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Design and Dynamic Analysis of a Gyroscopic Stabilization Platform: Analytical and Simulation-Based Study of Flywheel Stabilization

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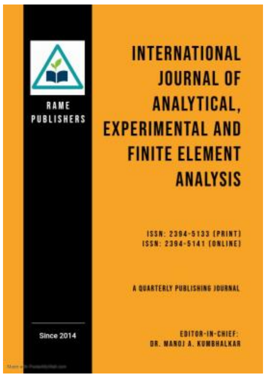

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Abstract: A gyroscopic stabilization platform is a mechanical system used to reduce unwanted angular motion by using the gyroscopic effect produced by a high-speed rotating flywheel. The present research focuses on the design and dynamic analysis of a scaled gyroscopic stabilization platform. The system consists of a flywheel, shaft, bearings, gimbal frame, and supporting housing. The main objective of this work is to study the relationship between flywheel inertia, angular velocity, precession velocity, and stabilizing torque. Analytical calculations are performed using the gyroscopic torque equation. For the selected flywheel of mass 5 kg and radius 0.15 m operating at 3000 RPM, the calculated moment of inertia is 0.05625 kg·m^2 and the stabilizing torque is 17.67 N·m at a precession speed of 1 rad/s. Finite element analysis is also considered for checking deformation, von Mises stress, and factor of safety of the flywheel, shaft, frame, and housing. The results show that stabilizing torque increases with increase in flywheel RPM. Among the compared design alternatives, the medium-weight flywheel design gives a balanced combination of torque output, structural safety, and practical suitability.

Keywords: Gyroscopic stabilization; flywheel; precession; stabilizing torque; finite element analysis; dynamic analysis; roll motion; ANSYS; CAD modelling.

1. Introduction

A gyroscopic stabilization platform is a mechanical system designed to resist unwanted angular motion of a body by using the gyroscopic effect. In this principle, a high-speed rotating flywheel resists any change in its axis of rotation and helps the system maintain stability. This concept is widely used in ships, aircraft, satellites, camera stabilizers, vehicles, and other balancing systems [1-4].

In this study, a scaled gyroscopic stabilization platform is designed and dynamically analyzed. The work mainly focuses on analytical calculations and simulation-based validation. Fabrication or physical prototype development is not included in this project. The main purpose of the study is to understand how a rotating flywheel generates stabilizing torque when the platform experiences roll motion or external disturbance [2-7].

The gyroscopic stabilization platform mainly consists of a flywheel, shaft, bearings, gimbal frame, and housing. Among these components, the flywheel is the main rotating element of the system. When the flywheel rotates at high speed, it stores angular momentum. When the platform undergoes roll motion, the rotating flywheel produces gyroscopic torque. This torque acts against the disturbance and helps in stabilizing the platform [8-10].

The basic gyroscopic torque equation used in this work is [11]

$$T = I\omega\Omega, \tag{1}$$

where T represents the stabilizing torque in N·m, I represents the moment of inertia of the flywheel in kg·m^2, ω represents the angular velocity of the flywheel in rad/s, and Ω represents the precession angular velocity in rad/s. From this equation, it can be understood that the stabilizing torque mainly depends on flywheel inertia, flywheel speed, and precession speed [12-13]. Therefore, the main design aim is to obtain sufficient stabilizing torque with minimum weight and safe stress value.

The literature related to gyroscopic stabilization shows that rotating masses and precession motion are widely used for generating stabilizing counter-torque in mechanical systems. Previous studies have explained the core principles of gyroscopic motion, angular momentum, flywheel spin, and precession, which form the foundation for stabilization platforms [14-17]. Several researchers have focused on CAD modelling and finite element analysis of high-speed rotating components to improve inertia while maintaining structural safety. Studies on marine gyrostabilizers and ship roll reduction have shown that flywheel speed, precession rate, and gyroscopic torque are directly related to the anti-roll performance of the system. Some works have also used mathematical modelling, MATLAB/Simulink simulation, PID controllers, fuzzy logic controllers, and nonlinear time-domain analysis to improve active stabilization performance under dynamic loading conditions [18-20]. Research on control moment gyroscopes and CubeSat actuators further highlights the importance of structural design, vibration analysis, and gimbal behavior in compact gyroscopic systems. Overall, the reviewed literature confirms that gyroscopic stabilization is an effective method for reducing roll motion and improving platform stability; however, there is still scope for simplified scaled models that combine analytical torque calculation, CAD design, finite element analysis, and dynamic simulation in a practical academic format [21-22].

