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A Comprehensive Study On The Design And Analysis Of A Differential Gearbox

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Abstract: The main objective of this project is to develop a parametric model of a differential gearbox using CATIA-V5, addressing various stages of the design process. Through the analysis, glass-filled polyamide composite material has been identified as the most suitable option for constructing differential gearboxes. It demonstrates effective performance under static loading conditions, particularly when subjected to a torque of 200 N·m. To evaluate material performance, a comparative analysis was conducted using ANSYS 14.5, focusing on different types of stress, including total deformation, equivalent stress, and shear stress. The performance of the glass-filled polyamide composite was compared with that of traditional metallic materials, such as grey cast iron and a Nickel-Chromium-Molybdenum (Ni-Cr-Mo) alloy. The results clearly indicate that the composite material exhibits significantly lower stress and deformation values, making it a superior choice for lightweight and efficient differential gearbox applications.

Keywords- ANSYS, Static Modal Analysis, Assembly Analysis Gearbox Design, Stress.

I. INTRODUCTION:

A differential is a specialized type of planetary gear train designed in such a way that the angular velocity of its carrier equals the average of the angular velocities of the sun and ring gears. This mechanical principle finds wide application across several fields, including automotive systems, aerospace engineering, and mechanical design. To facilitate this averaging function, the differential gear arrangement is configured to maintain a fixed carrier train ratio of R = -1. This ratio suggests that the sun and ring gears are of equal size, resulting in symmetric gear interactions. In practical terms, this configuration can be achieved by coupling the planetary gears of two identical and coaxial epicyclic gear trains, forming a spur gear differential. Alternatively, bevel gears may replace spur gears in the sun and ring gear positions, creating what is known as a bevel gear differential, where the planetary gear is also a bevel gear.

In automobiles, the differential plays a crucial role during turning maneuvers. As the vehicle turns, the outer wheel has to travel a longer distance and therefore rotates faster than the inner wheel. The differential enables this variation in wheel speed, preventing wheel slippage, reducing tire wear, and enhancing steering performance. It achieves this by transmitting input torque from the drive shaft to the rear axle while distributing it between the two wheels based on resistance and wheel path radius. As a result, the rotational speed of the drive shaft becomes the average of the speeds of the two wheels. If one wheel rotates faster, the other compensates by rotating slower, maintaining a balanced torque distribution. This torque transfer occurs through the pinion, which engages with the crown wheel inside the differential. The gear interaction also provides speed reduction through gear ratios. In rear-wheel-drive vehicles, the differential typically connects to the rear axle through half-shafts enclosed in the axle casing. In contrast, front-wheel-drive vehicles often house the differential within the gearbox casing, with the pinion directly mounted to the gearbox's main shaft. Each drive shaft extends from the differential to an individual wheel.

Figure No 1.1: Gear Box

In older 4WD vehicles and tractors, a solid front axle with a differential was standard. However, modern four-wheel-drive systems generally feature independent differentials and drive shafts for both front and rear wheels. Structurally, a differential has one input—connected to the drive shaft—and two outputs linked to the drive wheels. The differential ensures that under normal driving conditions, with minimal tire slippage, the rotational speed of the drive wheels is proportionate to the turning radius. This relationship is dictated by the vehicle's track width and the radius of the turning path.

Beyond automotive use, differentials have played a significant role in analog computing. They have been used to mechanically compute the sum or difference of two values represented by the angular displacements of rotating shafts. The earliest known example of this is found in the Antikythera Mechanism (circa 80 BCE), an ancient Greek device that used a differential to simulate the moon's phases based on its position relative to the sun. The mechanism displayed the moon's phases using a sphere painted with black and white hemispheres.

Similar mechanical principles were employed in other historical innovations, such as the Chinese south-pointing chariot and the 18th-century equation clock. In the 20th century, large assemblies of differentials were used in military analog computers to solve targeting problems, such as determining the correct direction to aim artillery. These applications have mostly disappeared with the advent of modern digital and electronic computing systems, although a few niche or military applications may still exist. Today, the vast majority of manufactured differentials are used in automotive and transport applications, where they continue to serve as essential components in delivering smooth, controlled, and efficient vehicle operation.

