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DESIGN AND ANALYSIS OF BEVEL GEARS FOR SPACE APPLICATIONS

G Sri Lakshmi Naimisha, **Kathravath Rahul Nayak, Mathangi Bharat Kumar,** Research Scholar, Department of Automobile Engineering, Maturi Venkata Subba Rao (MVSR) Engineering College, Hyderabad

ABSTRACT

The objective of this project is to design and analyse a bevel gears system suitable for space applications. Leveraging the proven technology used in Mars rovers, this report outlines the comprehensive design process, from conceptualization to finite element analysis (FEA), including material selection and stress analysis. The selected material is titanium alloy (Ti-6Al-4V) due to its excellent strength-to-weight ratio and thermal stability. The design is validated through simulations to ensure reliability in extreme space conditions. This report aims to provide a robust framework for developing gear systems in space exploration vehicles. The utilization of unmanned space vehicles has become increasingly prevalent in modern space exploration endeavours due to their versatility and cost-effectiveness. A crucial aspect of these vehicles is the suspension system, which plays a pivotal role in ensuring stability, manoeuvrability, and longevity in the harsh environment of space. This project aims to design and analyse a bevel gear system tailored specifically for unmanned space applications.

Key parameters, including tooth geometry, material selection, and surface treatments, are optimized to enhance the gear's durability and efficiency. Innovative lubrication methods and coatings are explored to address the vacuum environment where conventional lubrication is ineffective. Prototyping and experimental validation involve rigorous testing, including thermal cycling, vacuum chamber assessments, and mechanical load evaluations, ensuring the gears' reliability for space missions. Simultaneously, the project explores the use of bevel gears in suspension systems, where they can offer precise motion control and load distribution. The design process involves creating gear configurations optimized for shock absorption and load management. The analysis includes simulation of dynamic loading conditions typical in suspension systems, focusing on durability and performance under varying operational scenarios. The findings of this project aim to contribute to the development of advanced suspension systems, leveraging the unique properties of bevel gears. The successful implementation of bevel gear suspension systems could lead to significant improvements in vehicle dynamics, comfort, and durability, supporting applications in the automotive and aerospace industries.

Keywords: Bevel Gears for Space Applications, Design and Analysis, Titanium Alloy (Ti-6Al-4V), Finite Element Analysis (FEA), Suspension System, Unmanned Space Vehicles, Lubrication Methods, Coatings, Thermal Cycling and Vacuum Chamber, Dynamic Loading

Introduction

Unmanned space exploration has been crucial in expanding our understanding of the universe, driving scientific discovery, technological innovation, and fostering international collaboration. From early missions targeting the Moon and nearby planets to modern-day probes exploring the far reaches of the solar system and beyond, these missions have provided invaluable insights into celestial bodies and cosmic phenomena. Historically, unmanned spacecraft have evolved in their complexity and capability, starting from simple flyby missions to sophisticated rovers and orbiters equipped with advanced scientific instruments. This evolution has revolutionized our understanding of planetary bodies, comets, asteroids, and other objects in the cosmos.

A key focus of unmanned space exploration has been the development of robust mechanical systems, such as bevel gears, which are essential for the mobility and operation of space vehicles like Mars rovers. These gears must be designed to withstand the harsh environment of space, which is characterized by extreme temperatures, vacuum conditions, and high radiation levels. The reliability of these systems is critical, as space missions often involve prolonged operations in environments where maintenance opportunities are non existent.