Several studies highlighted the importance of CAD modelling, finite element analysis, structural optimization, and stress evaluation in mechanical component design. Research works on automotive suspension arms, MacPherson struts, differential covers, chassis structures, rotating mechanisms, turbine blades, windmill blades, and mechanical failure analysis show that simulation-based validation is an effective method for identifying deformation, von Mises stress, fatigue behavior, and factor of safety before physical fabrication [23-24]. These studies are relevant to the present work because the gyroscopic stabilization platform also involves rotating components, structural loading, dynamic forces, and the need for safe mechanical design. The reviewed studies support the use of analytical calculation and FEA-based validation for selecting a suitable flywheel design, checking stress concentration regions, and improving the reliability of the gyroscopic stabilization platform [25].

1.1 Problem Statement

Two-wheeled and narrow-body platforms are naturally unstable at low or zero velocity. Such systems require a continuous stabilization mechanism to prevent falling or excessive angular motion. Traditional stabilization methods may not be sufficient under high disturbance or high payload conditions.

In a gyroscopic stabilization system, high-speed rotation of the flywheel creates large angular momentum. However, this also creates structural stress in the flywheel, shaft, frame, and housing. If the platform is not properly designed, the system may experience deformation, vibration, resonance, or structural failure.

Therefore, there is a need to design and analyze a scaled gyroscopic stabilization platform that can generate useful stabilizing torque while maintaining structural safety.

1.2 Objectives

The main objective of this research is to design and analyze a scaled gyroscopic stabilization platform consisting of a fly-wheel, shaft, bearing, gimbal frame, and housing. The study focuses on calculating the moment of inertia of the flywheel, determining the angular velocity at different RPM values, and evaluating the stabilizing torque using the gyroscopic torque equation. It also aims to study the effect of flywheel RPM on stabilizing torque and compare different flywheel design options based on weight, torque output, and suitability. In addition, the research defines finite element analysis conditions for checking stress, deformation, and factor of safety. Finally, the work aims to select a balanced design suitable for a scaled gyroscopic stabilization platform.

1.3 Methodology

The methodology followed in this research begins with a literature study related to gyroscopic stabilization, flywheel design, dynamic analysis, and finite element analysis. After understanding the theoretical background, scaled model parameters such as flywheel mass, radius, RPM, and precession speed are selected. The moment of inertia of the flywheel is then calculated, followed by the calculation of angular velocity from the selected RPM values. Using these values, the stabilizing torque is determined with the help of the gyroscopic torque equation. Further, the stabilizing torque is compared at different RPM values to understand the effect of flywheel speed on stabilization performance. Different flywheel design options are also compared based on weight, torque, and practical suitability. Finally, finite element analysis conditions are defined for checking deformation, stress, and factor of safety, after which the final results are discussed and the most suitable design is selected.

2. Analytical Calculation

2.1 Moment of Inertia of Flywheel

The flywheel is considered as a solid circular disc. For a solid disc, the moment of inertia is given by

$$I = 1/2\ MR^2 \tag{2}$$

where I is the moment of inertia of the flywheel, M is the mass of the flywheel, and R is the radius of the flywheel.

For the selected design, $M = 5$ kg and $R = 0.15$ m. Therefore,

$$I = 1/2 \times 5 \times (0.15)^2 = 0.05625\ \text{kg} \cdot \text{m}^2. \tag{3}$$

Thus, the moment of inertia of the selected flywheel is 0.05625 kg·m^2.

2.2 Angular Velocity of Flywheel

Angular velocity is calculated from RPM using the following equation:

$$\omega = 2\Pi N/60 \tag{4}$$

where ω is angular velocity in rad/s and N is flywheel speed in RPM. For $N = 3000$ RPM,

$$\omega = 14.16\ \text{rad/s}. \tag{5}$$

Thus, the angular velocity of the flywheel at 3000 RPM is 314.16 rad/s.