II. LITERATURE SURVEY:

Saravanan et. al., and colleagues conducted a mechanical design and performance analysis of a differential gearbox under three varying load conditions. The study focuses on evaluating von Mises stress, strain, deformation, and transmission safety to determine the most suitable material for the gears, based on their specific strength under different operational loads. This research contributes to the development of more efficient differential gearboxes by aiming to reduce weight, enhance energy efficiency, and improve overall performance. Among the materials assessed, Manganese Chromium alloy steel (17Mn1Cr95) demonstrated favorable structural behavior under stress testing. The analysis revealed that this alloy exhibited significantly lower values of stress, strain, and deformation when compared to Carbon Steel and Nickel Chromium Alloy at all tested rotational speeds—2400 rpm, 1600 rpm, and 1000 rpm. These results suggest that Manganese Chromium alloy can be reliably used in differential gears without concerns regarding structural failure. Furthermore, due to its relatively low density, Manganese Chromium alloy contributes to a reduction in the overall weight of the gearbox assembly, thereby enhancing mechanical efficiency. The combination of superior mechanical properties and lighter weight positions Manganese Chromium alloy as a highly effective and practical choice for differential gearbox components. Based on the comparative structural analysis, the study concludes that Manganese Chromium alloy offers optimal performance and is one of the most promising material options for use in modern differential gearbox applications. [1]

Patil, Amey A.; Gaikwad, Vinayak P.; and their team emphasized the importance of weight optimization in engine components as a key factor in enhancing overall engine performance and efficiency. Reducing the weight of cast components can lead to significant cost savings both in the foundry during casting and in subsequent machining operations. To achieve this, reverse engineering techniques were effectively utilized to optimize the weight of the gear casing casting. Using 3D scanning technology, unnecessary and excessive material allowances in the original casting were identified and removed. This refined data was then used to redesign the component with updated allowances. Specialized industrial design and analysis software tools were employed to validate the structural soundness of the redesigned, lighter gear casing. After the digital validation, the optimized component was tested on an actual running engine to ensure functional integrity. The result of this optimization process was a reduction in the casting's weight by approximately 540 grams. This weight reduction not only contributed to lower production and machining costs but also helped reduce the machining cycle time, improving manufacturing efficiency. In financial terms, the optimization of the gear casing translates into an estimated annual savings of ₹2,17,080. This demonstrates that optimizing casting allowances not only benefits component performance but also offers tangible cost advantages by minimizing excess material and reducing processing time.[2]

According to research conducted by Satypal T. Warghat, Dhiraj V. Astonkar, and colleagues, a differential gear system is primarily designed to manage and distribute power to the rear wheels of a vehicle. One of the most critical functions in automotive design is enabling the rear wheels to rotate at different speeds during a turn. The differential assembly typically consists of a combination of gears and three shafts. The central shaft, known as the propeller shaft, transmits torque and rotational motion to the differential unit. The remaining two shafts act as axles for the rear wheels. These components are connected through a bevel gear arrangement involving a pinion and a crown gear. The pinion transfers torque from the propeller shaft, while the crown gear allows the vehicle to achieve the necessary turning speed. Together, the crown gear and pinion form the core mechanism of the differential, ensuring effective torque distribution and enhancing the durability of the transmission system. The study further focuses on evaluating various materials—such as Grey Cast Iron, Structural Steel, Titanium Alloy, and Polyethylene—for manufacturing these gears. The goal is to determine the most suitable material for high-speed applications based on performance factors like von Mises stress, deformation, and transmission safety. The 3D modeling of the crown gear and pinion was carried out using CATIA, while structural analysis, including stress and deformation evaluation, was conducted using ANSYS 15.0. A finite element method (FEM) was applied to compare performance across different materials, ultimately identifying the optimal choice for strength and reliability under high-speed operating conditions. [3]

Studies of this nature play a crucial role in identifying the most suitable material for Crown Gear and Pinion assemblies. Among the materials examined—Grey Cast Iron, Structural Steel, Titanium Alloy, and Polyethylene—Grey Cast Iron offers a balanced combination of properties that make it particularly effective for power transmission applications. This research involves the comprehensive design and simulation analysis of a crown gear and pinion set, evaluating performance across various materials. The study successfully demonstrates the importance of the differential system in efficiently transferring power within automotive applications. Using CATIA for modeling and ANSYS 15.0 for simulation, the crown gear and pinion assembly was tested with multiple material configurations. The results indicate that Grey Cast Iron outperforms the other materials considered in terms of stress resistance and structural stability. Specifically, the maximum von Mises stress observed in the pinion was 157.5 MPa, while the gear experienced a peak stress of 315.34 MPa. The total deformation across the assembly was found to be just 0.09 mm, indicating a high level of rigidity and durability. Based on these findings, Grey Cast Iron emerges as the most effective material for Crown Gear and Pinion assemblies when compared to alternatives like Structural Steel, Titanium Alloy, and Polyethylene. [4]