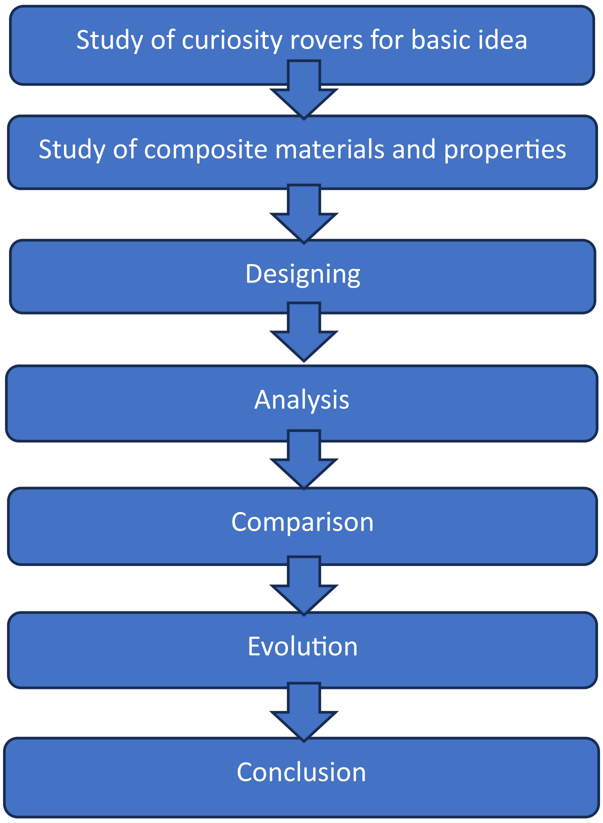
Designing bevel gears for space applications presents several challenges. These include extreme environmental conditions, such as temperature variations ranging from intense heat when exposed to sunlight to freezing conditions in shadowed areas. Additionally, the vacuum of space requires materials that do not outgas, as released volatile compounds could contaminate sensitive instruments. Another challenge is the need for materials and systems to resist radiation, which can degrade the structural integrity of gears over time. Space missions also impose strict weight and size constraints, making it essential for these systems to be lightweight and compact while still meeting performance requirements.

Moreover, bevel gear systems must be able to withstand the shocks and vibrations experienced during launch and operation. In extraterrestrial environments, such as the Martian surface, the presence of dust and particle contamination poses a risk of abrasive wear and damage to mechanical components. Implementing effective sealing mechanisms and dust mitigation strategies is critical for ensuring the longevity of these systems. The adaptability and flexibility of these systems are also paramount, as space rovers need to navigate diverse terrains and perform a variety of tasks, requiring gear systems that can handle changes in load, speed, and direction efficiently.

In terms of materials, titanium alloys are often favored for their high strength-to-weight ratio, corrosion resistance, and ability to withstand temperature extremes. These materials are well-suited to the unique demands of space exploration, offering durability and reliability in the face of harsh conditions. The selection of materials for bevel gears also involves careful consideration of their mechanical properties, including strength, stiffness, and fatigue resistance. The goal is to ensure that the gear systems can endure the mechanical stresses encountered during space missions, such as launch, orbital maneuvers, and landing.

Furthermore, space-grade materials must exhibit high thermal stability and resistance to radiation, ensuring that they remain functional over extended mission durations. The integration of these materials into spacecraft interfaces must also be seamless, ensuring compatibility with launch and deployment mechanisms, docking ports, and other subsystems. The mechanical interfaces between suspension components and other subsystems, such as propulsion and navigation, must be carefully designed to ensure interoperability and efficient integration. By addressing these challenges, engineers can design unmanned space vehicles that are capable of withstanding the rigors of space exploration, maintaining optimal performance and reliability throughout their missions.

II. Flow chart describing methodology opted



III. Properties and Advantages of Bevel Gears

Bevel gears are particularly advantageous in space applications due to their unique properties and capabilities. One of the primary properties of bevel gears is their ability to transmit power and motion between intersecting shafts, typically at a 90-degree angle. This makes them ideal for complex mechanical systems where space and weight are critical factors, such as in spacecraft and satellites. Bevel gears are known for their high efficiency in power transmission, which is crucial in space applications where energy conservation is paramount.

The ability of bevel gears to handle high torque loads is another significant advantage. This is essential in space, where mechanical components must withstand extreme forces and stresses without failure. Bevel gears can be designed to accommodate various torque requirements, making them versatile for different space missions, whether for propulsion systems, robotic arms, or other critical spacecraft components.

