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Design & Implementation of A transmission System for An SAE E-Baja Vehicle

Nikita Valiba Lagad[1], Sanket Goraksh Rahane[2], Tanmay Vilas Shinde[3], Dr. R. E. Gite[4]
[1,2,3,4,5] Department of Mechanical Engineering
Amrutvahini College of Engineering, Sangamner, Ghulewadi, Maharashtra

Abstract: *The transmission system plays a vital role in an electric All-Terrain Vehicle (ATV) by efficiently transmitting power from the motor to the wheels under varying terrain conditions. This study presents the design and analysis of a two-wheel-drive transmission system for an SAE e-BAJA vehicle. The objective is to develop a compact, lightweight, and efficient transmission system capable of delivering high torque for off-road applications while maintaining the desired vehicle speed.*
A Permanent Magnet Synchronous Motor (PMSM) powered by a lithium-ion battery pack is selected as the prime mover. The transmission system consists of a two-stage reduction gearbox and a belt drive mechanism. Design calculations, including tractive effort, rolling resistance, aerodynamic drag, and transmission ratio, are performed to achieve the required vehicle performance. Spur gears made of 16MnCr5 material are selected due to their high strength and wear resistance. The gearbox components are designed using standard mechanical design procedures and modeled using CAD software.
Structural analysis of the transmission assembly is carried out using ANSYS to evaluate stress distribution, deformation, and factor of safety. The results indicate that the designed transmission system can safely withstand operating loads and provide reliable power transmission under off-road conditions. The proposed design satisfies the performance requirements of an SAE e-BAJA vehicle while ensuring durability, reliability, and efficiency.

Keywords: Electric ATV, SAE e-BAJA, Transmission System, Two-Stage Reduction Gearbox, PMSM Motor, Spur Gear, ANSYS Analysis.

I. INTRODUCTION

The transmission system is one of the most important subsystems in an All-Terrain Vehicle (ATV) because it transfers power from the motor to the wheels and controls the speed and torque of the vehicle. In electric ATVs, the transmission system plays a vital role in improving vehicle performance, acceleration, traction, and energy efficiency under different terrain conditions [1]. The growing demand for efficient and sustainable electric off-road vehicles has motivated the development of advanced drivetrain solutions tailored to the requirements of competitive ATV platforms. The - proposed project focuses on the design and implementation of a two-wheel-drive transmission system for an electric BAJA vehicle. The system uses a Permanent Magnet Synchronous Motor (PMSM) powered by a lithium-ion battery pack due to its high efficiency, compact size, and excellent torque characteristics [5]. A two-stage reduction gearbox is incorporated to multiply torque and reduce speed according to the tractive requirements of the vehicle. Spur gears are selected because of their simple design, high efficiency, and ease of manufacturing [6]. The design of the transmission system involves the calculation of tractive effort, rolling resistance, drag resistance, and gear reduction ratio to achieve the required acceleration and top speed [7]. Proper selection of shafts, gears, and bearings is necessary to ensure reliability, durability, and smooth power transmission under dynamic loading conditions [8]. Advanced CAD modeling and ANSYS analysis are also used to validate the design by evaluating stress distribution, deformation, and factor of safety of gearbox components [9]. The developed transmission system aims to improve off-road capability, traction, acceleration, and durability while maintaining a lightweight and compact structure. The project also contributes toward the development of efficient and sustainable electric mobility systems for future off-road vehicle applications [10].

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II. LITERATURE REVIEW

The literature review provides a comprehensive understanding of the research carried out on transmission systems for All-Terrain Vehicles (ATVs), particularly focusing on gearbox design, drivetrain optimization, torque transmission, and performance enhancement under off-road operating conditions. The transmission system plays a vital role in determining vehicle acceleration, traction, climbing ability, and overall efficiency. Researchers have investigated various transmission configurations, gear reduction mechanisms, material selections, and design methodologies to improve drivetrain performance while maintaining reliability and durability.

Saini et al. [1] developed a transmission system for an ATV with the objective of improving torque delivery and off-road capability. Their study emphasized the importance of gear ratio selection and drivetrain component optimization. The results demonstrated that an appropriately designed transmission system significantly enhances acceleration and tractive effort, although the overall system weight increased due to the robust gearbox structure. Kanase et al. [2] designed and manufactured a two-stage speed reduction gearbox for a BAJA ATV and reported improved torque multiplication, drivetrain efficiency, and durability. The authors concluded that a two-stage reduction system effectively balances speed and torque requirements but requires precise manufacturing processes.

