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Dynamic Analysis of PTO Shaft Using Ansys

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ABSTRACT

The PTO shaft is a crucial component in agricultural machinery, responsible for transferring power from tractors to attached implements. Ensuring its reliability and performance is vital to prevent mechanical failures that can lead to downtime and increased maintenance costs. This study presents a comprehensive dynamic analysis of a PTO shaft using FEM software ANSYS (Student's version). The analysis begins with the creation of a detailed finite element model of the PTO shaft, incorporating material properties, geometric dimensions, and boundary conditions reflective of real-world operating scenarios. The results of simulations are first verified using an experimental result. The structural analysis is then carried out and the results are further verified through the relevant data in literature. The work is then extended to simulate the dynamic behavior of PTO shaft. Modal analysis is conducted to identify findings provide valuable insights into the design and optimization of PTO shafts, thereby suggesting modifications to enhance their durability and operational efficiency. The results have been reported to include three types of alloy material: a) SAE 4140 used in literature to verify the results, b) P100/6160 Al and c) Boron Al, latter are alloys of aluminum, hence provide good strength to weight ratio maintain desired stiffness. The structural and modal analysis of PTO shafts have been carried for all the three types of materials and comparative study has been presented. From the structural analysis, it is observed that the stresses in all the materials are almost same however the new materials have been stiffer as compared to the traditional one. Using the new materials, the corresponding weight is significantly reduced. The natural frequency of Boron Al is significantly higher than the other two materials. Boron Al performs well in terms of natural frequency stability but shows the highest deformations at lower frequencies, suggesting it may be less suitable for applications with high dynamic loading at those frequencies. SAE 4140, on the other hand, provides the highest stiffness and lowest deformation at lower natural frequencies, making it the best choice for environments where resistance to resonant vibrations is critical. Thus, by leveraging ANSYS for dynamic analysis, this research contributes to the development of more robust agricultural machinery, thereby improving reliability and reducing maintenance costs.

Keywords

PTO shaft, ANSYS (Student's version), Finite element model, Modal analysis, SAE 4140, P100/6061 Al, Boron Al, Natural frequencies, Mode shapes, Fatigue, Failure, Reducing maintenance costs

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Introduction

Power Take-Off (PTO) shafts are pivotal to the versatility and functionality of modern tractors, transforming them from simple transport vehicles into multifunctional agricultural powerhouses. The integration of PTO shafts enables tractors to drive a myriad of implements, making it possible to complete multiple farming tasks with a single piece of equipment. This adaptability not only saves time and labor but also reduces the need for multiple dedicated machines, thus lowering overall operational costs.

For instance, a single tractor equipped with a PTO shaft can seamlessly switch between mowing fields, tilling soil, planting crops, and harvesting produce, showcasing the incredible versatility that PTO technology brings to agricultural operations. PTO shafts are subjected to high torsional loads and frequent cycles of stress during operation.

Therefore, materials with high strength and fatigue resistance are preferred. Materials used include metal matric composites such as SAE 4140, P100/6061 Al and Boron Al, which offer excellent tensile strength and toughness to withstand the rigors of agricultural tasks. Agricultural environments can be harsh, with potential impacts and abrasive forces. Materials with good fracture toughness, such as high-strength alloys or certain grades of stainless steel, are chosen to minimize the risk of sudden failures and ensure reliability over extended use.

Johnson and Thompson (2017) explored various safety mechanisms and devices integrated into modern PTO shafts. These include the use of protective guards, slip clutches, and overrunning clutches, which prevent accidental entanglement and reduce the risk of injury. The study emphasized the need for regular maintenance and user education to mitigate hazards associated with PTO shafts.

Edwards *et al.,* (2018) delved into the biomechanics involved in handling PTO shafts. The study analyzed the physical strain on operators during the connection and disconnection of PTO shafts, highlighting the risk factors for musculoskeletal injuries. The research suggested ergonomic improvements in shaft design and the implementation of assistive devices to reduce operator strain and enhance safety.

Johnson and Davis (2018) analyzed the impact of PTO shaft length on power transmission efficiency. The research found that improper shaft length could lead to power losses, increased wear, and operational inefficiencies. The study recommended the use of adjustable-length shafts and proper length selection to optimize power transmission and ensure reliable operation.

Kursat Celik *et al.,* (2018) focused on a detailed analysis of PTO shaft failure in agricultural tractors using finite element analysis (FEA). It effectively highlights the impact of shock torsional loading as the primary failure mechanism, identifying stress distribution and critical failure zones with precision.

The findings, including a maximum equivalent stress of 632.08MPa, offer valuable insights for improving PTO shaft design and durability. While the research is thorough, it could benefit from specific recommendations for mitigating shock loading effects. Overall, this study is a significant contribution to advancing the reliability of agricultural machinery.

Rawal (2001) studied from the onset of the space era, both organic-matrix and metal-matrix composites (MMCs), with high specific stiffness and near-zero coefficient of thermal expansion (CTE), have been developed for space applications. Of the organic-matrix composites, graphite/epoxy (Gr/Ep) has been used in space for truss elements, bus panels, antennas, wave guides, and parabolic reflectors in the past 30 years.

MMCs possess high-temperature capability, high thermal conductivity, low CTE, and high specific stiffness and strength. Those potential benefits generated optimism for MMCs for critical space system applications in the late 1980s. 1,2 The purpose of this article is to detail the history, status, and opportunities of MMCs for space applications.

Kumar *et al.,* (2018) focused on predicting the fatigue life of PTO shafts under cyclic loading conditions. Using a combination of experimental testing and computational modeling, the study identified critical factors affecting fatigue life, such as stress concentrations, material properties, and load spectra. The findings underscored the importance of incorporating fatigue-resistant materials and designs to enhance the durability of PTO shafts in agricultural applications.

Garcia and Rodriguez (2018) analyzed the impact of shaft alignment on the performance and reliability of PTO shafts. The study highlighted that misalignment can cause excessive wear, increased vibration, and premature failure. The researchers proposed guidelines for proper alignment practices, including the use of alignment tools and regular inspections, to ensure optimal performance and longevity of PTO shafts.

Green *et al.,* (2018) analyzed the life cycle of PTO shafts, from raw material extraction to disposal, and identified key environmental concerns such as energy consumption, emissions, and waste generation. The research proposed several sustainable practices, including the use of recycled materials, energy-efficient manufacturing processes, and the implementation of take-back programs to minimize the environmental footprint of PTO shafts.

Ahmed and Zhang (2020) developed a smart PTO shaft system equipped with sensors and IoT connectivity to monitor real-time performance parameters such as torque, speed, and temperature. The system provided valuable data for predictive maintenance and operational optimization, enabling farmers to enhance the efficiency and reliability of their agricultural machinery.