2.3 Stabilizing Torque Calculation

Using Eq. (1), with $I = 0.05625$ kg·m^2, $\omega = 314.16$ rad/s, and $\Omega = 1$ rad/s,

$$T = 0.05625 \times 314.16 \times 1 = 17.67\ \text{N} \cdot \text{m}. \tag{6}$$

Thus, the selected scaled gyroscopic stabilization platform can generate approximately 17.67 N·m stabilizing torque.

3. Result and Discussion

Table 1: Design Parameters of the Scaled Gyroscopic Stabilization Platform

Parameter	Symbol	Value	Unit
Flywheel mass	M	5	kg
Flywheel radius	R	0.15	m
Flywheel diameter	D	0.30	m
Flywheel speed	N	3000	RPM
Angular velocity	ω	314.16	rad/s
Precession angular velocity	Ω	1	rad/s
Moment of inertia	I	0.05625	kg·m^2
Stabilizing torque	T	17.67	N·m

Table 2: RPM Versus Stabilizing Torque

Sr. No.	Flywheel Speed, N (RPM)	Angular Velocity, ω (rad/s)	Stabilizing Torque, T (N·m)
1	1000	104.72	5.89
2	2000	209.44	11.78
3	3000	314.16	17.67
4	4000	418.88	23.56
5	5000	523.60	29.45

From Table 2, it is observed that the stabilizing torque increases with increase in flywheel RPM. This is because angular velocity is directly proportional to RPM. Since stabilizing torque is directly proportional to angular velocity, the torque output also increases linearly with flywheel speed when moment of inertia and precession velocity are constant.

Table 3: Design Iteration Comparison for Flywheel Selection

Parameter	Design 1	Design 2	Design 3
Flywheel mass	3 kg	5 kg	7 kg
Diameter	250 mm	300 mm	350 mm
Radius	0.125 m	0.150 m	0.175 m
RPM	3000	3000	4000
Calculated moment of inertia	0.02344 kg·m^2	0.05625 kg·m^2	0.10719 kg·m^2
Calculated stabilizing torque at $\Omega = 1$ rad/s	7.36 N·m	17.67 N·m	44.90 N·m
Weight level	Low	Medium	High
Stress tendency	Low	Safe	High
Suitability	Less effective	Best balanced	Heavy/risky

From Table 3, Design 2 is selected as the most suitable option because it provides a balanced combination of stabilizing torque, moderate weight, and safe stress tendency. Design 1 is lightweight but produces lower stabilizing torque. Design 3 produces higher torque but is heavier and may create higher stress in the structure.

Table 4: Finite Element Analysis Setup

Analysis item	Input / condition	Purpose
Material	Mild steel / EN8 steel	To check structural strength
Load condition	Rotational velocity on flywheel	To simulate centrifugal stress
Constraint	Shaft hole area constrained	To represent shaft support
Mesh refinement	Fine mesh near centre hole and outer edge	To capture stress concentration
Output 1	Total deformation	To check dimensional stability
Output 2	Equivalent von Mises stress	To check failure possibility
Output 3	Factor of safety	To verify safe design
Output 4	Stress concentration region	To identify weak zones

Table 4 shows the finite element analysis setup used to check the structural safety of the gyroscopic platform. The material, rotational load, constraint, and mesh refinement are selected to identify deformation, von Mises stress, factor of safety, and stress concentration regions. This helps in verifying whether the flywheel and supporting components can safely withstand high-speed operating conditions.

Table 5 explains the research gap and the contribution of the present work. Most previous studies focus on large-scale marine gyrostabilizers or advanced control systems, while this work focuses on a simplified scaled academic model. The present study combines analytical torque calculation, flywheel design comparison, and FEA setup for practical design validation.

