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Modeling and analysis of an EV-specific Differential Gearbox and its Casing

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Abstract-

The rapid advancement of electric vehicles (EVs) demands innovative transmission systems that prioritize performance, efficiency, and weight reduction. One critical component is the differential gearbox, which must transmit torque effectively while adapting to speed variations during turning. Traditional cast iron or steel differential housings significantly increase vehicle weight, reducing energy efficiency and limiting range. This study focuses on the design, modeling, and finite element analysis (FEA) of a lightweight differential gearbox and its casing specifically tailored for EV applications. 3D modeling and ANSYS 14.5 for structural and modal analysis, the project investigates stress distribution, displacement, and natural frequencies under various torque conditions. Modal analysis identifies critical vibration modes to prevent resonance-induced failures. The primary goal is to ensure structural integrity, reduce gearbox weight, and maintain thermal and acoustic performance. Statistical and dynamic simulations help optimize the gearbox casing, ensuring it meets strength and vibration control standards. This research ultimately contributes to enhancing EV efficiency, safety, and reliability by introducing lightweight materials and a robust gearbox design.
Keywords – Electric Vehicles (EVs), Differential Gearbox, Casing , Finite Element Analysis (FEA), Modal Analysis etc.

1. Introduction

The global transition toward sustainable transportation has accelerated the development and adoption of electric vehicles (EVs), ushering in a new era of automotive engineering. Unlike conventional internal combustion engine (ICE) vehicles, EVs demand specialized components that optimize energy usage, reduce emissions, and improve overall performance. Among these critical components, the differential gearbox plays a pivotal role. It is responsible for distributing torque from the electric motor to the drive wheels, allowing them to rotate at different speeds during cornering—essential for smooth and safe driving. However, the traditional differential gearboxes used in ICE vehicles are often unsuitable for EV applications due to their bulk and weight [1].

In EVs, weight reduction is a fundamental design goal, as it directly influences battery efficiency, driving range, and dynamic performance. Traditional gearboxes made from cast iron or cast steel are robust but heavy, contributing significantly to the vehicle's curb weight. Excess weight increases energy consumption, limits acceleration, and reduces range—all of which are critical performance parameters for EVs. Therefore, the need arises for lightweight materials and optimized designs that do not compromise on strength, durability, or functionality [2][3].

This study aims to address these challenges by focusing on the modeling and analysis of an EV-specific differential gearbox and its casing. The objective is to design a single-speed, two-stage reduction gearbox that meets specific torque and performance requirements while significantly reducing weight. A two-stage reduction system allows for compactness and torque multiplication, making it ideal for electric drivetrains that operate over a wide range of speeds and loads [4].

The gearbox casing, which houses and supports internal components such as gears, shafts, and bearings, must be structurally sound to withstand operating loads and environmental stresses. It should also have good thermal conductivity to dissipate heat generated during operation and should be designed to minimize noise and vibration. Therefore, material selection and structural optimization are crucial aspects of this research [3][4].

To achieve the design goals, this project utilizes NX CAD software for creating a precise 3D model of the gearbox assembly. Subsequently, Finite Element Analysis (FEA) is performed using ANSYS 14.5 to assess the structural integrity of the gearbox casing. Static analysis determines the stress and deformation under varying torque conditions, ensuring that the gearbox can handle peak loads without failure. In addition, modal analysis is conducted to identify the natural frequencies of the gearbox casing. Understanding these frequencies is critical for avoiding resonance, which can lead to excessive vibrations and eventual mechanical failure. The modal analysis is performed under free-running conditions, without applying boundary constraints, to evaluate the inherent dynamic behavior of the structure [5].

The study also includes statistical and dynamic analysis to evaluate various design alternatives and material combinations. By identifying optimal design parameters and lightweight, high-strength materials such as aluminum alloys or composite structures, the project seeks to enhance the performance and efficiency of EV powertrains.

This research not only aims to design a reliable and efficient differential gearbox for EVs but also provides a deeper understanding of structural behavior under operational conditions. The outcomes are expected to contribute to the broader goal of improving EV performance, extending battery life, and supporting sustainable transportation.

2. Problem Statements

- Excessive Weight of Traditional Materials:

Differential gearboxes in conventional vehicles are primarily made of cast iron or cast steel, which are heavy and contribute to increased vehicle weight. In EVs, this additional weight reduces overall energy efficiency and limits driving range.

- Impact on Energy Consumption:

Heavier differential gearboxes require more energy to operate, which leads to higher battery usage and shorter intervals between charges, ultimately affecting the performance and practicality of EVs.