Another key advantage is their ability to be made from various materials, such as titanium alloys, carbon fiber reinforced polymers (CFRP), and other advanced composites. These materials enhance the gears' strength-to-weight ratio, making them lighter yet stronger, which is a vital consideration in space applications where every gram counts. Additionally, the use of materials like CFRP provides excellent thermal stability and resistance to radiation, further ensuring the reliability of bevel gears in the harsh conditions of space.Bevel gears also offer precision and reliability, which are critical in space missions where mechanical failure is not an option. Their ability to maintain alignment and transmit power accurately even under varying loads and temperatures makes them indispensable in space technology. This precision ensures that the gears perform consistently throughout the mission, reducing the risk of mechanical failure and increasing the overall mission success rate.

Bevel gears are an excellent choice for space applications due to their efficiency in power transmission, ability to handle high torque loads, versatility in material selection, and reliability under extreme conditions. These properties make them an essential component in the design and operation of

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spacecraft, contributing to the success of various space missions. Their adaptability and precision make bevel gears a cornerstone in the advancement.

IV. THEORETICAL FRAMEWORK

4.1 Gear Design Principles:

Designing bevel gears for a compact rover intended for unmanned space applications involves careful consideration of various parameters to ensure optimal performance and reliability in the challenging conditions of space. Here are some key principles and parameters involved in the design process:

Module: The module defines the size of the teeth and is a fundamental parameter in gear design. It determines the pitch diameter and tooth dimensions of the gears. For a compact rover, the module may need to be selected to minimize weight and size while maintaining sufficient strength and load-bearing capacity.

Number of Teeth: The number of teeth on the bevel gears influences the gear ratio and smoothness of operation. It's essential to select an appropriate number of teeth to achieve the desired gear ratio for the rover's propulsion system or other mechanical components while ensuring adequate strength and meshing characteristics.

Pitch Diameter: The pitch diameter is the diameter of the imaginary circle that intersects the gear teeth. It determines the overall size of the gear and affects the gear ratio and meshing behaviour. The pitch diameter should be chosen carefully to balance space constraints with gear performance requirements.

Pressure Angle: The pressure angle is the angle between the line of action and the tangent to the pitch circle. It affects the contact pattern, load distribution, and efficiency of the gears. Common pressure angles for bevel gears are 20° and 14.5°. The pressure angle should be selected based on considerations such as load capacity and efficiency requirements for the rover's transmission system.

Face Width: The face width is the width of the gear tooth along the axis of rotation. It influences the contact area and distribution of forces between the gear teeth, affecting load-carrying capacity and durability. For a compact rover, the face width should be optimized to ensure sufficient strength and stiffness while minimizing weight and size.

Material Selection: Material selection is crucial for ensuring the durability and reliability of the gears in space environments. Common materials for bevel gears include steel alloys, titanium alloys, and advanced composites. The selected material should exhibit high strength, wear resistance, and corrosion resistance while being lightweight and suitable for space conditions.

Manufacturing Considerations: The manufacturing process for bevel gears should be considered during the design phase to ensure feasibility and cost-effectiveness. Techniques such as precision machining, forging, or additive manufacturing may be employed depending on the chosen material and design requirements.

By carefully considering these design principles and parameters, engineers can develop bevel gears tailored to the specific needs and constraints of compact rovers for unmanned space applications, achieving optimal performance, reliability, and efficiency in extraterrestrial environments.

4.2 Design Parameters:

4.2.1 Basic Gear Design Calculations:

Given Parameters:

Module (m) (size of gear teeth) = 2.5 mm
Number of Teeth (z) = 24 for the pinion, 48 for the gear (2:1 ratio)
Pressure Angle (α) = 20°
Face Width (b) = 10 m

4.2.2 Material selection:

Material = Titanium alloy (Ti-6Al-4V)
Density = 4.43 g/cm³

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Ultimate Tensile Strength	=	900 MPa
Young's Modulus	=	110 G Pa
Thermal Conductivity	=	6.7 W/m·K

Pitch Diameter:

$$d = m \times z$$

- For the pinion: $d_1 = 2.5 \times 24 = 60 \text{ mm}$
- For the gear: $d_2 = 2.5 \times 48 = 120 \text{ mm}$