Karikalan et al. [3] carried out the design and analysis of a two-stage reduction gearbox using CAD modeling and ANSYS simulation tools. Their investigation focused on stress distribution, deformation analysis, and gear strength validation under operating loads. The results confirmed that the gearbox components operated within permissible stress limits and provided reliable performance under off-road conditions. Similarly, Chaudhari et al. [4] developed a two-stage single-speed gearbox for an SAE BAJA vehicle and optimized the gear reduction ratios to achieve the required torque output and vehicle speed. ANSYS validation confirmed the structural integrity of the gearbox without fatigue failure.

Shukla and Tiwari [5] studied the performance of Continuously Variable Transmission (CVT) systems and observed that CVTs provide smoother power delivery and improved efficiency compared to conventional gear transmission systems. However, the authors highlighted the challenges associated with higher maintenance requirements and design complexity. Saha and Farooqui [6] investigated gearbox design and gear ratio optimization for SAE BAJA vehicles. Their study demonstrated that optimized transmission ratios improve acceleration, vehicle control, and overall drivetrain efficiency while ensuring effective torque utilization.

George et al. [7] proposed an innovative transmission system for off-road vehicles and reported improvements in power transmission efficiency and vehicle maneuverability. Their work emphasized minimizing drivetrain losses to maximize vehicle performance. Yadav et al. [8] analyzed the transmission system of an ATV and focused on shaft design, bearing selection, and gearbox housing strength. The study concluded that proper material selection and structural optimization significantly enhance the reliability and service life of transmission components.

Perez and Bachman [9] presented the design of a manual gearbox for a Baja SAE vehicle and discussed the trade-off between simplicity, manufacturability, and performance. Their research highlighted the importance of selecting suitable reduction ratios to achieve the desired balance between torque and speed. Lechner and Naunheimer [10] provided a detailed understanding of automotive transmission fundamentals and emphasized that gearbox efficiency and proper gear selection are critical for achieving optimal vehicle performance.

Recent studies have focused on transmission optimization for electric vehicles. Hofman and Salazar [11] investigated transmission ratio design for electric vehicles using analytical modeling techniques and concluded that optimized transmission ratios improve motor efficiency and reduce energy consumption. Borsboom et al. [12] further explored transmission control and design optimization methods and reported significant improvements in drivetrain performance through advanced analytical approaches. Beaudoin and Boulet [13] applied reinforcement learning techniques to electric vehicle gearshift control and demonstrated enhanced responsiveness and efficiency of the transmission system.

Subhashini et al. [14] investigated the design and analysis of a four-wheel-drive ATV gearbox and reported improved traction and load distribution under off-road conditions. Similarly, Jaijy [15] analyzed a four-wheel-drive ATV drivetrain and concluded that optimized gearbox design improves vehicle stability and climbing performance.

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Allampallewar et al. [16] developed and manufactured a 4WD ATV gearbox and reported enhanced drivetrain durability and transmission efficiency through optimized gear geometry and material selection.

The reviewed literature indicates that gearbox design, gear ratio optimization, component material selection, and structural analysis are the primary factors influencing transmission system performance. Most researchers observed that multi-stage reduction gearboxes provide superior torque multiplication and off-road capability compared to conventional systems. Furthermore, CAD modeling and finite element analysis have become essential tools for validating transmission components before manufacturing. However, challenges related to drivetrain weight, manufacturing complexity, power losses, and compact packaging continue to exist.

Based on the literature survey, it is evident that there is a need for an efficient, lightweight, and durable transmission system capable of delivering high torque while maintaining sufficient vehicle speed for electric ATV applications. Therefore, the present work focuses on the design and implementation of a two-wheel-drive transmission system incorporating a two-stage reduction gearbox and belt drive mechanism. The proposed system aims to improve traction, torque transmission, off-road capability, and drivetrain efficiency while ensuring reliability and structural safety through proper design calculations and ANSYS-based validation.