Researchers Subhajit Konar, Vijay Gautam, and their team highlighted the critical role of the differential gear system in enabling smooth vehicle turning by allowing differential motion between the left and right drive axles. During a turn, the outer wheels must cover a greater distance than the inner wheels, and the differential facilitates this variation in wheel rotation. Additionally, it transfers torque from the propeller shaft to the drive wheels. In rear-wheel drive vehicles, the differential is typically located on the rear axle, while all-wheel drive vehicles require differential systems on each axle. The study focuses on the design and analysis of an open differential for a widely used automobile model. To assess the mechanical behavior of the system, the researchers applied the AGMA standard equations, Hertzian contact stress formulas, and a modified Lewis equation. These theoretical results were validated and compared with Finite Element Analysis (FEA) using ABAQUS. It was observed that the Lewis equation yields more conservative estimates than AGMA, though there was strong correlation between the analytical and FEA outcomes. The maximum bending and contact stresses in the gear teeth were computed using the Lewis, AGMA, and Hertzian equations, as well as through FEM simulation. The differential analyzed in the study was made from AISI 4340—a high-strength alloy steel. The calculated values for both maximum bending and contact stresses were found to be significantly below the allowable limits, and all safety factors exceeded one, indicating a reliable and robust design. In conclusion, the use of multiple analysis methods—including Lewis and Hertz equations, AGMA standards, and FEM—provided consistent and reliable data. The Lewis method, though more conservative, aligns closely with the numerical findings and confirms the structural safety of the differential gear under expected operating conditions. [5]

As highlighted by R. Karthick, V. Mohan Kumar, and colleagues, modern businesses and infrastructure heavily depend on vehicles for the transportation of goods, with tippers playing a vital role in logistics. A key component in these vehicles is the differential, which is responsible for transferring torque from the engine to the rear wheels, especially under heavy loading conditions. Ashok Leyland tippers, in particular, utilize a dual differential and dual rear axle system. While this setup is designed to handle heavy loads, it can be prone to failure under extreme stress. To address these challenges, the present research aims to enhance the durability and performance of the differential system. Specifically, it focuses on the design and analysis of the crown wheel and pinion of the rear axle differential, which are made from G-45 forged steel. The objective is to develop a precise geometric model of these components using CATIA V5 software. Following this, HyperMesh 12 is employed to refine the geometry and generate a detailed finite element mesh. The finite element analysis is carried out using ABAQUS software to evaluate deformation and stress variations in the differential assembly. This analytical approach helps assess strength characteristics and predict potential failure points. Ultimately, this research supports optimizing the design to ensure long-term reliability and performance of the differential under demanding operational conditions. [6]

K. Dinesh Babu, M. Siva Nagendra, and their team have focused their research on the mechanical design of a differential gearbox, including a detailed study of the gears within it. In their analysis, both grey cast iron and aluminum alloy were considered as potential materials. Currently, cast iron and cast steel are the dominant materials used for gears and gear shafts. However, to reduce the overall weight of light utility vehicles, the use of aluminum alloy in the differential gearbox is being explored. For this study, a friction coefficient of 0.2 between the gear teeth was assumed. The results indicate that both grey cast iron and aluminum alloy are suitable for automotive differential gearboxes, with aluminum alloy preferred for SUVs and light utility vehicles due to its significantly lower weight. Separately, Toshita Dhande, R. B. Patil, and their collaborators have emphasized the importance of the gearbox casing in pipe-pulling machines. Vibrations occurring in the gearbox housing during operation can lead to premature failure of the bearings and worm gear. Reducing these vibrations can significantly enhance the lifespan of these components. To achieve this, resonance within the gearbox casing is mitigated through design optimization. This involves adjusting the housing's shape, structure, and the profile and thickness of stiffeners to improve rigidity. The vibration characteristics of the gearbox cover were investigated using both analytical and experimental approaches. ANSYS software was utilized to compute the natural frequency response of the gearbox housing. The study also employed FFT analysis to validate the accuracy of the results, thereby enabling precise determination of the casing's true resonant frequencies. [7]