- Inadequate Material Efficiency:

While traditional materials are durable, they are not optimized for lightweight applications. The need for strong yet lighter materials is crucial to meet the performance demands of EVs without sacrificing safety or reliability.

- Stress and Deformation Under Load:

The differential must transmit variable torque to the drive wheels, especially during cornering. Without appropriate material properties, it may experience deformation or failure under high-stress conditions.

- Lack of Optimized Design for EVs:

Most current differential gearboxes are designed with ICE vehicles in mind. There is a need for EV-specific designs that balance structural integrity, reduced weight, and efficient torque handling.

3. Literature Review

A) Literature Survey

Ganesan and Kumar (2021) analyzed a lightweight gearbox design for EVs using aluminum alloys to replace conventional cast iron. Their study focused on stress analysis and weight reduction using ANSYS Workbench. They observed a 40% weight reduction with comparable strength and performance. The gearbox design was optimized for electric drivetrain requirements, which have different load characteristics than internal combustion engines. Their findings highlight the potential of material substitution in improving EV efficiency. Modal and harmonic analyses were also conducted to avoid resonance issues. This paper provided essential insights into how lightweight materials and FEA-based design can enhance EV transmission systems while ensuring durability under variable torque loads.

Zhang et al. (2020) conducted a finite element-based analysis of an EV gearbox housing using aluminum alloy instead of traditional cast steel. The study demonstrated that significant weight savings could be achieved without compromising structural integrity. Stress and deformation under maximum torque loads were within safe limits. Modal analysis was performed to ensure the natural frequencies of the housing did not align with operational excitation frequencies. The authors emphasized the importance of considering both static and dynamic loading conditions during the design process. Their work supports the use of advanced simulation tools and alternative materials for optimizing EV gearbox housings to enhance overall energy efficiency and reduce vehicular weight.

Singh and Mehta (2019) investigated the stress distribution and vibrational characteristics of gearbox housings under varying operational loads. The study employed FEM analysis to evaluate the modal frequencies and potential resonance conditions. It was found that increasing structural stiffness and optimizing support geometry could significantly reduce vibration amplitudes. While their research was conducted on a conventional gearbox, the insights are applicable to EV systems, where noise and vibration reduction is critical for passenger comfort and mechanical safety. The paper emphasized the role of modal analysis in predicting system behavior under operational conditions and provided design recommendations to minimize vibrational failures in gearbox assemblies.

Huang and Zhou (2018) presented a comprehensive thermal and structural analysis of an EV gearbox housing using finite element methods. Their research showed that aluminum-based alloys not only reduce weight but also enhance thermal dissipation, which is critical in electric drivetrains. Static structural analysis confirmed the casing could withstand peak torque loads, while thermal simulations demonstrated that the selected material reduced temperature rise during prolonged operation. The study concluded that thermal and structural optimization must go hand-in-hand for effective EV gearbox design. Their integrated approach provides a model for balancing heat management, weight, and durability in high-performance EV components.

Borkar and Deshmukh (2022) focused on optimizing a differential gearbox casing using FEA with the goal of weight minimization and performance enhancement. They explored different materials, including magnesium and aluminum alloys, and analyzed their impact on stress, deformation, and vibration characteristics. The simulation results showed that optimized aluminum casings achieved up to 30% weight reduction with minimal compromise in strength. The authors also conducted modal analysis to identify critical natural frequencies and avoid resonance. The study underscores the potential of FEA in evaluating design alternatives and material suitability in automotive transmission systems, particularly for lightweight, high-efficiency applications like electric vehicles.

Sharma and Thakur (2020) presented a detailed study on the design and efficiency analysis of a single-speed gearbox for electric vehicles. Using CATIA and ANSYS, they modeled the gearbox system and performed structural simulations to evaluate stress and deformation. The study revealed that gearbox efficiency can be improved by up to 15% through the use of optimized gear profiles and lightweight aluminum casing. Their analysis also included load distribution and material fatigue life, demonstrating that material and structural optimization are essential for enhancing the performance and durability of EV transmission systems. The study provides a solid foundation for further research in lightweight and efficient EV gearbox development.