Table 5: Research Gap and Contribution Mapping

Identified research gap	Contribution of present work
Most studies focus on large marine gyrostabilizers or advanced controllers.	This work focuses on a simplified scaled academic gyroscopic stabilization model.
Less attention is given to basic mechanical design of flywheel, shaft, bearing, and frame.	The work includes flywheel sizing, torque calculation, shaft/frame safety considerations, and FEA setup.
There is a need to explain the relation between inertia, RPM, precession, and torque.	The work uses the equation $T = I\omega\Omega$ and presents RPM based torque comparison.
Structural safety at selected RPM must be studied.	FEA setup is defined for deformation, von Mises stress, and factor of safety.
Design comparison is required for optimized selection.	Three flywheel designs are compared and the balanced design is selected

Table 6: Summary of Results

Result parameter	Observation
Stabilizing torque at 3000 RPM	17.67 N·m
Torque trend	Torque increases with increase in RPM
Effect of flywheel radius high RPM selection	Larger radius increases moment of inertia and stabilizing effect Effect of Higher RPM improves torque but also increases structural stress best design Design 2
Reason for selection	Balanced torque, moderate weight, and safe stress tendency Fabrication status Design and analysis only
Main validation method	Analytical calculation and simulation-based verification

Table 6 summarizes the main results obtained from the analytical and design study. The selected design produces 17.67 N·m stabilizing torque at 3000 RPM, and the torque increases with increase in RPM. Design 2 is selected as the best option because it provides a balanced combination of torque output, moderate weight, and safe stress tendency.

4. Finite Element Analysis

Finite element analysis is used to check the structural safety of the gyroscopic stabilization platform. The main purpose of FEA is to determine the deformation, stress distribution, and factor of safety of the flywheel, shaft, frame, and housing under operating conditions.

The flywheel rotates at high speed, and centrifugal force acts on it. Due to this, tensile stress develops inside the flywheel. Therefore, structural analysis of the flywheel is necessary to ensure that the design remains safe at the selected RPM.

The shaft supports the flywheel and transfers rotational motion. It is subjected to bending stress, torsional stress, and reaction force from the flywheel. Shaft analysis is required to check maximum stress, deflection, safety factor, and suitability of shaft diameter.

The gimbal frame and housing support the complete gyroscopic assembly. When stabilizing torque is generated, reaction forces act on the frame. Therefore, the frame should be strong and rigid enough to avoid excessive deformation.

The expected FEA outputs are:

1. Total deformation.
2. Equivalent von Mises stress.
3. Factor of safety.
4. Stress concentration regions.

The design is considered safe if the maximum von Mises stress remains below the yield strength of the selected material and the factor of safety is within the acceptable design limit.

5. Working Principle

The gyroscopic stabilization platform works on the principle of conservation of angular momentum. When the flywheel rotates at high speed, it develops angular momentum. This angular momentum resists any change in the direction of the rotating axis.

When the platform experiences roll motion, the flywheel undergoes precession. Due to this precession, gyroscopic torque is generated. This torque acts opposite to the roll disturbance and helps in stabilizing the platform.

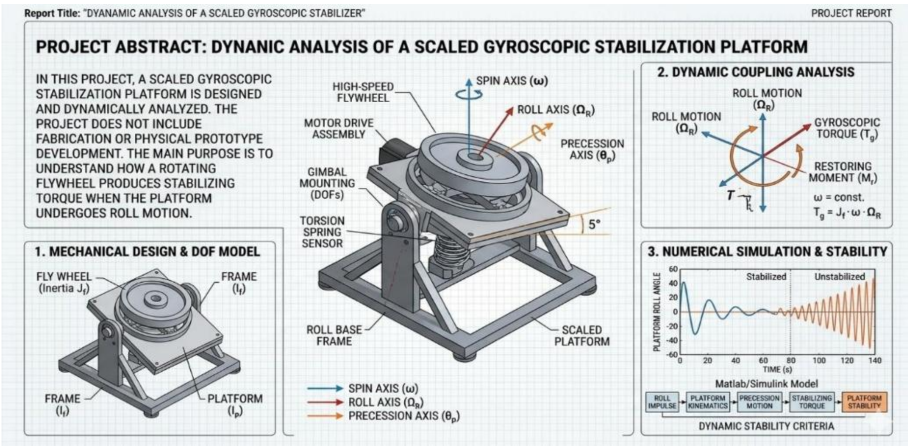

Figure 1: Conceptual layout and dynamic coupling of the scaled gyroscopic stabilization platform.