Gear Ratio (i):

$$i = \frac{z_2}{z_1} = \frac{48}{24} = 2$$

Pitch Angle:

$$\delta_1 = \tan^{-1}\left(\frac{z_1}{z_2}\right) = \tan^{-1}\left(\frac{24}{48}\right) = 26.57^\circ$$

$$\delta_2 = \tan^{-1}\left(\frac{z_2}{z_1}\right) = \tan^{-1}\left(\frac{48}{24}\right) = 63.43^\circ$$

3.2.3 Challenges faced:

Designing gear systems for space applications presents several challenges:

Extreme Temperatures:

The system must function reliably in a wide temperature range (-100°C to 150°C). Extreme temperature variations in space, ranging from extremely cold conditions in shadowed areas to intense heat in direct sunlight, can cause significant thermal expansion and contraction of gear materials. This thermal cycling can lead to dimensional changes and stresses within the gear system, affecting meshing tolerances and gear accuracy.

Design considerations may include selecting materials with low coefficients of thermal expansion and implementing thermal management strategies to mitigate temperature-induced stresses.

Material Selection:

Gear materials must withstand a wide range of temperatures encountered in space without compromising mechanical properties or dimensional stability. Traditional steel alloys may experience embrittlement or softening at extreme temperatures, necessitating the use of advanced materials such as titanium alloys, ceramics, or composites with superior thermal stability and mechanical properties. Material selection should consider not only the gear's operating temperature range but also its compatibility with other spacecraft components and environmental factors such as radiation exposure.

Lubrication and Wear: Extreme temperatures can affect the performance and longevity of gear lubricants, leading to changes in viscosity, degradation of lubricant properties, and increased friction and wear. Lubrication systems must be designed to operate effectively across a wide temperature range, with consideration for lubricant selection, application methods, and maintenance procedures. Dry lubricants or solid lubricant coatings may be preferred in certain space environments where traditional liquid lubricants are impractical.

Sealing and Contamination Control: Thermal cycling can also impact the integrity of gear seals and housing assemblies, leading to leaks or ingress of contaminants that compromise gear performance and reliability. Sealing systems must be designed to maintain a hermetic seal under extreme temperature conditions while accommodating differential thermal expansion between mating components. Special attention should be given to materials selection for seals and gaskets to ensure compatibility with temperature extremes and exposure to space vacuum.

Testing and Validation: Testing gear systems under realistic temperature conditions is essential to validate performance and reliability in space environments. Environmental test chambers capable of simulating temperature extremes encountered in space, such as thermal vacuum chambers, are used to evaluate gear functionality, durability, and lubrication performance under controlled conditions. Prototypes and components undergo rigorous thermal cycling and temperature soak tests to identify potential failure modes and design weaknesses before deployment in space missions.

Material Compatibility: Materials used in gear construction must be compatible with the vacuum environment to prevent outgassing, material degradation, or contamination of surrounding components.

Certain materials may release volatile compounds or gases when exposed to vacuum, which can adversely affect gear performance and spacecraft operations. Selection of vacuum-compatible materials, such as stainless steel, titanium alloys, and ceramics, is crucial for ensuring the reliability and longevity of gear systems in space.

Material Outgassing: Some materials used in gear construction may outgas volatile compounds when exposed to vacuum, releasing gases that can contaminate surrounding surfaces or degrade optical components in spacecraft instrumentation. Designing gear systems with low-outgassing materials and surface treatments can help minimize contamination risks and maintain the cleanliness of spacecraft interiors. Testing gear components for outgassing characteristics under vacuum conditions is essential to ensure compliance with spacecraft contamination control requirements.

Thermal Management: In vacuum environments, heat dissipation becomes more challenging due to the absence of convective heat transfer mechanisms. Gear systems must be designed with efficient thermal management strategies to prevent overheating and thermal stress buildup in critical components. Incorporating heat sinks, thermal insulation, or active cooling systems into gear assemblies can help regulate temperatures and maintain optimal operating conditions in vacuum environments.

Vacuum Environment: Materials and lubricants must be suitable for use in a vacuum.

Radiation Exposure: Prolonged exposure to space radiation can degrade materials.

Vibration and Shock: The system must withstand vibrations during launch and operation.