The gearbox plays a vital role in all mechanical systems. Minimizing vibrations within the gearbox housing is essential to prolong the lifespan of the internal gears and bearings. Previous research indicates significant potential for improvements in this area. Finite element analysis (FEA) is the most commonly used method for identifying vibration mode shapes. Virtual prototyping is primarily carried out using ANSYS software. Researchers have also compared results from different simulation tools, while some have conducted physical tests using specialized equipment. Additionally, many studies utilize FFT analyzers to validate the simulation data. Overall, there is strong correlation between the simulated results and experimental observations. [8]

According to researchers Vijayababu, Ch. Sekhar, and colleagues, a differential is engaged when the outer wheel of a vehicle follows a larger radius than the inner wheel during a turn. In such cases, the outer rear wheel rotates faster than the inner one. If the rear wheels are rigidly connected on the same axle, the inner wheel tends to slip, causing uneven tire wear, steering difficulties, and unstable load handling. The inner axle housing assembly contains the rear differential axles, wheels, and bearings. The differential itself consists of gears arranged to transmit power from the drive shaft to the rear wheels. This study focuses on identifying the best material for the gears within the differential gearbox under higher speed conditions by analyzing stress, displacement, and weight reduction. The project specifically examines the differential gearbox of the Ashok Leyland 2516M model. Load calculations are performed when the gears operate at varying speeds within an RPM range of 2400 to 5000. Structural analysis is carried out to determine the optimal material based on parameters like stress, displacement, and weight. Results indicate that aluminum alloy exhibits stress levels within acceptable limits, making it a safe choice for the differential gears. Across all tested speeds, aluminum alloy shows lower stress values compared to alloy steel and cast iron. Consequently, aluminum alloy is identified as the most suitable material for the differential. [9]

III. EXPERIMENTAL INVESTIGATION:

The main aim of this project is to identify the most suitable material for the gears in a gearbox operating at high speeds. This involves analyzing factors such as stress, displacement, and shear stress, while also prioritizing weight reduction in the mechanical design. Additionally, a contact analysis of the gear assembly, designed to transmit 200 Newton-meters of torque, is conducted. The study also includes evaluating different material options by altering the components under consideration. The differential gear was modeled using CATIA software, and the structural performance of various traditional and composite materials under the specified loading conditions was assessed using the ANSYS 14.5 finite element analysis program.

Problem Identification & Objective are as follows:

Solid modeling refers to a set of foundational principles used for the mathematical and computational representation of three-dimensional solid objects. It encompasses the theories and algorithms that enable the creation, modification, and manipulation of physical objects, their properties, and associated abstract concepts. In this context, parametric modeling techniques are employed to develop solid models of bevel and spur gears. By adjusting key variables—such as the number of teeth, pressure angle, helix angle, tooth thickness, and module—bevel gears with various dimensional configurations can be generated. The model highlights dependent parameters and their interrelationships, alongside the essential variables used during the bevel gear generation process. The reference model includes five distinct bevel gears, each with unique parameter values based on specific inputs. The workflow for producing a parametric solid model of a bevel gear is illustrated in a figure, which also displays examples of the resulting solid gear models.