The gyroscopic torque is given by Eq. (1). The direction of gyroscopic torque depends on the direction of flywheel rotation, direction of precession, and axis of roll motion. By controlling these parameters, the platform can be stabilized against angular disturbances.

6. Results and Discussion

The analytical calculation shows that a flywheel of mass 5 kg and radius 0.15 m has a moment of inertia of 0.05625 kg·m^2. At 3000 RPM, the angular velocity of the flywheel is 314.16 rad/s. For a precession angular velocity of 1 rad/s, the stabilizing torque is calculated as 17.67 N·m.

The RPM versus torque comparison shows that stabilizing torque increases with increase in RPM. At 1000 RPM, the torque is 5.89 N·m, while at 5000 RPM, the torque increases to 29.45 N·m. This proves that flywheel speed has a major effect on stabilization performance.

The design comparison shows that increasing mass and radius increases the moment of inertia and torque output. However, higher mass and higher RPM also increase stress and weight. Therefore, the design should not be selected only on the basis of maximum torque. It should also consider structural safety, weight, manufacturability, and practical usability.

Among the three compared designs, Design 2 is found to be the most suitable option. It provides 17.67 N·m stabilizing torque with moderate weight and safe stress tendency. Design 1 is lighter but less effective, while Design 3 gives higher torque but is heavy and may produce higher stress.

The FEA setup helps in validating the structural safety of the selected design. The flywheel, shaft, frame, and housing should be analyzed for deformation, von Mises stress, and factor of safety before fabrication.

7. Conclusions

The design and dynamic analysis of a scaled gyroscopic stabilization platform has been carried out successfully. The study shows that the stabilizing torque depends on the moment of inertia of the flywheel, angular velocity of the flywheel, and precession angular velocity.

For the selected flywheel of mass 5 kg and radius 0.15 m, the moment of inertia is calculated as 0.05625 $kg \cdot m^2$. At 3000 RPM and 1 rad/s precession speed, the gyroscopic stabilizing torque is found to be 17.67 N·m.

The RPM versus torque analysis shows that stabilizing torque increases with increase in flywheel speed. The design comparison shows that a medium-weight flywheel gives better practical performance than a very light or very heavy flywheel. Therefore, Design 2 is selected as the balanced design.

Finite element analysis is necessary to verify the structural safety of the flywheel, shaft, frame, and housing. The design should be checked for total deformation, equivalent von Mises stress, and factor of safety before physical development.

Overall, the study confirms that a gyroscopic stabilization platform can be effectively designed and analyzed using analytical calculations and simulation methods.

8. Future Scope

The future scope of this work includes:

1. Fabrication of the physical prototype of the gyroscopic stabilization platform.
2. Experimental testing of the platform under real roll disturbance.
3. Use of sensors for measuring roll angle and angular velocity.
4. Development of a closed-loop control system using PID or LQR controller.
5. Dynamic simulation using ANSYS Motion, MATLAB Simulink, or Adams software.
6. Modal analysis to check vibration and resonance conditions.
7. Optimization of flywheel geometry to reduce weight and improve torque output.
8. Use of advanced materials such as aluminum alloy, AISI 4340 steel, or composite materials.
9. Integration of the system in two-wheeled vehicles, unmanned ground vehicles, or marine platforms.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] M. A. Kumbhalkar, "Core Principles of Mechanical System Stabilization Using Rotating Masses and Dynamic Modeling of Precession Motion," 2020.

[2] Dhiraj and Manoj, "CAD Modeling and Finite Element Analysis (FEA) of High-Stress Rotating Mechanical Components for Maximizing Inertia," 2021.

[3] M. A. I. *et al*., "Analytical and Computational Analysis of Gyroscopic Forces in Mechanical Stabilization Platforms Under Dynamic Load Conditions," 2022.

[4] Hu *et al*., "Mathematical Modeling of Ship Roll Motion with Gyrostabilizers: The Relationship Between Flywheel Spin, Precession, and Stabilizing Counter-Torque," 2023.