III. MATERIALS AND METHODS

3.1 Materials

The transmission system components were designed and manufactured using materials selected based on strength, wear resistance, durability, and suitability for off-road operating conditions. The major components of the transmission system include spur gears, shafts, bearings, gearbox casing, belt drive mechanism, and drive shafts. Among these components, the gears play a critical role in transmitting power and torque from the electric motor to the driving wheels.

For the gear pair, 16MnCr5 alloy steel was selected due to its excellent mechanical properties, including high surface hardness, superior wear resistance, good fatigue strength, and excellent carburizing characteristics. These properties make 16MnCr5 a widely preferred material for automotive gearbox applications where components are subjected to repeated dynamic loading and high contact stresses. The material properties used for gearbox design are presented in Table 1.

Table 1. Mechanical Properties of 16MnCr5 Gear Material

Property	Value
Ultimate Tensile Strength (Sut)	1000 MPa
Yield Strength (Syt)	800 MPa
Brinell Hardness Number (BHN)	650
Density	7.85 g/cm³
Elastic Modulus	210 GPa

The transmission system utilizes a Permanent Magnet Synchronous Motor (PMSM) rated at 5 kW as the primary power source. PMSM motors are preferred in electric ATV applications due to their high efficiency, compact size, low maintenance requirements, and superior torque characteristics at low speeds. Energy is supplied through a lithium-ion battery pack designed to provide adequate voltage and current for off-road vehicle operation.

The gearbox consists of a two-stage reduction mechanism employing spur gears to achieve the required torque multiplication and speed reduction. Spur gears were selected because of their simple geometry, high transmission efficiency, ease of manufacturing, and reliable performance under moderate to high loading conditions. Deep groove ball bearings were incorporated to support rotating shafts and minimize friction losses during operation.

Figure 1 illustrates the CAD model of the developed transmission system, including the motor, belt drive, gearbox assembly, shafts, and two-wheel-drive mechanism. The complete assembly was modeled using CAD software and subsequently analyzed using ANSYS Workbench to evaluate stress distribution, deformation behavior, and structural safety under operating loads.

The selected materials and components provide a suitable balance between strength, durability, weight, and manufacturing feasibility, ensuring reliable operation of the transmission system under harsh off-road conditions encountered in SAE e-BAJA competitions. The material selection also contributes to improving drivetrain efficiency, torque transmission capability, and overall vehicle performance.

3.2 Design, Manufacturing and Testing Methodology

The development of the transmission system was carried out through a systematic design, manufacturing, assembly, and testing procedure. Initially, the design requirements were established based on the performance objectives of the electric All-Terrain Vehicle (ATV), including maximum vehicle speed, required tractive effort, acceleration, torque demand, and off-road operating conditions. The specifications of the Permanent Magnet Synchronous Motor (PMSM), battery pack, and drivetrain components were carefully analyzed to determine the required transmission ratio and gearbox configuration.

Based on the design calculations, a two-stage reduction gearbox was selected to achieve the desired torque multiplication and speed reduction. Spur gears were designed using standard gear design procedures considering bending strength, wear strength, gear module, face width, and transmission ratio. The input, intermediate, and output shafts were designed according to ASME standards to withstand combined torsional and bending loads during vehicle operation. Deep groove ball bearings were selected based on load-carrying capacity, rotational speed, and expected service life.

After completing the design phase, three-dimensional models of the gearbox, shafts, bearings, and transmission assembly were developed using CAD software. The CAD models were then imported into ANSYS Workbench for structural analysis. Equivalent stress, total deformation, and factor of safety were evaluated under operating conditions to verify the structural integrity of the transmission components before manufacturing.

The gearbox gears were manufactured using 16MnCr5 alloy steel, while the shafts were fabricated from high-strength steel material. Precision machining processes such as turning, milling, drilling, and gear hobbing were employed to achieve the required dimensional accuracy. The gearbox casing was manufactured and assembled to provide proper alignment and protection for the internal components. A belt drive mechanism was incorporated as the first stage of power transmission between the motor and gearbox to ensure smooth power transfer and reduce shock loading.

Following manufacturing, all transmission components were assembled, including the motor, belt drive, gearbox, shafts, bearings, and two-wheel-drive mechanism. Proper alignment of gears and shafts was maintained to minimize vibration, noise, and transmission losses. The complete assembly was then integrated into the ATV chassis according to SAE e-BAJA design requirements.