The main objectives of this study includes, to carry out static structural analysis of PTO shaft to determine stresses and deformation. To determine the dynamic analysis of PTO shaft to determine critical speeds, natural frequency and mode shape. To modify and optimize the geometry of PTO shaft for improved perform. `

Materials and Methods

Importing CAD model

The methodology process encompasses CAD modeling of PTO shaft, importing CAD design of shaft in ANSYS design modeler. The CAD modeling of the PTO shaft was carried out using Creo Parametric, a sophisticated 3D CAD software. The PTO shaft design was based on standard dimensions and specifications commonly used in agricultural machinery. The model included critical components such as the shaft, splines, yokes, and universal joints. Key dimensions were derived from existing literature and manufacturer specifications, ensuring the model's accuracy and relevance. The PTO shaft model was created with high precision, incorporating intricate details like chamfers, fillets, and keyways to simulate real-world geometry accurately. The completed model was exported in Parasolid (.x_t) and IGES (.iges) formats for subsequent analysis in ANSYS.

Meshing in ANSYS (student version) 2024 R2 software

Meshing is a critical step in computational simulations, involving the division of a complex physical structure or geometry into smaller, more manageable elements (or cells) for analysis. This process is fundamental to finite element analysis (FEA), computational fluid dynamics (CFD), and other simulation techniques in ANSYS, as it enables numerical solutions to physical problems. In ANSYS, meshing breaks a continuous domain—whether a solid, fluid, or structural component—into discrete finite elements.

These elements serve as the basis for mathematical computations. The quality of the mesh significantly influences both the accuracy and efficiency of the simulation, making proper meshing an essential part of the workflow. Meshing process was conducted using ANSYS. The imported CAD model was subjected to a high-quality meshing process to ensure accurate results during the analysis.

A combination of tetrahedral and hexahedral elements was used to capture the complex geometry of the PTO shaft. The element size was refined around critical areas such as the splines and keyways to capture stress concentrations effectively as shown in fig.4.2.

Loads and boundary conditions

A torsional load of 830 Nm was applied to the input yoke to simulate the torque transmitted from the tractor. Fixed boundary conditions were applied at the mounting points of the PTO shaft, replicating the constraints imposed by the tractor and the implement as shown in fig.4.3. The modal analysis is conducted on agricultural PTO shaft. The boundary condition includes fixed support at the left face and right face. The number of modes to extract is 6. The stiffness coefficient and mass coefficient are set to null as shown in fig.4.4.

Materials Considered

To carry out the numerical investigation further to include different types of materials and observe their dynamic behavior, three types of novel materials have been identified. These materials are used extensively in diverse areas of applications including automobiles, aerospace and nuclear technology. A list of significant properties of the materials considered has been tabulated in Table no. 4.4. A brief discussion on the behavior of these materials has also been reported.

Material type 1 (M1) SAE 4140

SAE 4140 is a tough and durable alloy steel known for its strength, wear resistance, and ability to handle high stress. It contains chromium and molybdenum, which improve its hardness and toughness, especially after heat treatment like quenching and tempering. This steel is commonly used in making gears, crankshafts, axles, and PTO shafts, as well as in heavy machinery and drilling equipment. It has decent machinability and weldability, but proper preheating and post-weld treatment are needed to avoid cracking. With its strong combination of durability and performance, SAE 4140 is a go-to material for applications that require both strength and reliability.

Material type 2 (M2) P100/6061 Al

P100/6061 Aluminum composite is a lightweight, high-strength material made by reinforcing 6061 aluminum alloy with P100 carbon fibers. This combination enhances stiffness, strength, and wear resistance while keeping the material lightweight. 6061 aluminum is known for its good corrosion resistance, machinability, and weldability, while P100 carbon fibers significantly improve its tensile strength and stiffness, making it ideal for high-performance applications.

This composite is commonly used in aerospace, automotive, and high-performance mechanical components, where both strength-to-weight ratio and durability are critical. It offers excellent fatigue resistance, making it a good choice for dynamic load applications like drive shafts, structural frames, and advanced engineering components.

However, its thermal conductivity and expansion properties depend on fiber orientation, which should be considered in design and analysis.

Material type 3 (M3) Boron Al

Boron/Aluminum (B/Al) composite is a high-strength, lightweight material made by reinforcing aluminum with boron fibers. This combination significantly improves stiffness, tensile strength, and fatigue resistance, making it ideal for applications requiring both low weight and high mechanical performance. The aluminum matrix provides good corrosion resistance and machinability, while boron fibers add exceptional rigidity and strength, especially along the fiber direction. This composite is widely used in aerospace, defense, and structural applications, including aircraft fuselage frames, space structures, and high-performance sporting equipment. Its high stiffness-to-weight ratio makes it particularly useful for load-bearing components.

However, its cost and difficulty in fabrication can be limiting factors, and special processing techniques are needed to ensure proper bonding between the fibers and the aluminum matrix. In the next chapter the validation of the numerical study and results of the numerical investigations through simulations of the PTO shaft has been reported.

Modal analysis

Modal analysis is one of the methods used to evaluate the dynamic characteristics of mechanical components. Moreover, this technique can explain a structure in terms of its natural characteristics. The natural characteristics are natural frequency, damping, and mode shapes.

Modal analysis is the most fundamental type of structural dynamics analyses. The information extracted from modal analysis often acts as inputs to other types of analyses such as:

- Response Spectrum Analysis
- Random Vibrations Analysis
- Harmonic Analysis

Proper implementation of modal analysis enables engineers to design robust structures by minimizing the likelihood of undesirable mechanical vibrations.

Natural frequency

Frequency is the number of times an event happens in a given time. In wave theory, the frequency of a wave is the number of waves passing through a point in a given time. If a system, after an initial disturbance, is left to vibrate on its own, the frequency with which it oscillates without external forces is known as its natural frequency.

As will be seen later, a vibratory system having n degrees of freedom will have, in general, n distinct natural frequencies of vibration. The natural frequency is a characteristic of the system and depends only on the stiffness and mass.

Mode shapes

When a component or system vibrates at its natural frequencies it vibrates in certain "patterns". The patterns (or shapes of the structure) are determined by the directions in which the various parts of the component or system deflect.

These patterns are call mode shapes, modal shapes or simply modes. The number and shapes of the modes depend on various factors including the relative stiffness of the components and the way they are constrained in the system.

Results and Discussion

Modal Structural Analysis

In this section, numerical simulations of PTO shafts made up of various material types as considered previously have been extended to study the dynamic response and modal analysis. The results have been considered up to 5^{th} natural frequency of the PTO shaft and the corresponding deformation pattern (mode shape) of the shafts are pictorially presented.

Results for material type M1 (SAE 4140)

The numerical simulation for study of natural frequency of material type M1 i.e. SAE 4140 is carried out in this section. The first five natural frequencies are mentioned in Table 5.1. The contour plot of modal deformation corresponding to the first five natural frequency is shown in Fig. 5.1-5.5.

Results for material type M2 (P100/6061 Al)

The natural frequency of material type M2 is calculated and reported below in Table 5.2. The contour plots for first five natural frequencies are presented in Fig. 5.6-5.10.

