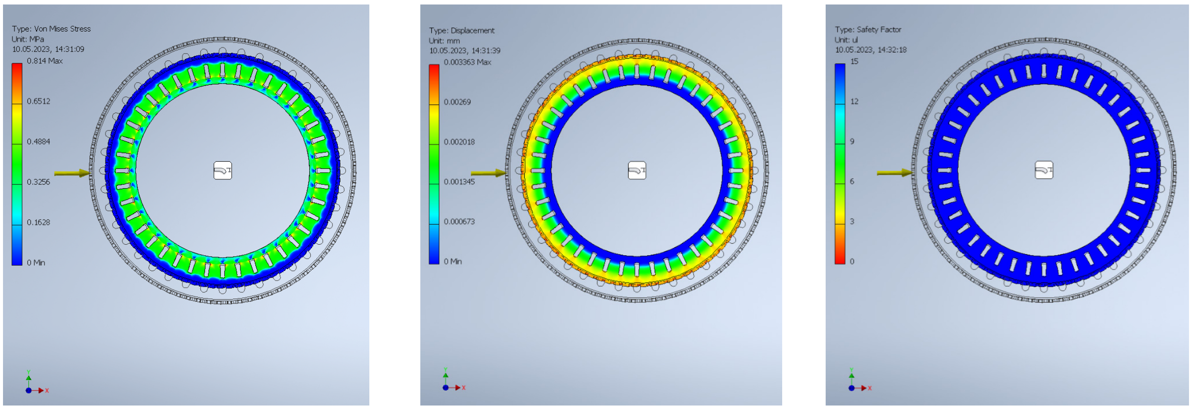

Figure 5. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of ABS material airless UAV wheel under 625 N.

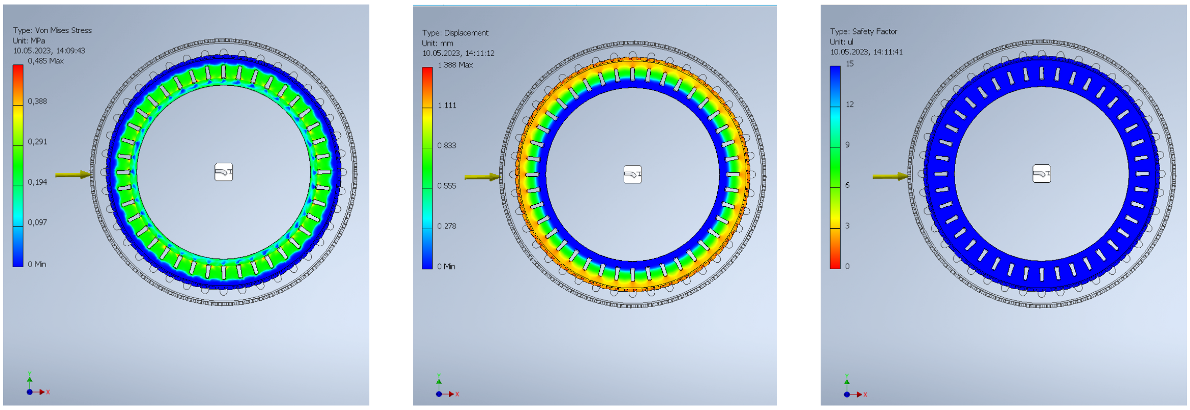

Figure 6. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of Rubber Silicone material airless UAV wheel under 375 N.

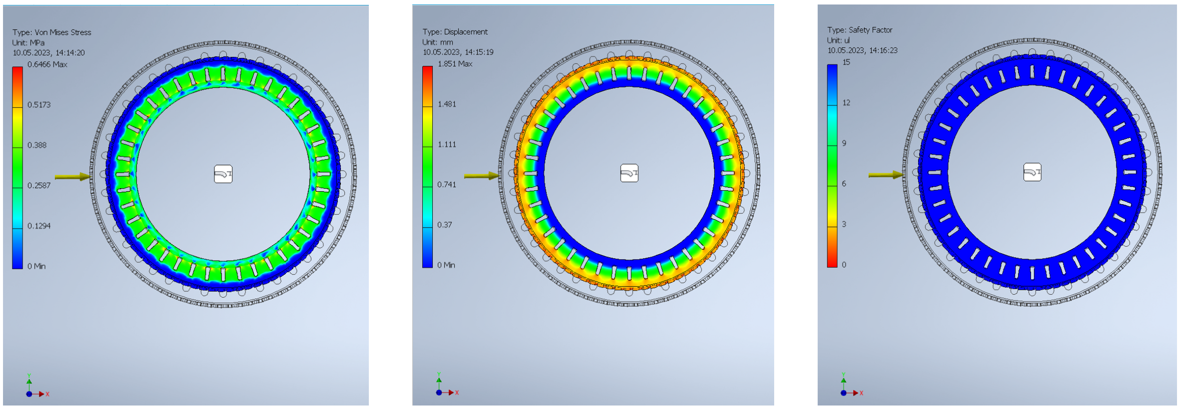

Figure 7. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of Rubber Silicone material airless UAV wheel under 500 N.