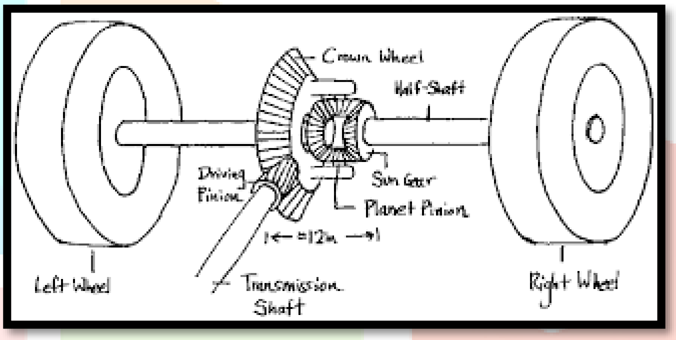

Figure 3.1: Gear Box Setup

IV. EXPERIMENTAL RESULTS:

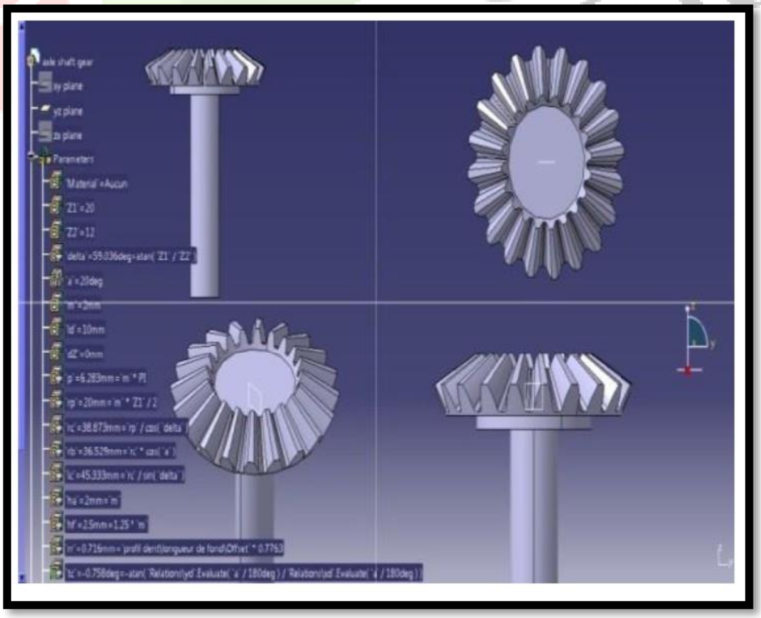

Figure 4.1: Axle Side Shaft Gear

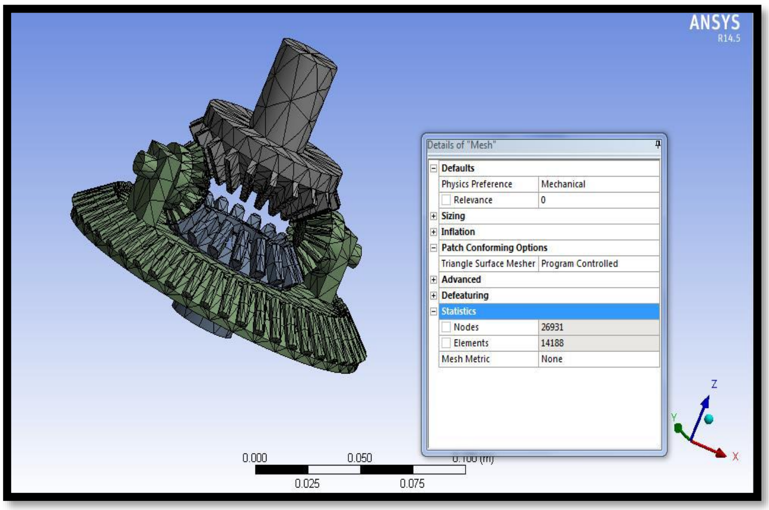

Figure 4.2: Gear Box Meshing

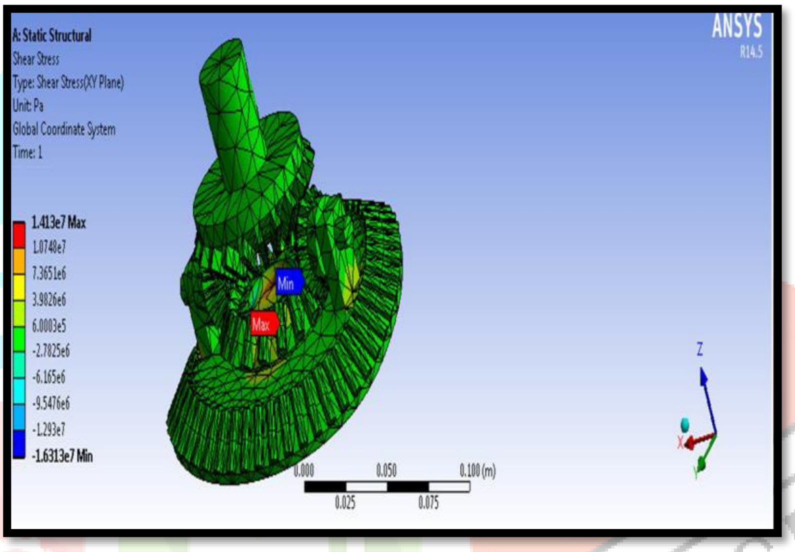

Figure 4.3: Shear Stress of Grey Cast Iron

This research is conducted to investigate structural parameters such as stresses, shear stresses, deformation, and related factors. The study specifically examines the performance of two materials: grey cast iron and polyamide.

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