Experimental testing was conducted to evaluate the performance of the developed transmission system. The system was tested under different operating conditions to assess torque transmission capability, speed reduction, drivetrain efficiency, and operational reliability. The gearbox assembly was further validated through ANSYS static structural analysis to determine stress distribution and deformation characteristics. The analysis results confirmed that the maximum equivalent stress and total deformation values remained within permissible limits, indicating safe operation of the transmission system.

Furthermore, the transmission system was optimized by considering weight reduction, ease of manufacturing, and maintenance requirements. Component selection was carried out to achieve a balance between strength, durability, and overall system efficiency. Proper lubrication arrangements were incorporated within the gearbox to reduce frictional losses and enhance the service life of gears and bearings. During testing, the performance data obtained from the transmission system were compared with the design calculations to verify the accuracy of the developed model. The close agreement between theoretical and experimental results validated the effectiveness of the transmission design for SAE e-BAJA electric ATV applications.

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The experimental procedure demonstrated that the developed two-stage reduction transmission system successfully achieved the required torque multiplication, vehicle acceleration, and traction performance while maintaining structural safety and durability.

IV. DESIGN CALCULATIONS

4.1 Drag Resistance (RD) :

RD = Q × A × Cd × V^2/2 ……..(1)

Where,

RD = Drag Resistance

Q = Density of Air = 1.225 Kg/ m^3

A = Cross sectional Area = 1 m^2

Cd = Coefficient of drag = 0.45

V = Speed of vehicle = 60 Km/ h =16.67 m/s

RD = 1.225 × 1 × 0.45 × $(16.67)^2$ / 2

RD = 76.59 N

4.2 Rolling Resistance (RR):

RR = Fr × mg ……..(2)

Where,

Fr = Coefficient of rolling resistance = 0.043

m = Mass of Vehicle

RR = 0.0435 × 240 × 9.81

RR = 102.41 N

4.3 Static Resistance (RS):

RS = μ × mg ………(3)

Where,

μ = Coefficient of Friction = 0.65

m = Mass of vehicle

RS = 0.65 × 240 × 9.81

RS = 1530.36 N

4.4 Gradient Resistance (GR) @ 40°

GR = m × mg × sinθ ……...(4)

Where,

m = Mass of vehicle

GR = 240 × 9.81 × sin(40)

GR = 1513.38 N

4.5 Tractive Effort (FT)

FT = RD + RR + RS ……...(5)

FT = 76.59 + 102.41 + 1530.36

FT = 1709.36 N

4.6 Selection of Tyre:

Tyre Size = 23 × 7 × 10

4.7 Minimum Required Torque

T = FT × (Radius of Tyre) Dynamic(r) ……..(6)
Where,
FT = Tractive Effort
r = Dynamic radius of Tyre = 0.2921
T = 1709.36 × 0.2921
T = 499.30 Nm

4.8 Transmission Ratio (Tr):

Tr = FT × (r)dynamic / Te × ηall …….(7)
Tr = 1709.36 × 0.2921 / 19.66 × 0.90
Tr = 28.2 : 1

4.9 Motor Specifications:

1. Motor : Pmsm Datai Motor
2. Power : **5 KW @ 3800 rpm**
3.Flyup Speed : **4300 ± 100 rpm**
4.Idle Speed : **4500 ± 100 rpm**

V. RESULTS AND DISCUSSION

The performance of the developed transmission system was evaluated through design calculations and ANSYS structural analysis. The analysis was carried out to assess the structural integrity, stress distribution, deformation characteristics, and overall safety of the transmission components under operating conditions. The obtained results are discussed in the following sections.

5.1 ANSYS Structural Analysis Results

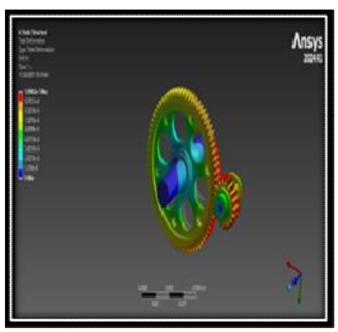

Figure 5: Equivalent Stress Analysis of Gear Pair

The static structural analysis of the gear pair was performed using ANSYS Workbench to evaluate the stress distribution under operating conditions. The maximum equivalent stress was observed near the gear tooth contact region due to load transmission between the pinion and gear. The obtained stress values were within the allowable limits of the selected material, indicating safe operation of the gearbox under loading conditions.