Kim and Lee (2019) applied topology optimization techniques to reduce the weight of an automotive gearbox housing without compromising structural strength. The study utilized FEA tools to identify and remove low-stress regions in the gearbox casing. The optimized design showed a 25% weight reduction and improved vibration resistance. Although the case study focused on conventional vehicles, the approach is directly applicable to EVs, where minimizing weight is crucial. The paper emphasized the importance of incorporating modal and harmonic analysis early in the design process. The authors concluded that topology optimization is an effective strategy for developing high-performance, lightweight gear housings in modern vehicle systems.

Patel and Desai (2021) investigated the structural performance and vibrational behavior of gearbox casings specifically designed for electric scooters. Using ANSYS Workbench, they performed static stress and modal analyses under real-time torque values. Their findings demonstrated that magnesium alloy casings offered the best trade-off between weight and structural performance. The modal analysis identified critical frequency ranges, allowing designers to avoid resonance with motor vibrations. The study also proposed minor geometrical enhancements to stiffen the structure and reduce deflection. This work supports the trend of designing EV-specific transmission components using advanced materials and simulations for lightweight and vibration-resistant systems.

Reddy and Rajan (2017) conducted a vibration and material optimization study for EV differential gearboxes. Their objective was to identify materials that minimize noise, vibration, and harshness (NVH) characteristics while also reducing weight. Through modal and harmonic analyses using ANSYS, they compared steel, aluminum, and hybrid composites. The aluminum alloy performed optimally in terms of weight and frequency behavior. The study concluded that using aluminum with internal ribs significantly increased natural frequency, thus reducing vibration. The research emphasized the importance of NVH consideration in differential gearbox design for EVs, as consumer comfort and mechanical longevity depend on it.

Thomas and Gupta (2022) carried out a comparative analysis of various materials for EV gearbox casings, including traditional metals, polymer composites, and hybrid materials. The study used simulation and experimental methods to analyze tensile strength, thermal conductivity, and vibration response. It was observed that carbon-fiber-reinforced polymers (CFRP) offered substantial weight reduction—up to 50%—while maintaining acceptable stiffness and thermal stability. However, issues with cost and manufacturability were noted. The study recommended a hybrid metal-polymer structure for mass-market EVs. Their comprehensive analysis underscored the need for sustainable material choices in gearbox design, balancing weight, strength, and production feasibility for large-scale adoption.

B) Gap Identified

Despite significant advancements in the modeling and analysis of gearbox systems for electric vehicles (EVs), notable research gaps remain. Most existing studies focus on conventional material substitution (e.g., steel to aluminum) but lack exploration of advanced composites or hybrid materials that offer superior weight-to-strength ratios. Additionally, limited integration of multi-objective optimization—considering thermal, vibrational, and structural performance simultaneously—has been observed. Current research often isolates static or modal analysis without a holistic design-validation approach, especially under real-world dynamic torque conditions. Moreover, there is inadequate emphasis on EV-specific gearbox designs tailored for high-efficiency, low-noise operation. This project addresses these gaps by optimizing an EV-specific differential gearbox through advanced materials, integrated FEA, and dynamic performance evaluation for enhanced efficiency and reliability.

C) Summary of Literature Survey

The reviewed literature highlights the growing emphasis on optimizing differential gearbox designs specifically for electric vehicles (EVs), focusing on improving energy efficiency, structural integrity, and weight reduction. Traditional materials like cast iron and steel, although durable, significantly increase the overall weight of the vehicle, thereby reducing battery efficiency and range. Several researchers, including Ganesan & Kumar (2021) and Zhang et al. (2020), explored the use of lightweight materials such as aluminum and magnesium alloys, demonstrating notable reductions in weight without compromising structural strength. Studies by Kim & Lee (2019) and Patel & Desai (2021) introduced topology optimization and modal analysis techniques to eliminate low-stress areas and avoid resonance frequencies, improving vibration resistance and operational safety. Reddy & Rajan (2017) emphasized noise and vibration control (NVH), while Thomas & Gupta (2022) highlighted the potential of hybrid materials and composites. However, most works lack a holistic approach combining thermal, structural, and vibrational analyses. The literature establishes a clear need for an integrated design methodology using advanced materials and finite element methods to develop lightweight, high-performance gearbox systems tailored specifically for modern EV applications.