Results for material type M3 (Boron Al)

Moving further in the study, the modal analysis using FEM is carried out for the third category of material (M3). The natural frequencies are presented in Table 5.3 and corresponding contour plots are drawn in Fig. 5.11-5.15 respectively.

Comparative Study of Modal Analysis

Natural frequencies are the frequencies at which a system tends to oscillate in the absence of any driving or damping force. In the context of the PTO shaft, these frequencies indicate the points at which resonance could occur, leading to potentially large amplitude oscillations and possible structural failure.

The first natural frequency for Boron Al is significantly higher compared to SAE 4140 and P100/6061 Al. This indicates that Boron Al provides greater resistance to resonant vibrations at lower frequencies, making it more stable under operating conditions that may induce such frequencies. Similar to the first natural frequency, Boron Al shows a higher second natural frequency compared to the other materials. This consistent pattern suggests superior performance in avoiding resonance-related issues in higher frequency ranges.

The third natural frequency of Boron Al is almost double that of SAE 4140 and P100/6061 Al. This indicates exceptional stiffness and structural stability, reducing the likelihood of resonance at even higher frequencies.

The SAE 4140 exhibits natural frequencies in the mid-range for the first and second modes, with a higher third mode. While adequate, it may be susceptible to resonant vibrations if the operating environment includes excitation frequencies close to these natural frequencies.

The P100/6061 Al shows slightly lower natural frequencies compared to SAE 4140 for the first and second modes, and slightly lower for the third mode as well. This suggests marginally lower stiffness but may still be suitable depending on the application's operational frequency range. The fourth and fifth frequencies of P100/6061 Al is slightly higher than SAE 4140, showing an improved stiffness in that range.

Table.1 Material properties of novel materials considered in this work

Properties	P100/6061Al (M1)	SAE 4140 (M2)	Boron/Al (M3)
Density (gm/cm^3)	2.5	7.85	**2.7**
Poisson ratio	0.295	0.27 - 0.30	**0.23**
Specific heat C_p(J/kg-K)	812	475	**801**
Young's modulus (GPa)	342.5	205 - 210	**235**
Yield tensile strength (MPa)	-	750	**830**
Ultimate tensile strength (MPa)	905	850 - 1000	**1100**
Thermal conductivity W/m-K)	**320.0**	**42.6**	—

Table.2 The modal analysis is conducted on PTO shaft using SAE 4140 material.

Mode No.	Frequency (Hz)
1	1655
2	1655.6
3	3452.8
4	5661.6
5	5664.5

Table.3 The modal analysis is conducted on PTO shaft using P100/6061 Al material.

Mode No.	Frequency (Hz)
1	1543.3
2	1543.6
3	3227.7
4	6087.4
5	6090.8

Table.4 The modal analysis is conducted on PTO shaft using Boron Al material.

Mode No.	Frequency (Hz)
1	2838.1
2	2838.7
3	6132.9
4	11164
5	11170

Table.5 Natural frequency comparison table at different frequencies

Material type	SAE 4140	P100/6061 Al	Borom Al
1st natural freq.	1655	1543.3	2838.1
2nd natural freq.	1655.6	1543.6	2838.7
3rd natural freq.	3452.8	3227.7	6132.9
4th natural freq.	5661.6	6087.4	11164
5th natural freq.	5664.5	6090.8	11170