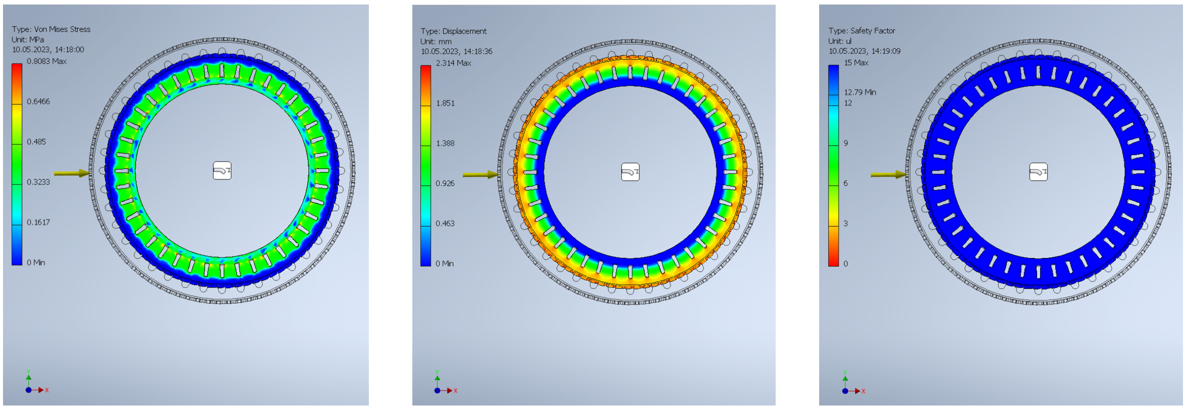

Figure 8. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of Rubber Silicone material airless UAV wheel under 625 N.

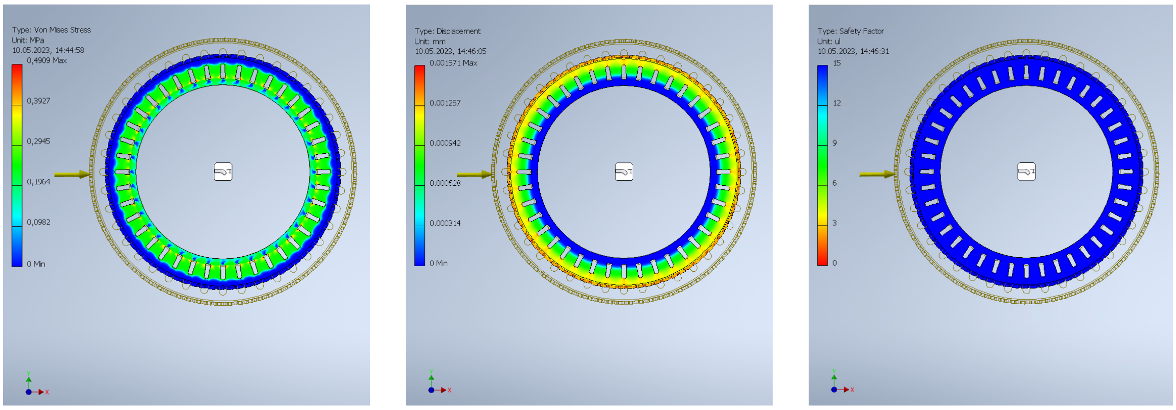

Figure 9. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of Nylone material airless UAV wheel under 375 N.

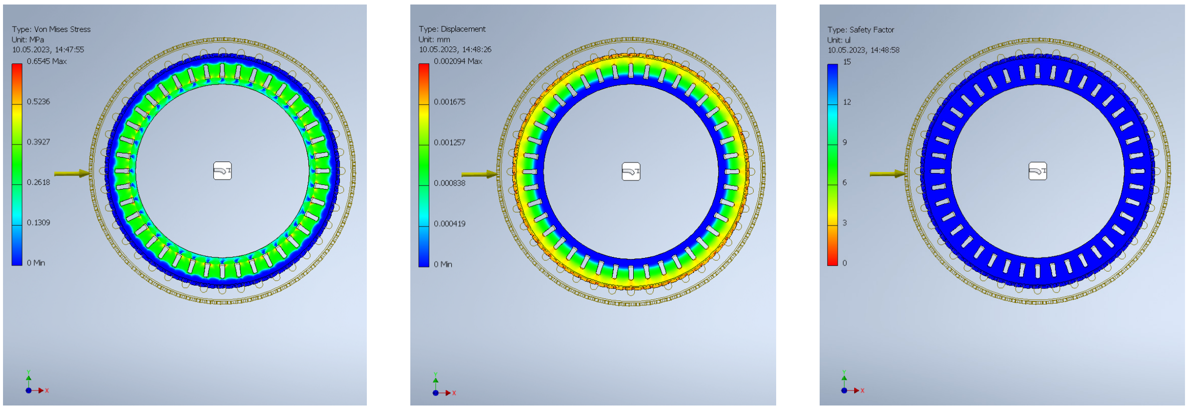

Figure 10. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of Nylone material airless UAV wheel under 500 N.