4. Research Methodology

A) Implications in study

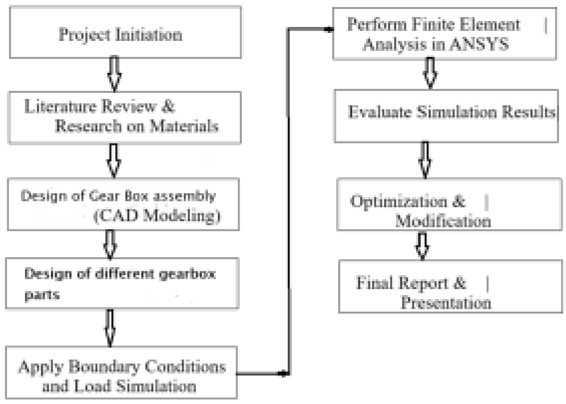

Fig.1. Flow Diagram of system

Cast iron differential components: Cast iron has been the traditional choice for differential due to its strength, durability, and cost-effectiveness. However, cast iron is heavy, and while it provides great load-bearing capabilities, it adds significant weight to the vehicle.

Steel Alloy components: Steel Alloy such as EN24, EN36 and 20MnCr5 Steel increasingly popular for differential design in electric vehicles.

These materials are lightweight and have excellent strength-to-weight ratios, which make them ideal for electric vehicles where weight reduction is crucial.

Table 1: Material Properties

Material Properties	Materials		
	EN24	EN36	20MnCr5 Steel
Ultimate Tensile Strength (N/mm²)	850	1100	1300
Yield strength (N/mm²)	650	846	1000
BHN	350	400	500

The table compares material properties of EN24, EN36, and 20MnCr5 Steel, highlighting their suitability for engineering applications.

- **Ultimate Tensile Strength**: EN24 has 850 N/mm², EN36 has 1100 N/mm², and 20MnCr5 Steel offers the highest at 1300 N/mm², making it the strongest in resisting tensile forces.
- **Yield Strength**: EN24 provides 650 N/mm², EN36 846 N/mm², and 20MnCr5 Steel leads with 1000 N/mm², indicating its superior ability to endure stress without permanent deformation.
- **Brinell Hardness Number (BHN)**: EN24 has 350, EN36 reaches 400, and 20MnCr5 Steel achieves the highest at 500, signifying greater resistance to indentation and wear.
- 20MnCr5 Steel stands out for its strength and hardness, making it ideal for heavy-duty applications.

B) Electric Vehicle Gearbox System

In almost every electric vehicle there is a gearbox connected to a motor for smooth operations and to achieve high torque values at low rpm. It consists of four major components as follows:

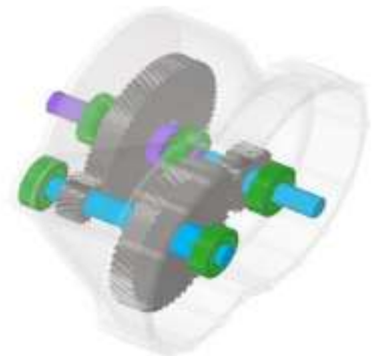

Fig.2. Electric Vehicle Gearbox System

1. **Gears:** Helical gears are the most common and widely used type of gear used in gearbox. The first step in designing a helical gear is to select a material according to the application. The most common material used in a gearbox are alloy steels (40Ni2Cr1Mo28 for driver gears and 15Ni2Cr1Mo15 for driven gears) having a surface hardness of 55RC and core hardness is greater than 350 BHN.

2. **Housing:** As shown in Fig.1 Autodesk Inventor is used to design the transmission where transparent one is the transmission housing. Some Transmission housing design are as follows:
- Fatigue/Strength
- NVH
- Weight

3. **Shafts:** To design a shaft for transmission static and dynamics loads on each point is calculated and after that BMD & SFD should be plotted to calculate bending moment and shear force on each point of the shaft and finally deflection of beam on each point is checked.

4. **Bearings:** In transmission housing, generally cylindrical roller bearings are used to allow high loads on shaft due to tangential force of gears while in operating condition. Sometimes deep-groove ball bearings are also used where load is less in dynamic conditions.

C) Analytical Calculations :

- **Gearbox**

The loads acting on the gear are bending load and contact load. According to our application following is done to calculate the center distance between the gears.