4.3 CAD Modelling:

In SolidWorks we have created a 2D sketch of the pinion gear. Setting the sketch plane and drawn the profile of the gear based on the specified parameters:

module (m) = 2.5mm,
number of teeth(z1) = 24
pitch diameter (d1) ×1 = 2.5 ×24 = 60 m×z1=2.5×24 = 60 mm
pressure angle (α) = 20°
face width (b) = 10mm.

Then extruded the sketch profile to create a 3D solid model of the pinion gear.

And repeated the sketching process to create a 2D sketch of the larger gear. Setting the sketch plane and drawn the profile of the gear using the specified parameters:

module (m) = 2.5mm,
number of teeth (z2) = 48
pitch diameter (d2)×2 = 2.5 ×48 = 120 m×z2 = 2.5×48 = 120 mm
pressure angle (α) = 20°
face width (b) = 10mm.

Hence, both the gears and pinion designing is done.

The below picture depicts the design and assembly of bevel gears that is designed and is to be analysed:

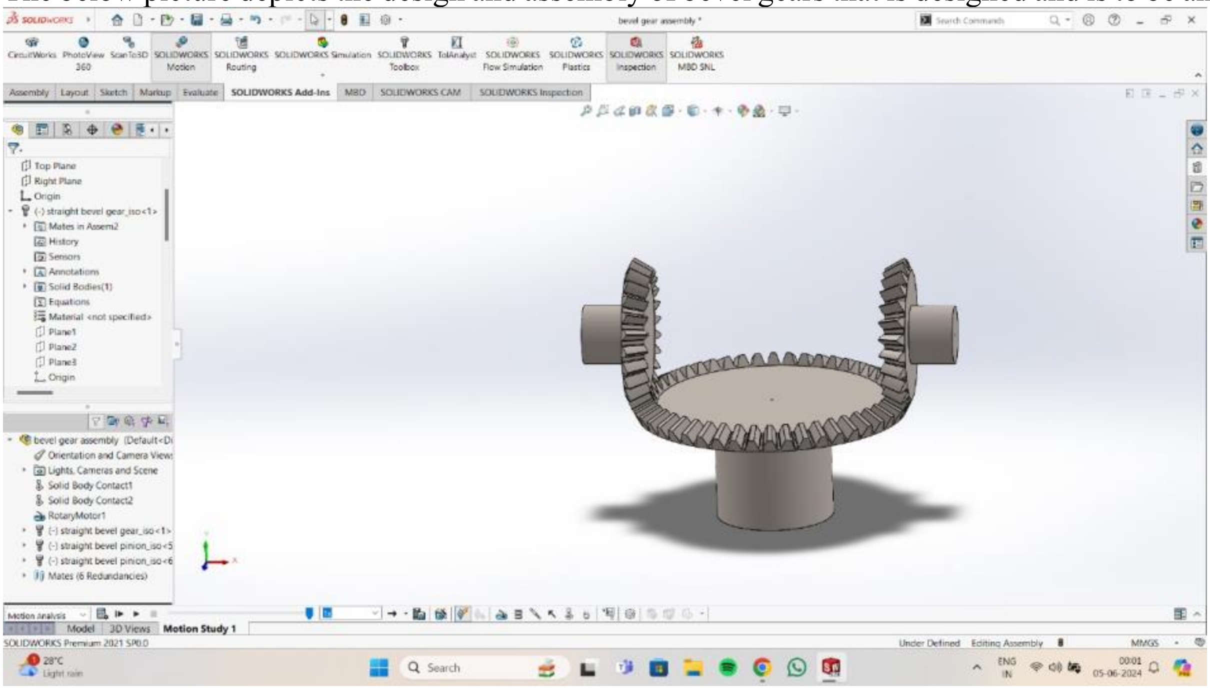

Fig 4.1 Bevel gears designed and assembled.