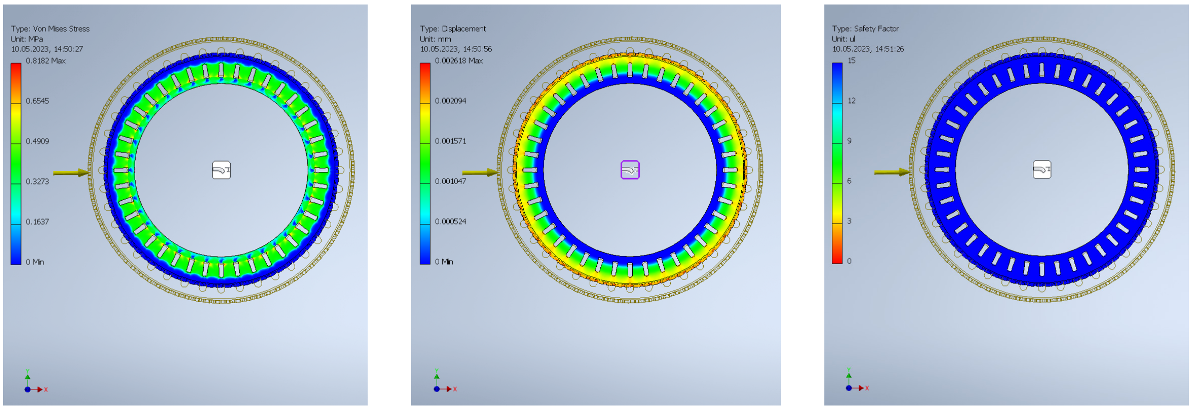

Figure 11. Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of Nylone material airless UAV wheel under 625 N.

Table 4 provides a summary of the Von Mises Stress (MPa), Displacement (mm), and Safety Factor (ul) for airless UAV wheels constructed from ABS, rubber silicone, and nylon materials. The table compiles the results under static loads of 375 N, 500 N, and 625 N.

Table 4. Summary of the Von Misses Stress (Mpa), Displacement (mm), and Safety Factor (ul) results of ABS, Rubber Silicone, and Nylone materials under various static loads.

Load (N)	Material	Von Misses Stress (Mpa)	Displacement (mm)	Safety Factor (ul)
375	ABS	0.4884	0.002018	15
500	ABS	0.6250	0.002690	15
625	ABS	0.8140	0.003363	15
375	Rubber Silicon	0.4850	1.388000	15
500	Rubber Silicon	0.6466	1.851000	15
625	Rubber Silicon	0.8083	2.314000	12.79
375	Nylon	0.4909	0.001571	15
500	Nylon	0.6545	0.002094	15
625	Nylon	0.8182	0.002618	15

The analysis showed that the 40-spoke Rubber Silicone material wheel was the strongest and the best option for shock absorbance with 2.314 mm displacement at 625 N. Prabhuram, et al. (2020) worked on static analysis of different spoke structures of airless and conventional tires with different materials. They found that the total deformation on ABS +PC material combination at Honeycomb, Diamond, Triangular spokes structure 0.286 mm, 0.053686 mm, 053703 mm; on PET material 0.24998 mm, 0.046625 mm, 0.046627 mm; on HIPS 0.41301 mm, 0.078062 mm, 0.78137 mm; on conventional tire 10.049 mm, -, -, respectively. Kumar et al. (2021) studied on design optimization of the airless tire-numerical approach. According to the design parameter, they found that the total deformation on spokes was 0.010543 mm, on triangular 0.019843 mm, on circular, 0.0067021 mm, on hexagon 0.0082758 mm, respectively. de Souza et. al (2013) worked on topological optimization and genetic algorithms used in a wheel project for a drone. The simulated values of the wheel to the deformation vary between 0,4561 mm and 0,8038 mm.

Conclusion

The wheel characteristics are important to know when operating all standard and older unmanned aerial vehicles. Airless tires offer a simplified solution, mitigating the complexities of terrain interaction, albeit at a higher initial cost. Despite the availability and cost-effectiveness of traditional rubber tires, the operational efficiency and durability of airless tires provide a compelling case for their adoption in UAV applications. Ultimately, airless tires emerge as the superior option, offering consistent performance advantages across diverse operating conditions. Tires that have been filled with air can be driven on asphalt and decent dirt roads. Also, a different type of rubber silicone must be used to get through the clay. Third, driving difficulties arise on sandy or sandy-like surfaces due to the instability of the soil. Considering that the study can be a basis for future studies, examining different ground and shape design computer-aided parameters has the potential to create alternative solutions.

Authors' Contributions

All authors contributed equally to the article.

Conflicts of Interest Statement

The authors declare that they have no conflicts of interest.

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