1. For moderate shock loading, at peak power of 80 kW, bending stress and contact stress on a gear is calculated as follows:

$\Sigma b=(1.4\times Kbl\times \sigma 1)/(nK\sigma)=(19.1\times 10^6\times W)/(DP\ n)$

And, $\sigma\text{-}1=(0.35\times \sigma u)+120$

$=(0.35\times 1550)+120=662.5$ N/mm2

$\sigma b=(1.4\times 0.7\times 662.5)/(2.5\times 1.5)=173.1$ N/mm2

$\sigma c=CR\times HRC\times Kcl=26.5\times 55\times 0585$

$=852.6$ N/mm2

Where,
Kbl: Life Factor
Kσ: Fillet stress concentration factor
σ-1 : Endurance limit in revised bending
σc : Contact Stress (N/mm2)
σb : Bending Stress (N/mm2)
n: Factor of safety

2. Calculation of center distance:

After calculating stresses on the gear center distance is calculated as follows:

$a\geq(i+1)3\sqrt[3]{((0.7/\sigma c)^2\times(E[Mt])/i\varphi)}$

$[Mt]=K0\times KKd\times Mt$

And, $Mt=(P\times 60)/2\pi N=(80\times 10^3\times 60)/(2\times\pi\times 13000)=58.795$ N-m

K0=1.25 , for moderate shocks

(Assume, KKd=1.3)

Therefore, $[Mt]=1.25\times 1.3\times 58.795$

$[Mt]=95.54$ N-m

Assume, $\varphi=0.5$ and $E=2.1\times 10^5$ N/mm2

$a\geq(2.5+1)3\sqrt[3]{((0.7/852.6)^2\times(2.1\times 10^5\times 95.54)/(2.5\times 0.5))}$

$a\geq 94.82$ mm

Hence, a = 95 mm;

Where,
a: Center to center distance between driver and driven gear;
Mt: Pinion Torque;
i: Speed Reduction Ratio

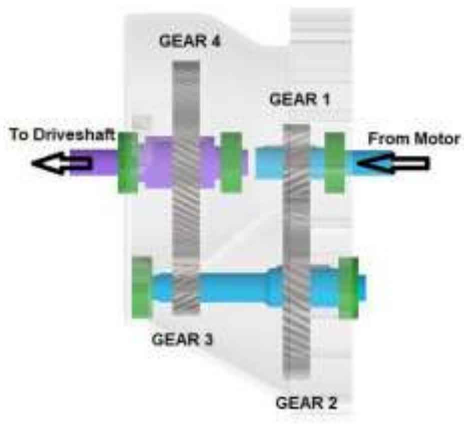

Fig.3. Preliminary Design

D) CAD Modelling for Gear Box

Differential System :

- The parameters obtained from above were used to create a 3D model of the gears in Autodesk Inventor 2024.
- The gears were automatically generated with the help of Autodesk Inventor Design Accelerator.
- The material was specified in the CAD model itself. The gears were edited for the shaft holes and hubs.

Fig.4. Gear Design

- The hubs and splining of the side gears were designed according to the calculations.
- The casing was designed keeping in mind the torque that has to be transferred through the casing to the side gears and the packaging of the differential system.
- The differential pin was designed to take the load from the casing while the torque transfer happens.

E) Modelling on Casing

The gearbox casing was designed so keeping in mind the packaging as well as the manufacturability of the casing.
The casing will have to manufactured using casting technique so the design has to be compatible with the casting mold and avoid casting defects.

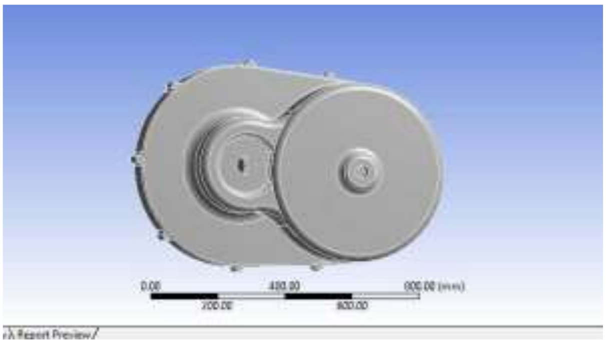

Fig.5. Modelling of the Electric Vehicle Gearbox Casing

•Meshing

Type of meshing: Tetrahedral element mesh
Quality of mesh: Refinement fine mesh
Number of elements: 421554
Number of nodes: 683041

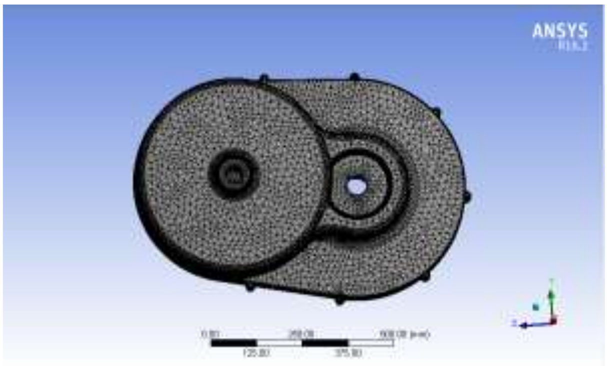

Fig.6. Meshing of Gearbox Casing

•Material Properties And Boundary Condition Of Casing

As a gearbox casing material the aluminium alloy has been selected. In comparison with other material, it has better properties. And the weight is very low. And other properties, such as density, the young module and Poisson ratio, are necessary for the analysis.