Figure.1 Imported CAD design of PTO shaft

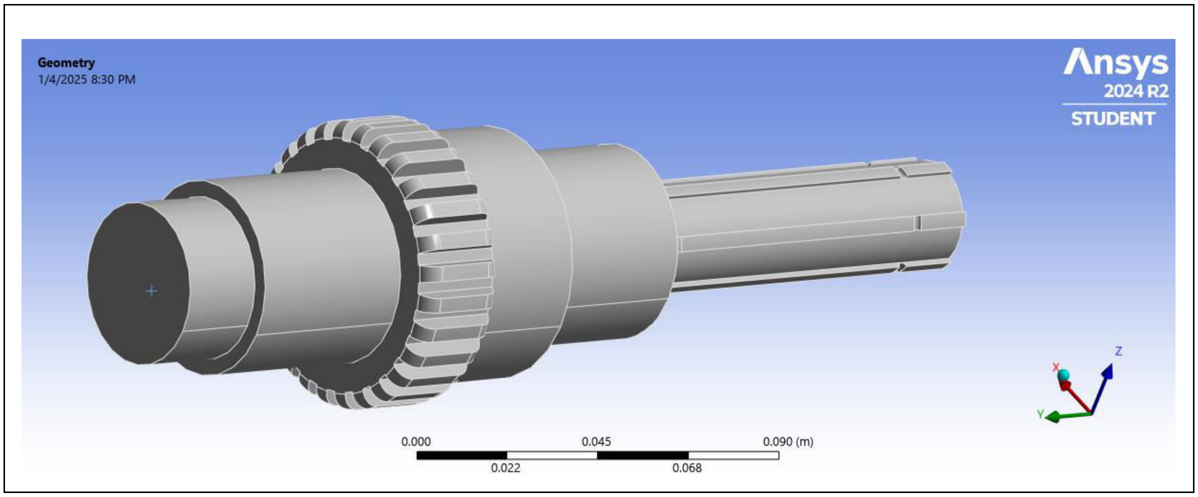


Figure.2 Meshed model of PTO shaft

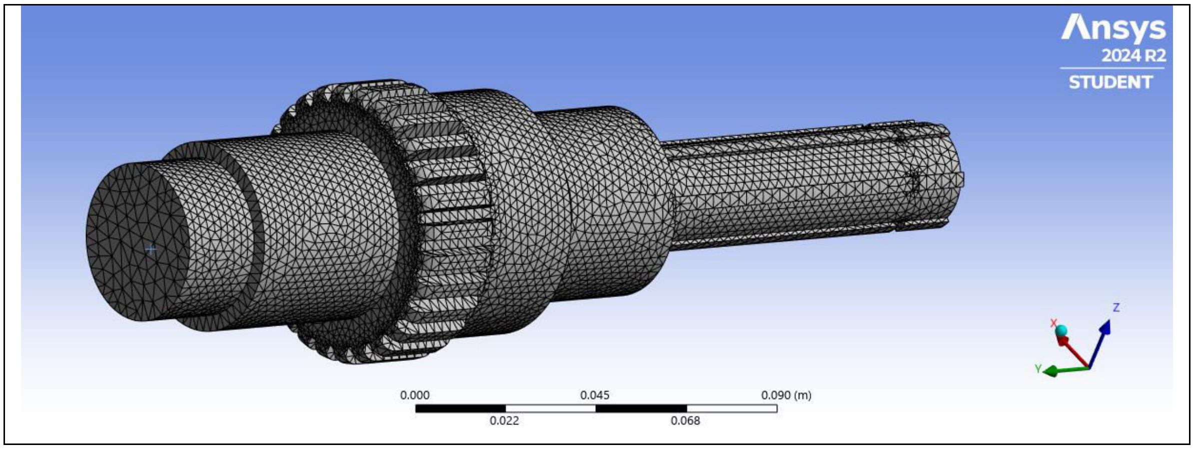


Figure.3 Boundary condition on agriculture PTO shaft

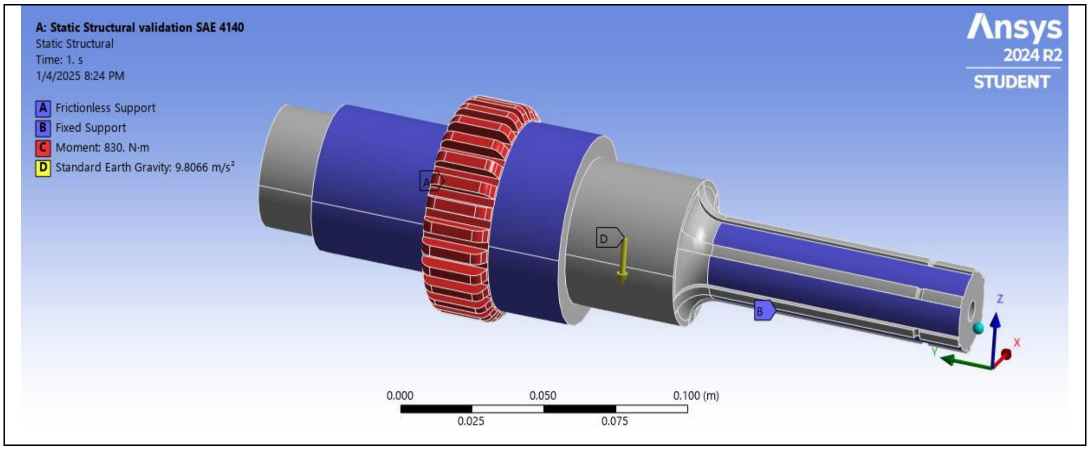


Figure.4 Boundary condition on agriculture PTO shaft for modal analysis

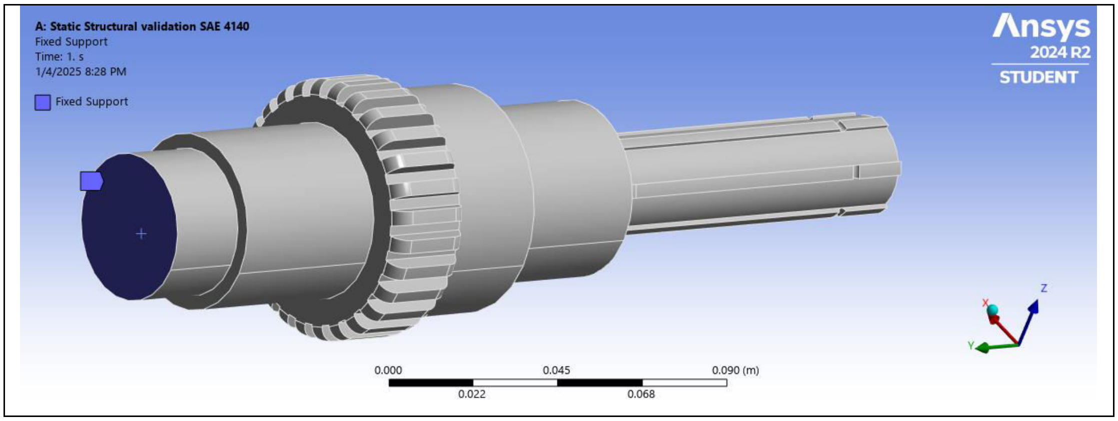


Figure.5 1st mode shape using SAE 4140

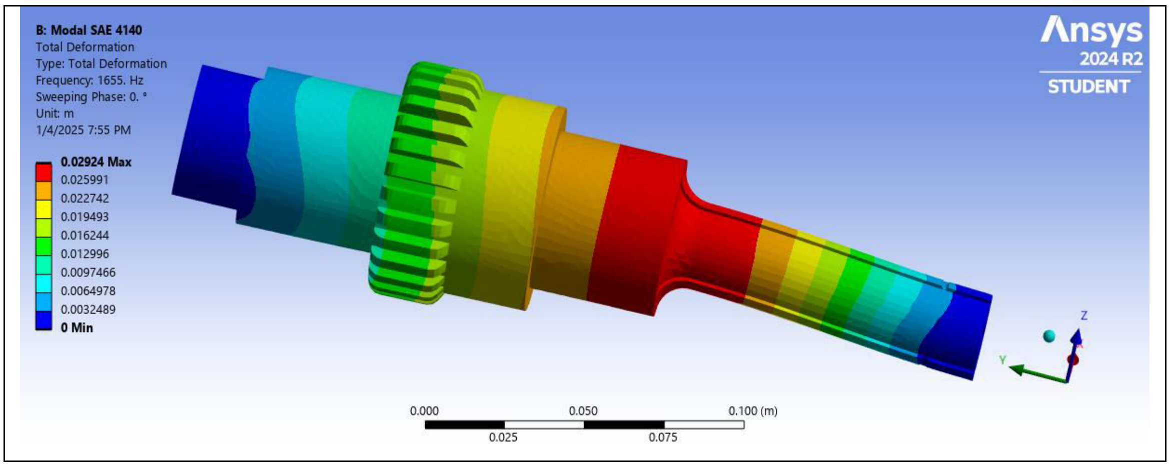


Figure.6 2nd mode shape using SAE 4140

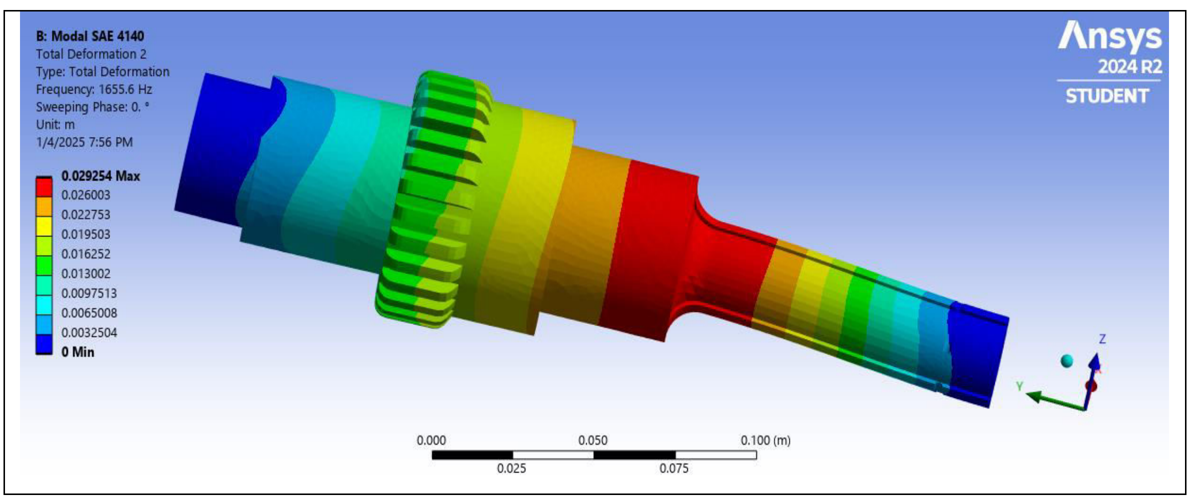


Figure.7 3rd mode shape using SAE 4140