[5] Li *et al*., "Anti-Roll Characteristics of Marine Gyrostabilizers Using Hydrodynamic Simulation," 2022.
[6] Frölander, "Implementation of a Practical Gyroscopic Stabilization Demonstrator Using PID Controllers," 2017.
[7] Zhang, "Dynamic Modeling of Active Gyro-Based Roll Stabilization for Slender Vessels," 2014.
[8] Lhee *et al*., "Simulation of a Fuzzy Logic-Based Controller for a Gyroscopic Inverted Pendulum Using MATLAB/Simulink," 2018.
[9] Técnico Lisboa Study, "Theoretical Study of Gyrodynamic Angles and Flywheel Angular Momentum in Vessel Roll Reduction," 2019.
[10] Sathit, "Linear and Non-Linear Time-Domain Simulations of Ship Roll Gyro-Stabilizer Control Systems at Zero Forward Speed," 2021.
[11] Gaude *et al*., "Structural Design and Finite Element Analysis of a Control Moment Gyroscope (CMG) Actuator for CubeSats," 2020.
[12] Pei *et al*., "Modeling and Testing of an Innovative Gyroscope System for Platform Counter-Torque and Precession Angular Displacement," 2021.
[13] Dede, "Mathematical Dynamic Modeling of a Scaled-Down Sea Vessel Gyrostabilizer Using MATLAB Multibody Simulation," 2025.
[14] Aris *et al*., "A Comprehensive Review of Modern Marine Gyro Stabilizer Designs and the Conservation of Angular Momentum," *IEEE Xplore*, 2025.
[15] Shi *et al*., "Coupled Dynamic Modeling of a Single Gimbal Control Moment Gyroscope and Micro-Vibration Analysis," *IEEE Xplore*, 2020.
[16] R. Tamrakar, C. Sahu, and P. S. Rao, "Multi-Objective Optimization and Stress Analysis of an Automotive Upper Control Arm of Double Wishbone Suspension," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 12, no. 1, pp. 1–5, Mar. 2025, doi: 10.26706/ijaefea.1.12.20250601.
[17] M. A. Kumbhalkar, "Railways Failure Analysis – Current Trends and Future Directions," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 11, no. 2, pp. 32–37, Jun. 2024.
[18] P. H. Sahare, J. Saji, G. Prasad, V. Satpute, and V. Gogulwar, "Development of a 360-Degree Rotating Vehicle Mechanism," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 11, no. 2, pp. 44–48, Jun. 2024.
[19] S. Rane, V. Patil, D. Seniyar, O. Yadav, and A. Patil, "Design and Analysis of Vertical Axis Windmill Blades," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 11, no. 1, pp. 17–24, Mar. 2024.
[20] R. Tamrakar, A. Sarda, and S. K. Shrivastava, "A Study of Finite Element Analysis and Topology Optimization of Upper Arm of Double Wishbone Suspension," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 10, no. 2, pp. 42–45, Jun. 2023, doi: 10.26706/ijaefea.2.10.icramen202303.
[21] R. Babu, R. H. Gajghat, A. Sarda, and P. S. Rao, "Design Optimization of Adaptive MacPherson Strut Using ANSYS Simulation: A Study," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 10, no. 2, pp. 62–67, Jun. 2023, doi: 10.26706/ijaefea.2.10.icramen202315.
[22] B. Sonkar, A. Sarda, and R. Babu, "Enhancing the Performance of Turbine Blades Through CAD-Based Design Optimization and Finite Element Analysis: A Comprehensive Review," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 10, no. 2, pp. 35–37, Jun. 2023, doi: 10.26706/ijaefea.2.10.icramen202301.
[23] A. Mahawadiwar, "Design, Analysis, and Development of a Portable Trolley for Stair Climbing," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 10, no. 3, pp. 96–101, Aug. 2023.
[24] S. D. Yawalkar and S. R. Pullivarti, "A Review on Utilization of Computer-Aided Design/Manufacturing Software in the Production of a Three-Wheeler Chassis," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 9, no. 4, pp. 62–69, Dec. 2022, doi: 10.26706/ijaefea.4.9.20221202.
[25] N. Duble and A. D. Diwate, "Design and Finite Element Analysis of Differential Cover for Rear Drive Axle of a Light Commercial Vehicle (LCV)," *Int. J. Anal. Exp. Finite Elem. Anal.*, vol. 7, no. 2, Jul. 2020.