4.4 ANALYSIS (ANSYS WORKBENCH)

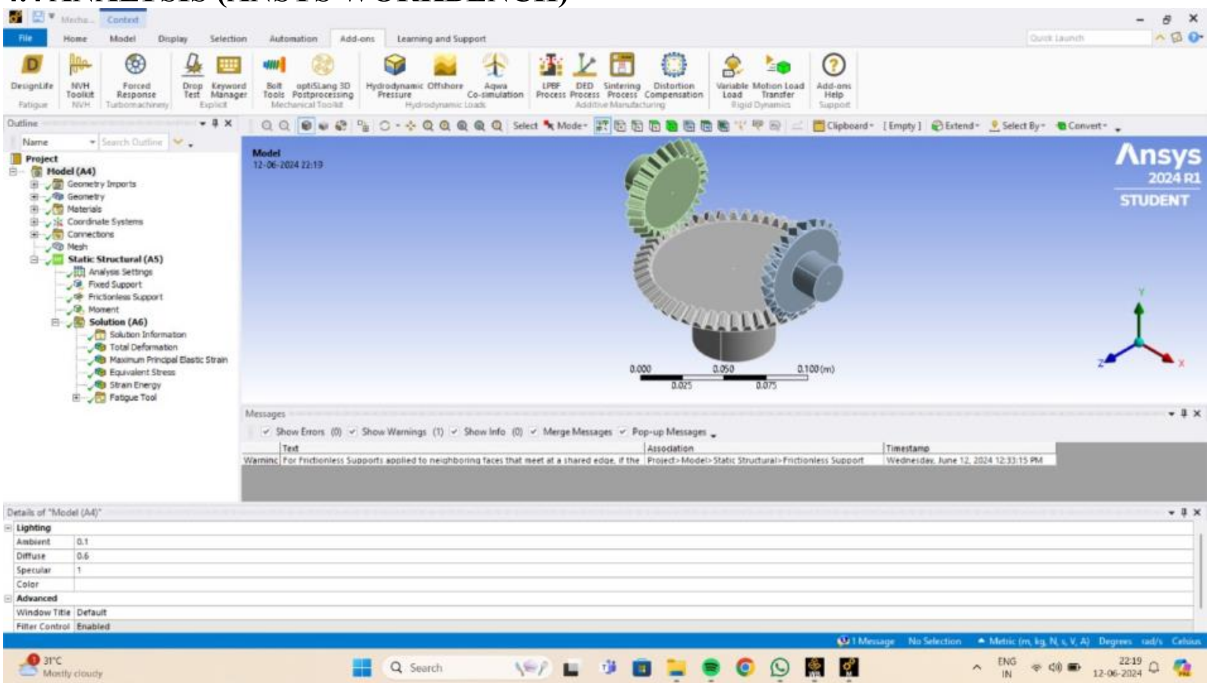

Fig 4.2 Open Design Modeler: Right-click on the ‘Geometry’ component and select ‘New Design Modeler Geometry.’ Create the Gear Profile.