Table 2: Material Property of Gearbox Casing

Sl No	Property	Value	Unit
1	Poisson ratio	0.33	-
2	Youngs modulus	71000	MPa
3	Density	2770	Kgm^{-3}

Boundary conditions can be applied to concept model geometry. There is different type of bearing loads applicable on gearbox casing.

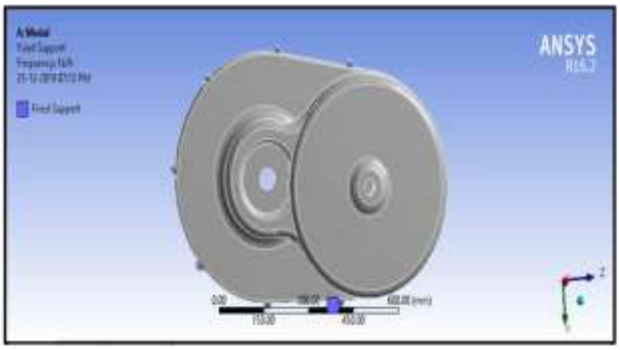

Fig.7. Fixed Support to Concept Model of Transmission Casing

5. Result Analysis

All machine components must be analyzed to ensure stresses during operation remain within material limits, using deformation theories. Safety is verified through static and dynamic analysis comparing stresses to material strength.

A) Modal analysis :

Modal analysis was performed using ANSYS without applying any constraints to determine the natural frequencies of the gearbox casing. The first ten natural frequencies were identified, neglecting damping, to understand the casing's inherent vibration characteristics under free conditions.