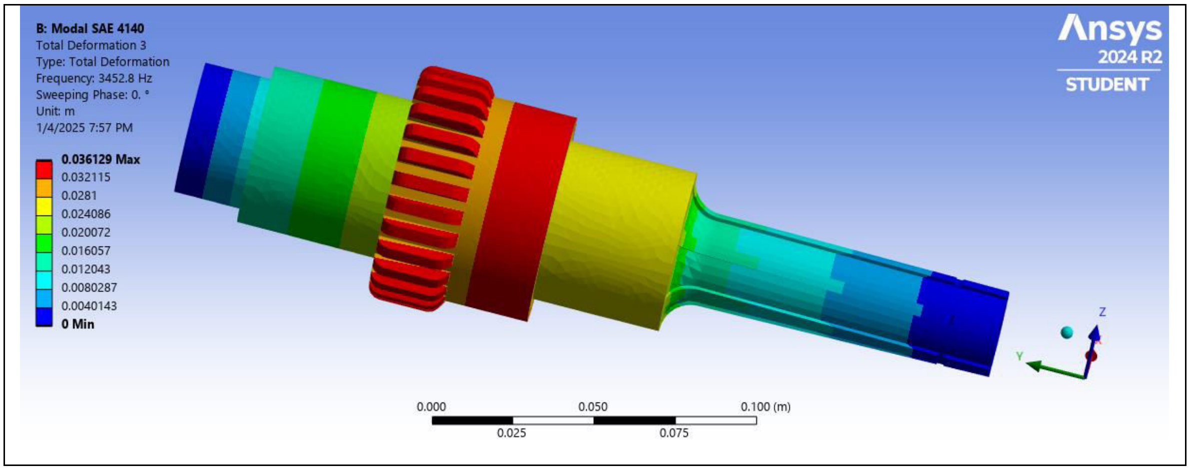


Figure.8 4th mode shape using SAE 4140

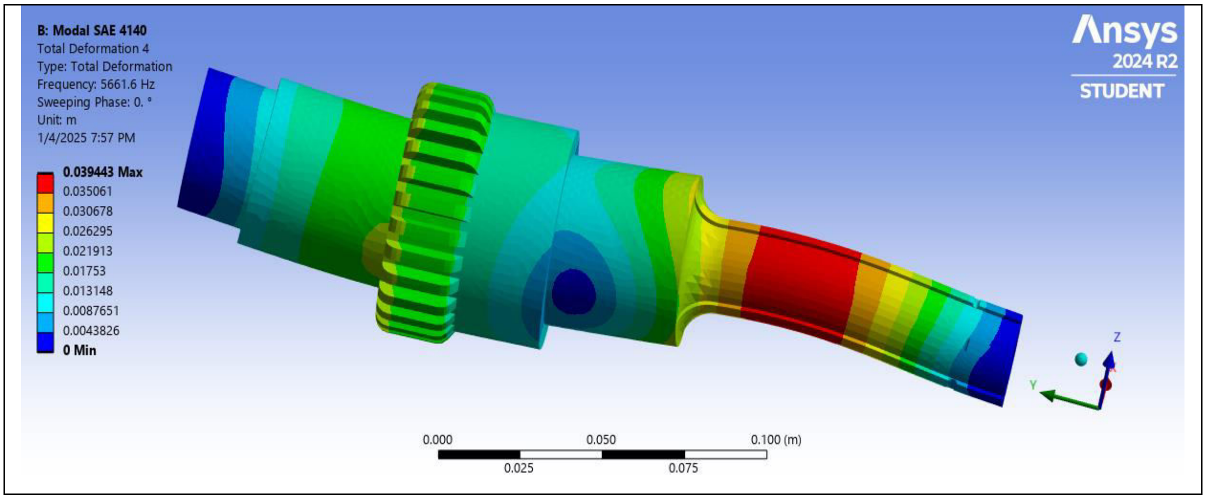


Figure.9 5th mode shape using SAE 4140

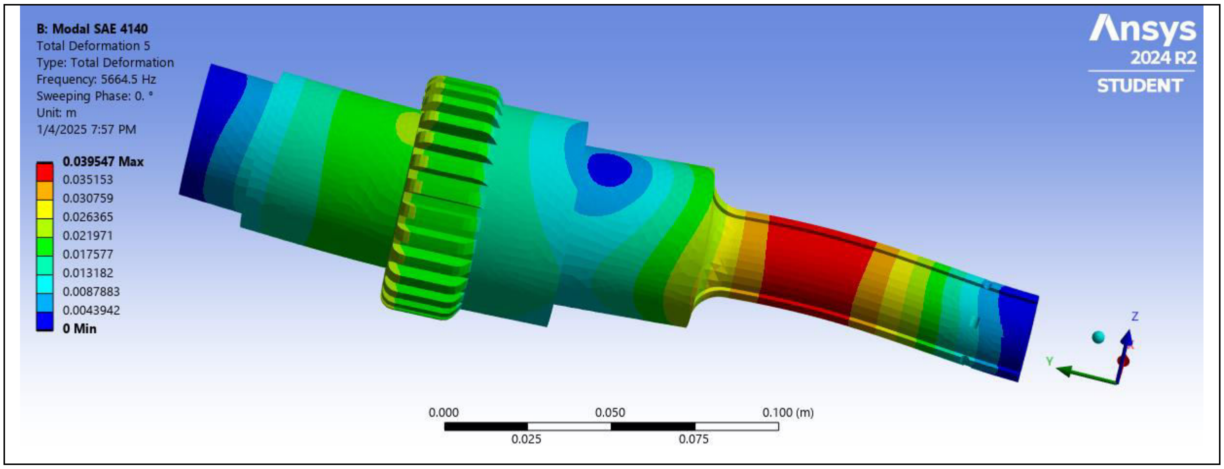


Figure.10 1st mode shape obtained using P100/6061 Al

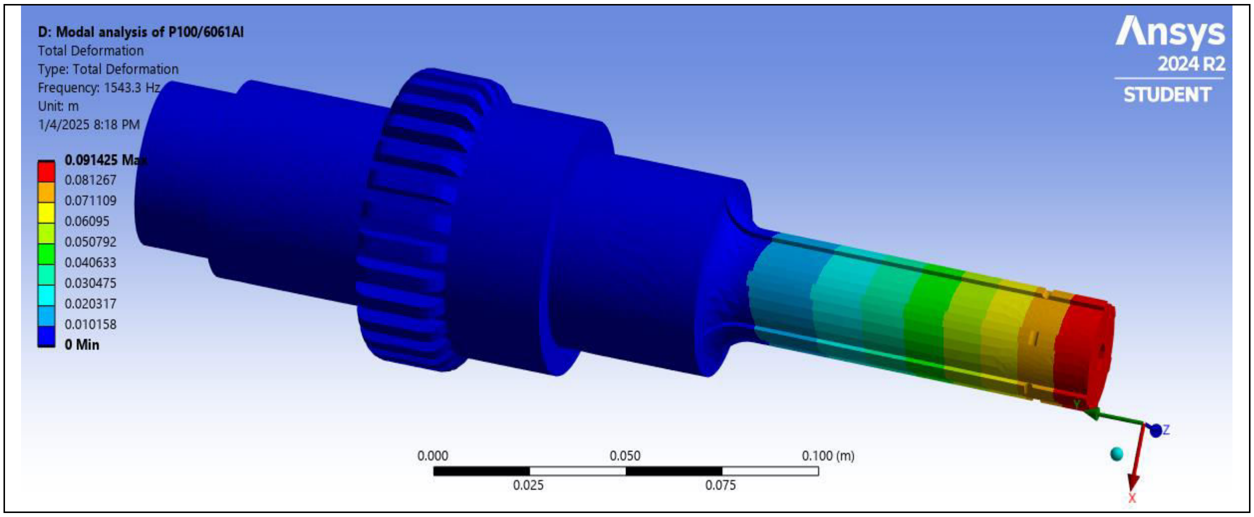


Figure.11 2nd mode shape obtained using P100/6061 Al

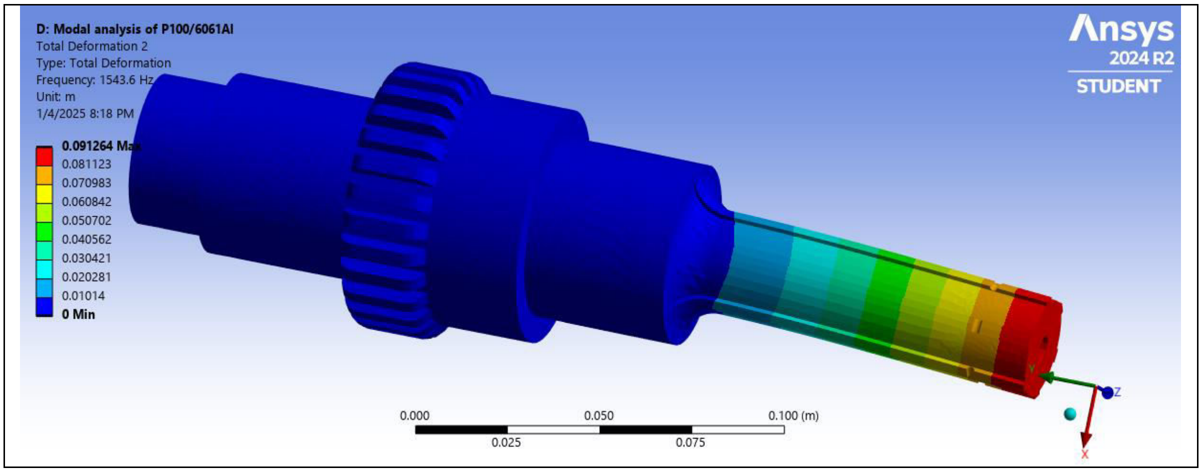


Figure.12 3rd mode shape obtained using P100/6061 Al

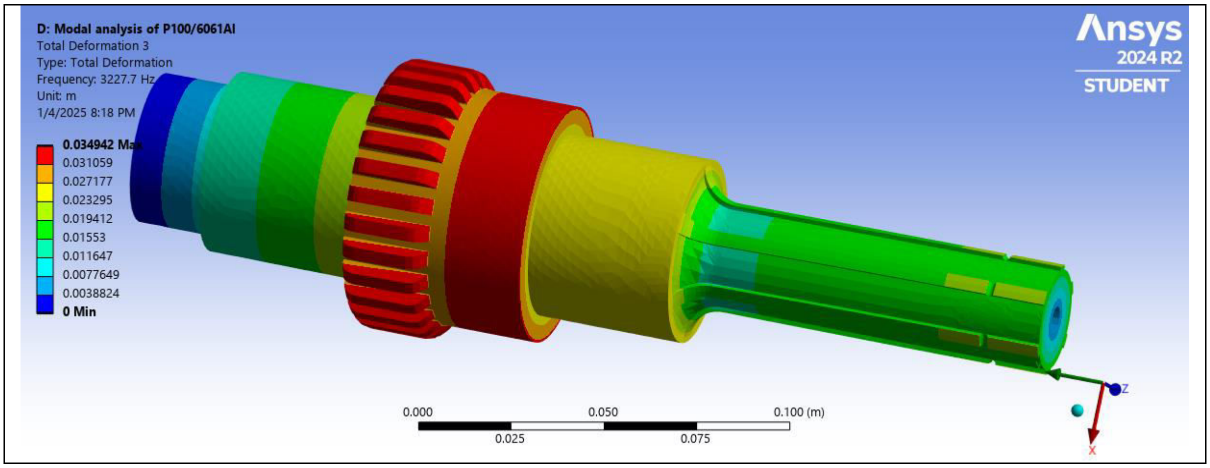


Figure.13 4th mode shape obtained using P100/6061 Al

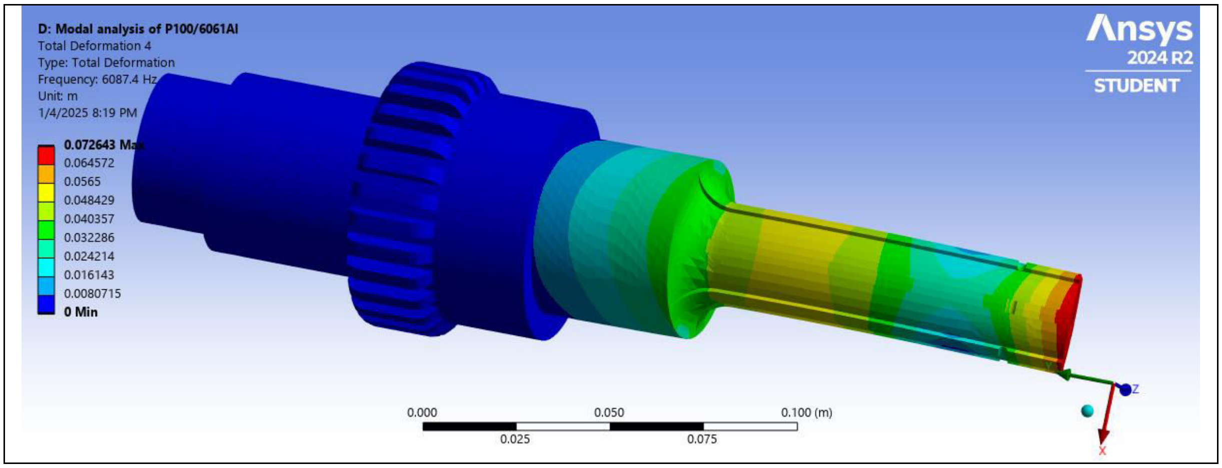