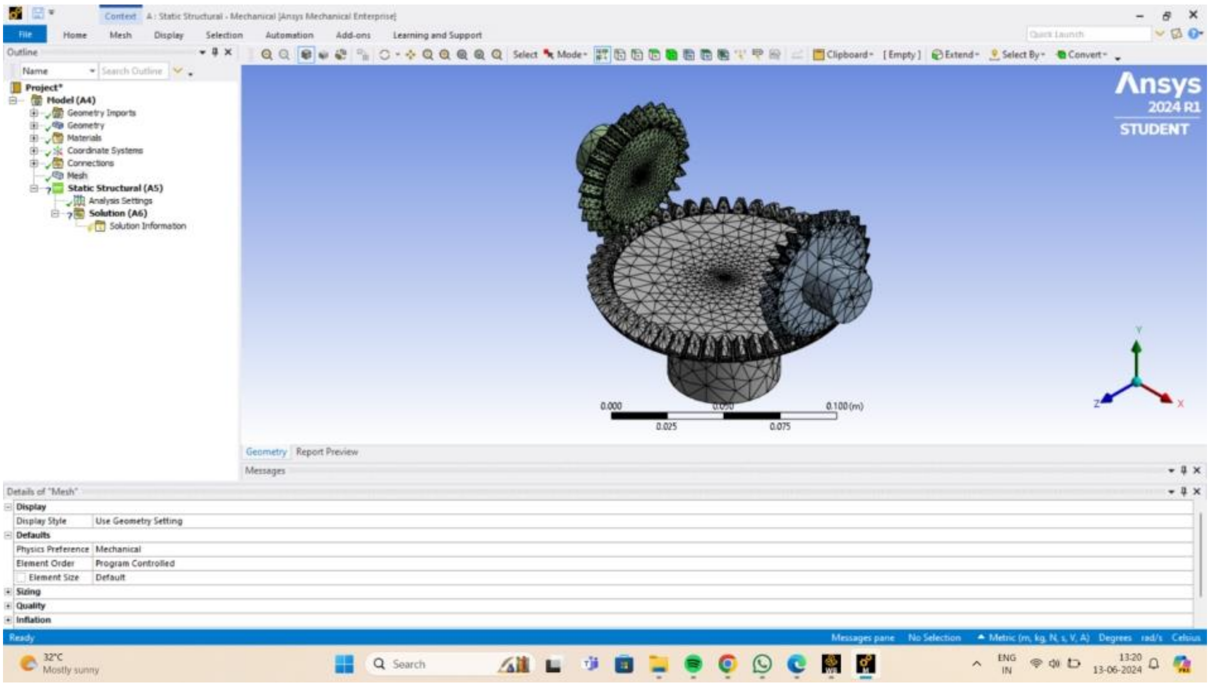

Fig 4.3 Double-click the ‘Mesh’ component to open it. Generate the Mesh.

V. RESULTS AND DISCUSSION

Through the design and analysis of bevel gears of Ti-6AI-4V and CFRP (Carbon Fibre-Reinforced Plastic) through some software of SolidWorks and ANSYS, we have found tremendous results. They, both are been compared in many aspects and parameters through which the idea of application of materials become much more effective. In order to know which material is better to use in space applications, one must test in all parameters to justify the result. Hence, we have performed many tests that includes, Von mises stress, Contact Stress, Total deformation, Elastic strain, Factor of safety, Fatigue Life, Temperature Distribution, Thermal stresses.

Aspect	**CFRP**	**Ti-6Al-4V**	**Comparison Summary**
Von Mises Stress	Higher allowable stress (600 MPa)	Lower allowable stress (450 Mpa)	CRFP can withstand higher
Contact Stress	Distributes stress efficiently due to flexibility	Higher stiffness, less deformation	CFRP handles contact stress better but deforms more.
Total Deformation	Higher deformation due to lower modulus	Lower deformation due to higher modulus	Ti-6Al-4V exhibits less deformation.
Elastic Strain	Higher strain tolerance	Adequate strain tolerance	CFRP tolerates more strain.
Factor of Safety	Higher due to higher allowable stress	Lower due to lower allowable stress	CFRP can achieve higher safety factors.
Fatigue Life	Superior fatigue resistance	Good fatigue resistance	CFRP is better for fatigue resistance.
Temperature Distribution	Good thermal stability	Excellent thermal stability and conductivity	Both perform well; Ti-6Al-4V better for heat dissipation.
Thermal Stresses	Lower thermal expansion, less thermal stress	Higher thermal expansion, more thermal stress	CFRP better for minimizing thermal stresses.

Table 4.1 states the clear information regarding the results obtained

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Comparison and Interpretation:
Von mises stress: The allowable stresses of both CFRP and Ti-6A-4V are found to be 600MPa and 450MPa respectively. So, when compared, CFRP has high allowable stresses than that of the Ti alloy that mostly used for space applications.
Contact stresses: It is observed that CFRP distributes stress efficiently due to flexibility and in case of Ti-6A-4V. It has got higher stiffness, less deformation. Which means CFRP handles contact stress better but deforms more.
Total Deformation: When bevel gears of CFRP and Ti-6A-4V materials are subjected to test Total deformation, CFRP undergoes Higher deformation due to lower modulus whereas Ti-6A 4V undergoes lower deformation due to higher modulus. Which means Ti-6Al-4V exhibits less deformation.
Elastic Strain: The materials of CFRP and Ti-6A-4V has tested for Elastic strain and found that Higher strain tolerance is for CFRP and Adequate strain tolerance. So, CFRP tolerates more strain than that of the Ti-6A-4V.
Fatigue Life: CFRP Possesses Superior fatigue resistance and Ti-6A-4V has got good fatigue resistance. And hence, again CFRP is that the CFRP is better for fatigue resistance.
Temperature Distribution: CFRP has a very good thermal stability and Ti-6A-4V has excellent thermal stability and conductivity. When compared, both perform well; Ti-6Al-4V better for heat dissipation.
Thermal Stresses: Lower thermal expansion, less thermal stress for CFRP and Higher thermal expansion, more thermal stress. And finally, CFRP better for minimizing thermal stresses.