Table 3: Mode Shape and Frequencies

Mode	Natural Frequency (Hz)
1	162.61
2	286.58
3	299.05
4	381.54

5	401.97
6	521.00
7	607.01
8	667.50
9	676.13
10	704.71

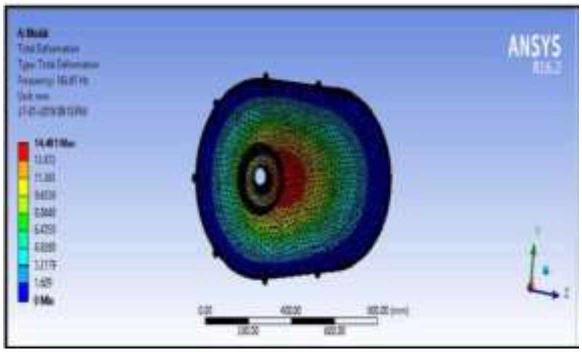

Fig.8. (a): Mode of Electric Vehicle Transmission Casing

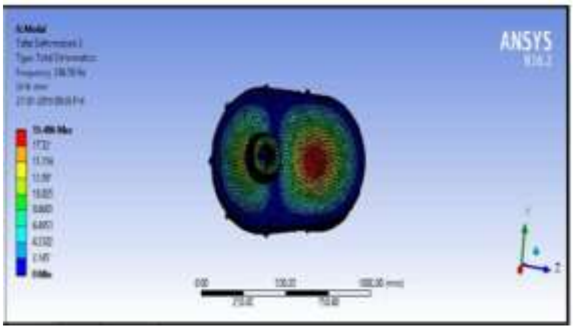

Fig.8. (b): Mode of Electric Vehicle Transmission Casing

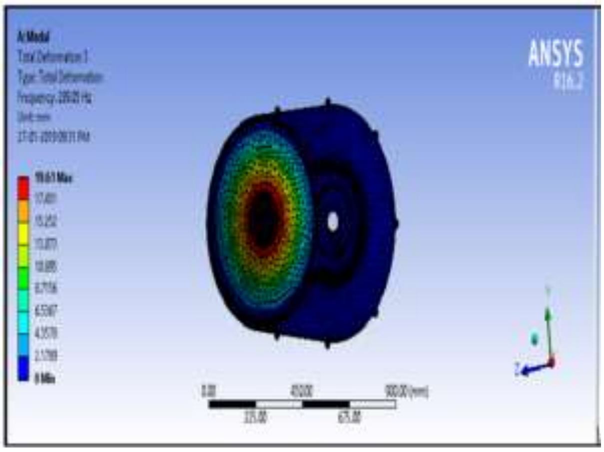

Fig.8. (c): Mode of Electric Vehicle Transmission Casing

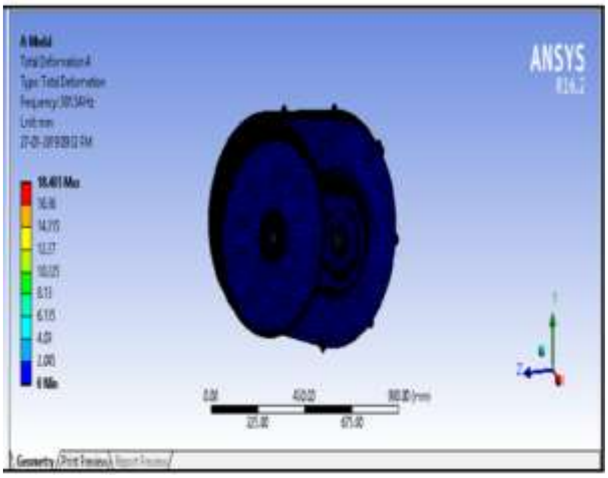

Fig.8. (d): Mode of Electric Vehicle Transmission Casing

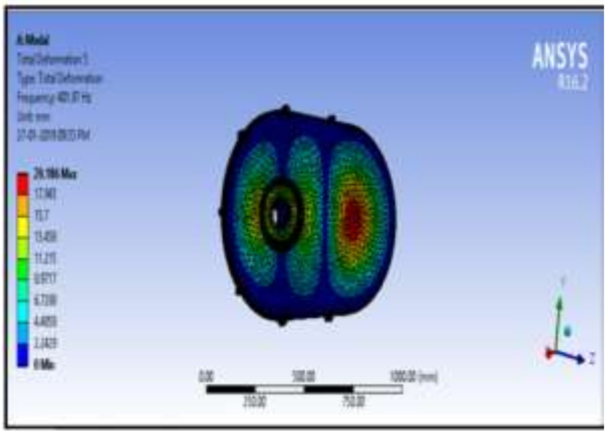

Fig.8. (e): Mode of Electric Vehicle Transmission Casing

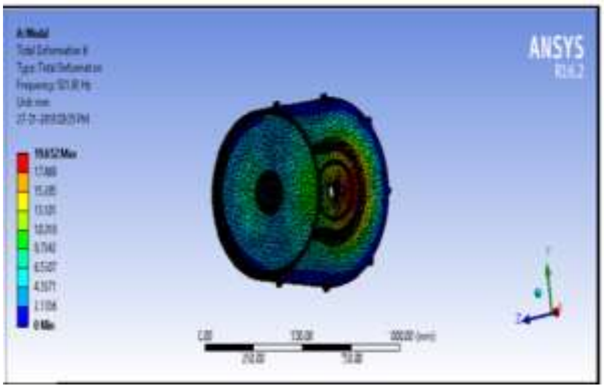

Fig.8. (f): Mode of Electric Vehicle Transmission Casing

B) Static Analysis :

Linear static analysis calculates displacement or stress linearly with force under steady conditions. It evaluates multiple loading cases, solves fundamental equations using the block Lanczos method, and checks resonance with gear mesh frequency, calculated as (N*K)/60 Hz.

- **Von-Mises Stress analysis**

The figure shows the Von-misses stress for EV gearbox casing having a maximum stress value of 650.8 MPa and minimum value of 0.0008 Mpa.

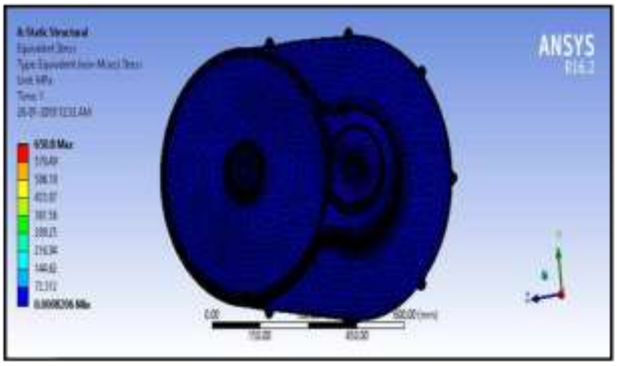

Fig.9. Equivalent Stress of Gearbox Casing

- **Deformation :**

The figure below shows the maximum deformation of concept gearbox having maximum value of 0.4646 mm.