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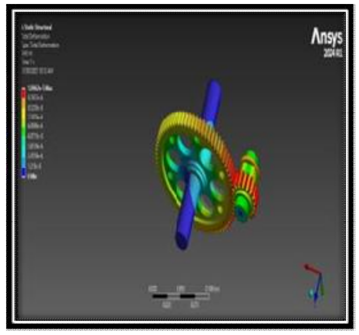

Figure 6: Total Deformation Analysis of Gear Pair

The total deformation analysis was carried out to determine the displacement developed in the gear assembly during power transmission. The maximum deformation occurred at the outer edge of the gear teeth, while minimum deformation was observed near the shaft mounting region. The obtained deformation values were very small and within acceptable limits, confirming the rigidity and stability of the gearbox design. The results indicate that the transmission system can operate efficiently without excessive vibration or structural failure.

Table. 2 Results Analysis Of Transmission System

Parameter	Value
Analysis Type	Static Structural Analysis
Software Used	ANSYS 2024 R1
Gear Material	16MnCr5
Maximum Equivalent Stress	Within Safe Limit
Minimum Equivalent Stress	Approximately 0 MPa
Maximum Total Deformation	Within Permissible Limit
Gearbox Reduction Ratio	8.6 : 1
Overall Transmission Ratio	28.2 : 1
Maximum Vehicle Speed	57.33 km/h
Minimum Required Torque	499.30 Nm
Vehicle Acceleration	7.23 m/s²
Gearbox Condition	Safe for Operation

The ANSYS structural analysis results indicate that the designed transmission system is safe and suitable for SAE e-BAJA applications. The gearbox was analyzed using ANSYS 2024 R1 with 16MnCr5 gear material under static structural loading conditions. The maximum equivalent stress and total deformation were found to be within safe and permissible limits, confirming the structural integrity of the gearbox components. The developed transmission system achieved a gearbox reduction ratio of 8.6:1 and an overall transmission ratio of 28.2:1, which provided the required torque multiplication and speed reduction. The vehicle attained a maximum speed of 57.33 km/h and a minimum required torque of 499.30 Nm, resulting in an acceleration of 7.23 m/s². These results demonstrate that the proposed transmission system can efficiently transmit power while maintaining safety, durability, and reliable performance under off-road operating conditions.

VI. CONCLUSION

1. A two-stage reduction gearbox integrated with a belt drive mechanism and PMSM motor was successfully designed and developed for an SAE e-BAJA electric ATV.

2. The designed transmission system achieved a gearbox reduction ratio of 8.6:1 and an overall transmission ratio of 28.2:1, providing the required torque multiplication and speed reduction.
3. The vehicle attained a maximum speed of 57.33 km/h and a minimum required torque of 499.30 Nm, ensuring satisfactory performance under off-road operating conditions.
4. The developed drivetrain achieved an acceleration of 7.23 m/s^2, contributing to improved traction and vehicle performance.
5. ANSYS structural analysis confirmed that the maximum equivalent stress and total deformation remained within permissible limits, indicating safe and reliable operation of the transmission system.
6. The use of 16MnCr5 gear material provided adequate strength, wear resistance, and durability for gearbox applications.
7. The developed transmission system satisfies the performance requirements of an SAE e-BAJA vehicle and offers a reliable, efficient, and cost-effective drivetrain solution for electric off-road applications.

VII. FUTURE SCOPE

The future scope of this project includes further improvement of the transmission system by reducing the overall weight and increasing efficiency through the use of advanced lightweight materials and optimized gear design. The system can be further enhanced by implementing an automatic or multi-speed transmission mechanism to achieve smoother power delivery and improved adaptability to different terrain conditions. Integration of regenerative braking, advanced battery management systems, and intelligent motor control techniques can further improve energy efficiency and vehicle performance. In addition, the transmission system can be enhanced with real-time monitoring sensors, IoT-based diagnostics, and improved thermal management for better reliability and durability. The developed drivetrain can also be adapted for various electric off-road vehicles, utility vehicles, and future autonomous ATV applications, contributing to the growth of sustainable electric mobility technologies.

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