VI. Conclusions

In the "Design and Analysis of Bevel Gears for Space Applications" project, a comprehensive evaluation of two critical materials, Ti-6Al-4V (Titanium Alloy) and Carbon Fiber Reinforced Polymer (CFRP), was conducted to determine their suitability for the design of bevel gears intended for use in the harsh conditions of space. The analysis focused on material properties, mechanical and thermal performance, integration and manufacturing challenges, and environmental considerations, providing a detailed understanding of each material's advantages and drawbacks.
Ti-6Al-4V, a widely used titanium alloy, exhibits a high strength-to-weight ratio, excellent thermal stability, and superior fatigue resistance, making it a strong candidate for various aerospace applications. Its ability to perform robustly under high loads and extreme temperatures is well documented. However, Ti-6Al-4V has certain limitations that impact its suitability for space applications, particularly in weight-sensitive designs. The higher density of Ti-6Al-4V contributes to increased overall mass, which is a significant drawback in space missions where weight reduction is crucial. Additionally, Ti-6Al-4V is prone to significant outgassing under vacuum conditions, which can interfere with the spacecraft's delicate instruments and systems. The complexities associated with machining and handling Ti-6Al-4V further add to its manufacturing cost and time, making it less favorable for applications requiring rapid production and integration.
On the other hand, CFRP demonstrates several properties that make it an attractive alternative to traditional metallic materials like Ti-6Al-4V in space applications. CFRP offers an exceptional strength-to-weight ratio, being significantly lighter than Ti-6Al-4V, which directly translates to enhanced performance in weight-sensitive applications. The material also boasts excellent thermal stability and a low thermal expansion coefficient, critical factors in maintaining the structural integrity of components in the fluctuating temperatures of space. CFRP's high resistance to radiation and minimal outgassing make it particularly well-suited to the vacuum and radiation conditions of space, reducing the need for additional protective coatings or treatments. Furthermore, advanced manufacturing processes for CFRP, such as automated fiber placement and resin transfer molding, enable high precision and customization, simplifying assembly and integration into spacecraft systems.
The project's findings emphasize that while Ti-6Al-4V remains a strong candidate for applications requiring minimal deformation and excellent thermal conductivity, CFRP is superior in scenarios

where weight reduction, high fatigue resistance, and higher stress tolerance are paramount. CFRP's advantages in terms of lower thermal stress, better strain tolerance, and superior fatigue resistance make it more suitable for high-performance, weight-sensitive designs, particularly in unmanned space applications. The project underscores the importance of material selection based on the specific requirements of the application, as the choice between Ti-6Al-4V and CFRP can significantly impact the performance, reliability, and efficiency of space missions.

Looking forward, the project highlights several areas for future research and development. These include the creation of new materials with improved strength, thermal stability, and resistance to radiation and wear, which could offer even better performance than current options. The use of AI and machine learning to optimize gear design and the development of miniaturized, lightweight gear systems are also recommended to enhance efficiency and reduce the mass of space systems further. Additionally, innovative lubrication techniques, such as solid lubricants or self-lubricating materials, are necessary to improve the longevity and reliability of gears in space. Finally, the project calls for interdisciplinary collaboration and extensive testing in simulated space environments to validate the performance of materials and designs, ensuring their suitability for real-world applications. Through these efforts, the future of bevel gear design for space applications can be significantly advanced, leading to more robust, efficient, and reliable space missions.

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