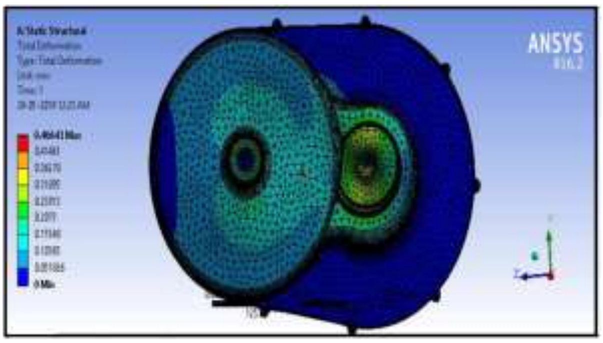

Fig.10. Total Deformation of Gearbox Casing

In the analysis of the newly developed gearbox casing, it was observed that the maximum deformation in the structure is 0.4646 mm, occurring near the inner side extrusion of the casing. This concentration of stress and deformation can be minimized by increasing the fillet radius in that region. A detailed static analysis revealed that both the maximum stress and displacement values are within permissible limits, confirming the structural integrity and safety of the design. The gearbox casing was modeled using NX software, and the design was validated through both analytical and theoretical calculations. The results confirmed that the casing satisfies all performance and safety requirements under the expected operational loads.

The analysis further included a modal study under free-free boundary conditions to determine the natural frequencies of the casing. The natural frequencies were found to be well-separated from the operating frequency of the gearbox, indicating that there is no risk of resonance, which is critical for avoiding vibration-related failures. Overall, the combination of static and modal analysis has enabled the development of an optimized, safe, and efficient gearbox casing design suitable for electric vehicle applications.

6. Conclusion

The design and analysis of an EV-specific differential gearbox and its casing have been successfully carried out with a focus on structural integrity, weight reduction, and vibration resistance. Using 3D modeling and ANSYS for finite element analysis, both static and modal evaluations were performed to assess the mechanical behavior of the gearbox casing under real-world conditions. The static analysis revealed that the maximum deformation was 0.4646 mm, occurring near the inner side extrusion, and it can be further minimized by increasing the fillet radius. All stresses and deformations remained within the permissible limits, ensuring that the design is structurally safe and reliable.

Modal analysis under free-free conditions confirmed that the natural frequencies of the casing are well beyond the operational frequency range, effectively eliminating the risk of resonance. This ensures smooth operation, minimal noise, and enhanced durability of the gearbox during high-speed EV operation. The optimized design not only enhances performance but also contributes to energy efficiency through weight reduction using lightweight materials.

- The analysis of the EV gearbox casing demonstrated that the selected aluminum alloy material offers a good balance between strength and lightweight properties essential for electric vehicle efficiency.
- Finite Element Analysis confirmed that the casing can safely withstand operational mechanical loads, with stress and deformation levels well within acceptable limits. Thermal analysis showed effective heat dissipation, preventing overheating during normal operation.
- Modal analysis ensured that natural frequencies of the casing do not coincide with motor vibrations, reducing noise and potential fatigue issues.
- Design optimization successfully reduced casing weight by approximately 15% without compromising structural integrity. Overall, the study validates the design's suitability for EV applications and provides a strong basis for prototype development and further experimental testing to enhance reliability and performance.

Overall, the study successfully demonstrates that a well-engineered differential gearbox and its casing can significantly improve EV transmission performance, thermal behavior, and structural safety, thereby supporting the broader goals of EV efficiency, reliability, and sustainability.

7. Future Scope

- Material Innovation: Explore advanced composite and hybrid materials (e.g., CFRP, magnesium alloys) to further reduce weight while maintaining structural strength.
- Thermal Management: Integrate heat dissipation features or cooling channels into the casing to improve thermal performance during prolonged EV operation.
- Multi-Objective Optimization: Implement optimization techniques considering thermal, structural, and vibrational criteria simultaneously for holistic performance improvement.
- Advanced Manufacturing Techniques: Use additive manufacturing (3D printing) for complex geometries and internal rib structures for enhanced strength-to-weight ratio.
- Real-Time Monitoring: Embed sensors for stress, vibration, and temperature monitoring to enable predictive maintenance in smart EVs.
- Dynamic Load Testing: Perform fatigue and life-cycle analysis under real driving conditions to validate long-term reliability of the gearbox casing.

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