Figure.14 5th mode shape obtained using P100/6061 Al

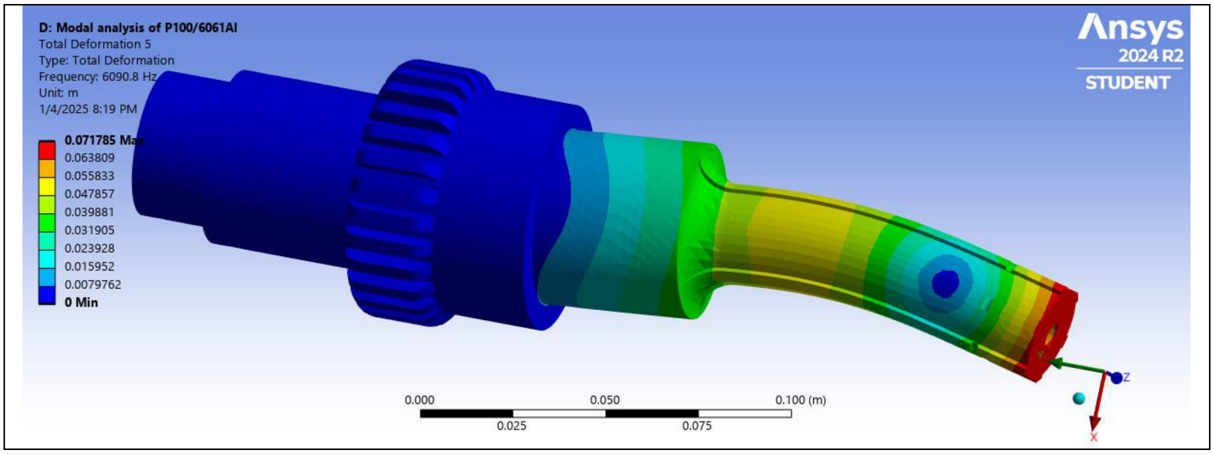


Figure.15 1st mode shape using Boron Al

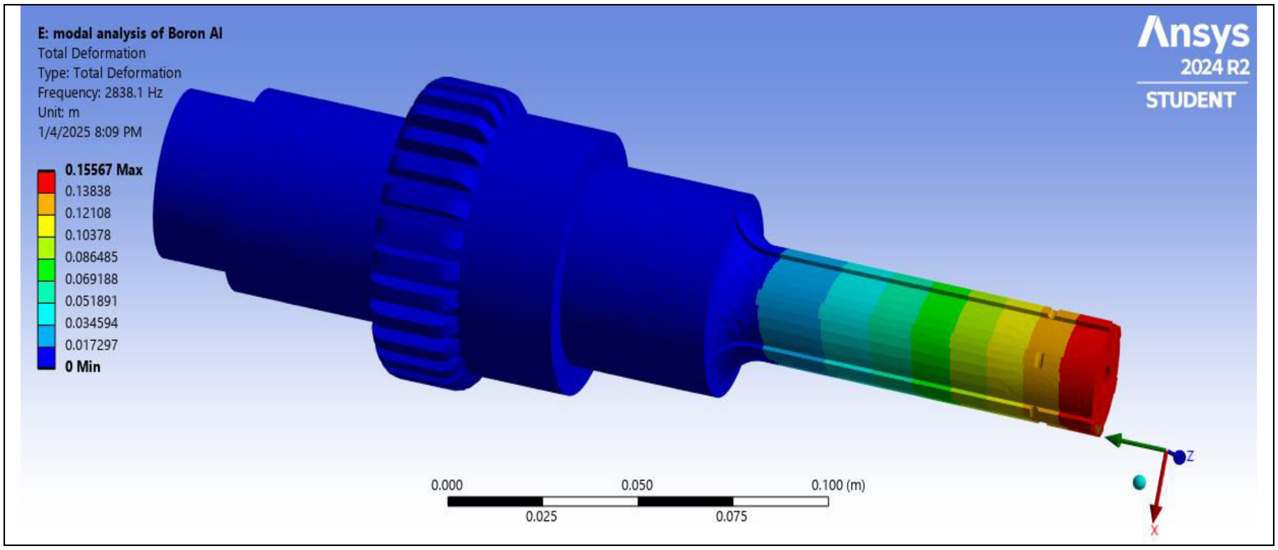


Figure.16 2nd mode shape using Boron Al

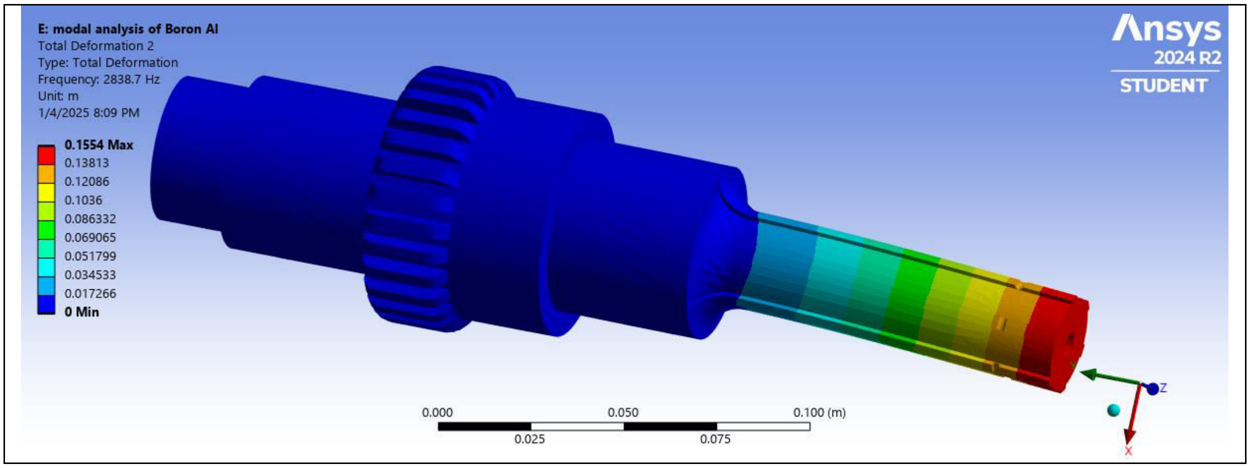


Figure.17 3rd mode shape using Boron Al

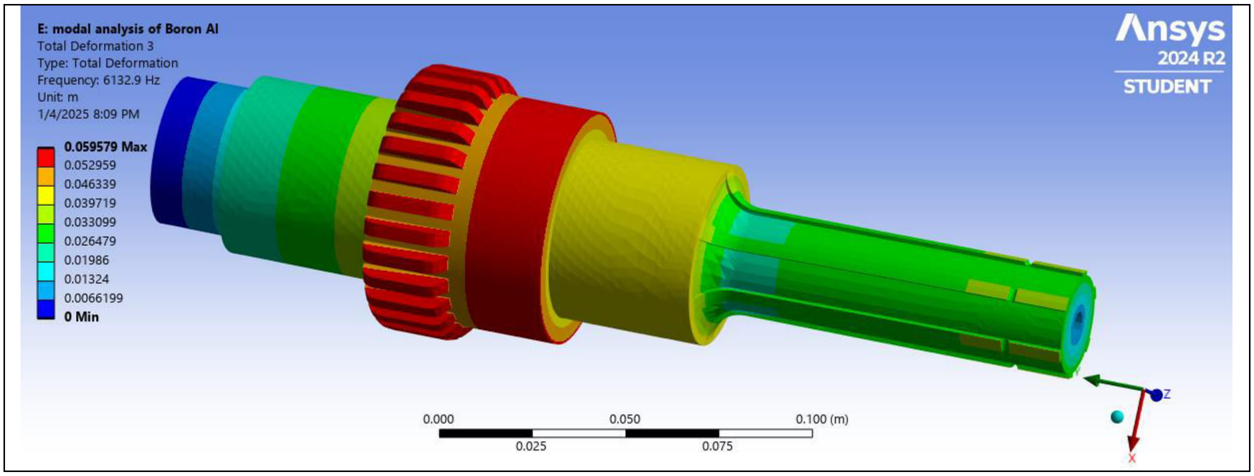


Figure.18 4th mode shape using Boron Al

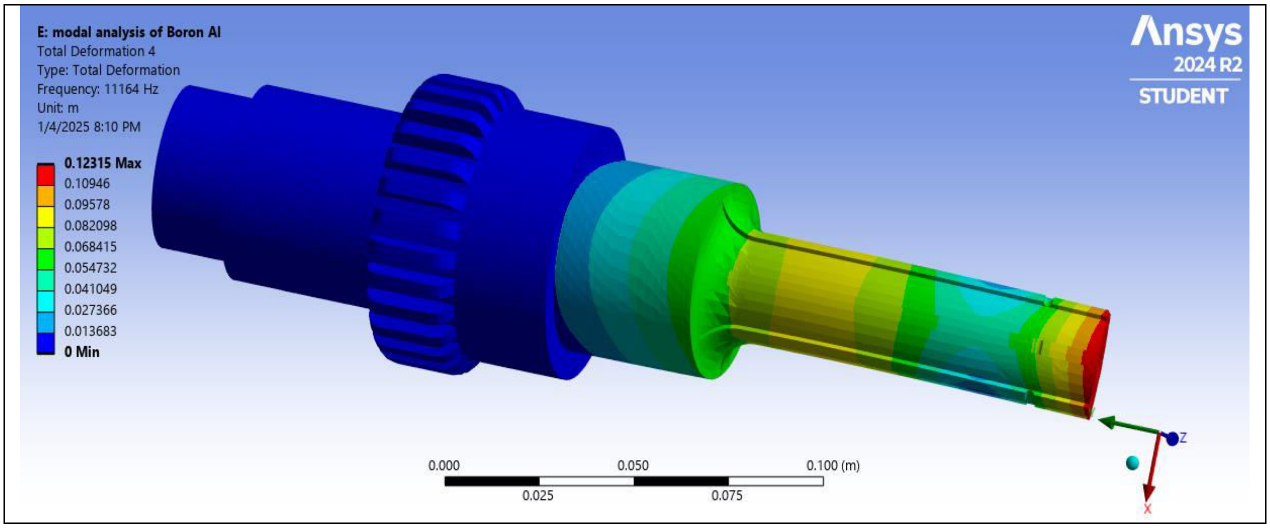
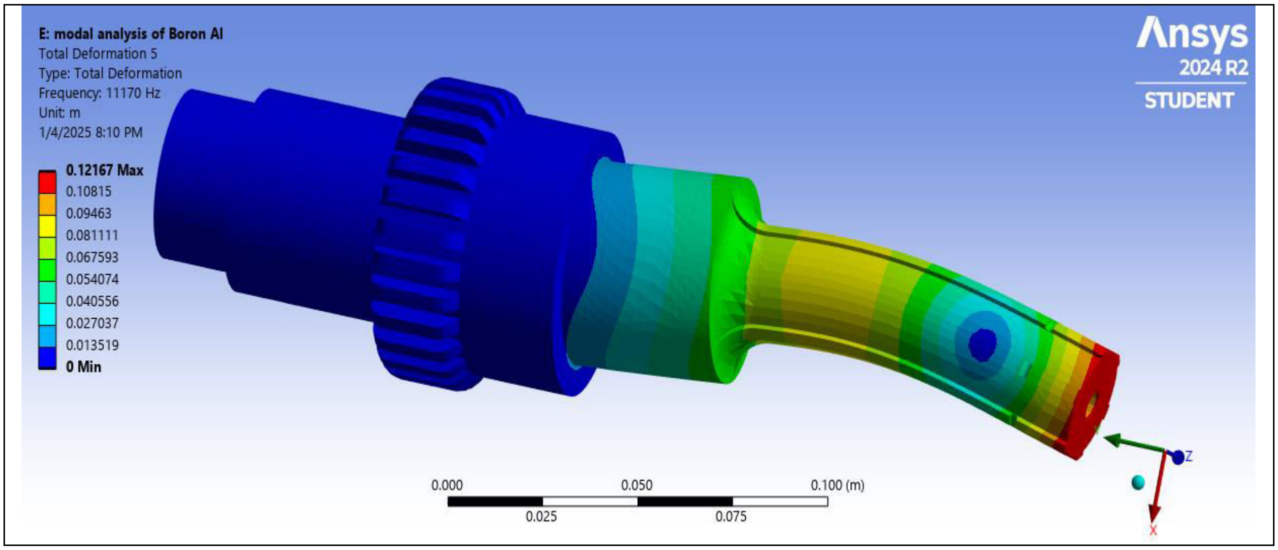


Figure.19 5th mode shape using Boron Al



Future scope

The modal structural analysis reveals that Boron Al exhibits the highest natural frequencies across all modes, indicating superior stiffness and resistance to resonance.

SAE 4140 shows moderate frequencies, while P100/6061 Al has slightly lower values in the first three modes but higher in the fourth and fifth, suggesting varied stiffness across modes. Overall, Boron Al offers the best vibrational stability, especially in higher frequency ranges.

The future of PTO shaft development focuses on exploring advanced materials like carbon fiber and hybrids to improve strength, durability, and weight efficiency.

Research into fatigue behavior and wear characteristics will enhance reliability and maintenance planning. Design optimization techniques aim to balance performance, cost, and manufacturability. Hybrid designs integrating smart materials and sensors can enable real-time monitoring, enhancing safety and operational efficiency in agricultural machinery.

Author Contributions

Abdul Malik Khan: Investigation, formal analysis, writing—original draft. Deepak Mahapatra: Validation, methodology, writing—reviewing. Ajay Verma:—Formal analysis, writing—review and editing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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