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Design, Structural Evaluation, and Vibration Analysis of Lightweight Alloy Wheels for Motorcycle Applications

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Abstract

This paper presents the design and finite element analysis of an alloy wheel for a Bajaj Pulsar 150 cc motorcycle, aimed at improving structural performance while minimizing stress concentration and deformation. Four spoke configurations—straight, inclined, Y-shaped, and spiral—were modeled in SolidWorks based on standard wheel dimensions (490 mm outer diameter, 60 mm width, 54 mm hub bore) and imported into ANSYS Workbench for static structural and modal analysis. Five candidate materials (Aluminum Alloy, Magnesium Alloy, Titanium Alloy, Glass, and PEEK) were evaluated for suitability in lightweight wheel applications. Static analysis applied a tire pressure of 0.46 MPa, a vertical load of 2000 N, and a rotational speed of 650 RPM to simulate realistic service conditions, and the resulting deformation, equivalent stress, equivalent strain, and shear stress were compared across configurations with 4, 5, and 6 spokes. Results show that the 6-spoke Y-shaped configuration provides the best overall balance of stress, strain, and deformation among the geometries tested, and that Aluminum Alloy offers the best trade-off between structural performance and manufacturability among the materials studied, despite Titanium Alloy showing superior raw mechanical performance. Modal analysis of the optimized 6-spoke Y-shaped Aluminum Alloy wheel yielded a first natural frequency of 216.3 Hz, well separated from typical in-service excitation frequencies, confirming satisfactory dynamic stability.

Keywords: **Alloy wheel, finite element analysis, spoke geometry, modal analysis, lightweight materials, motorcycle wheel.**

I. Introduction

The wheel is one of the most critical structural components of a motorcycle, supporting the vehicle load and transmitting driving, braking, and steering forces to the road [1]. Growing demand for fuel efficiency and improved handling has driven the automotive and two-wheeler industries toward lightweight components, and wheels—being a significant contributor to unsprung mass—are a natural target for weight reduction [2]. Alloy wheels, typically manufactured from aluminum or magnesium alloys, have replaced conventional steel wheels in many applications because they combine reduced weight with good strength, corrosion resistance, and heat dissipation, while also offering greater design flexibility [3].

During service, alloy wheels experience combined static and dynamic loading arising from vehicle weight, tire inflation pressure, braking and cornering forces, road impacts, and centrifugal effects during rotation. These loads generate stress concentrations, particularly at the spoke–rim and spoke–hub junctions, which can lead to fatigue failure if not properly accounted for in the design stage [4]. Consequently, structural optimization of spoke geometry and careful material selection are essential to achieving a wheel that is simultaneously lightweight, strong, and vibration-resistant.

This paper reports the design and finite element evaluation of an alloy wheel for a Bajaj Pulsar 150 cc motorcycle. Four spoke configurations (straight, inclined, Y-shaped, and spiral) with 4, 5, and 6 spokes were modeled and analyzed under identical

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loading and boundary conditions, and five candidate materials were compared to identify the configuration and material combination offering the best balance of strength, stiffness, weight, and vibration performance.

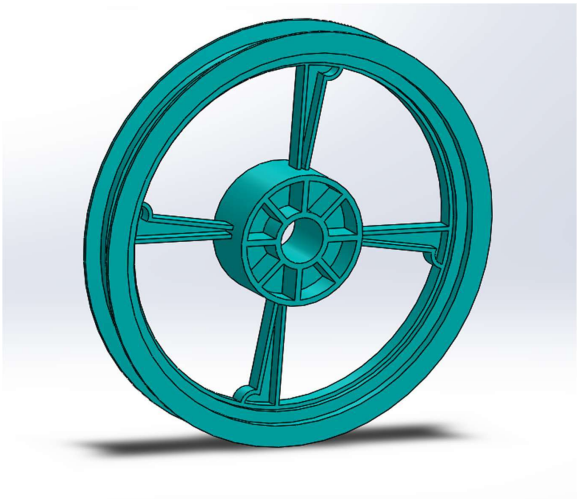


Fig. 1. Representative motorcycle alloy wheels.

II. Literature Review

A number of studies have examined the structural and vibration behavior of automotive alloy wheels using experimental and finite element methods. Malaimeham and Vinaitheerthan correlated FEA wheel-crushing simulations with physical tests and reported over 87% agreement between simulation and experiment, demonstrating that FEA can reliably predict deformation and failure behavior while reducing development cost [1]. Somayaji et al. performed modal analysis of carbon-fiber-reinforced aluminum wheels and found that reinforcement raised natural frequencies and reduced deformation relative to conventional materials [2]. Topaloğlu et al. proposed a neural-network-based approach for rim design optimization that reduced computational effort while improving modal performance [3], and Shahbazian et al. showed that geometric optimization of aluminum wheels can improve fatigue life and impact strength while satisfying ISO requirements [4].

Padmanabhan et al. compared aluminum, magnesium, and titanium wheel designs in ANSYS and concluded that material selection strongly influences deformation and reliability [5]. Hebbal and Dabair conducted static, modal, and harmonic analyses of alloy wheel rims, underlining the importance of modal analysis in wheel design [6], while Suman et al. compared impact and vibration behavior across several material combinations [7]. Multi-objective optimization studies by Wang et al. improved wheel strength while reducing mass through combined FEA and optimization algorithms [8], and Dong et al. used coupled simulation and experiment to optimize the low-pressure die-casting process for A356 aluminum wheel hubs [9]. Further work has examined crashworthiness modeling approaches [10], impact-test simulation [11], rim geometry optimization [12], the influence of tire properties on impact performance [13], wheel–rail rolling contact behavior [14], and simplified modeling of wheel impact considering material inhomogeneity [15]. Additional studies addressed optimization of car wheel rims using FEA [16], stress and deformation prediction using ANSYS for aluminum wheel rims [17], three-dimensional simulation of crack formation in wheel rims [18], the influence of rim offset on deformation [19], and cornering-fatigue simulation of steel wheels [20], [21]. More recent studies have investigated additive-manufactured wheel rims [22], carbon-fiber-reinforced hybrid wheel systems [23], and lightweight titanium/magnesium wheel development [24], [25], collectively motivating the combined geometry–material optimization approach adopted in the present work.

III. Methodology

The wheel geometry corresponds to a Bajaj Pulsar 150 cc motorcycle wheel, with an outer diameter of 490 mm, a width of 60 mm, a hub inner (bore) diameter of 54 mm, and a hub outer diameter of 155 mm. These dimensions were held constant across all spoke configurations to enable a fair comparison.

A. CAD Modeling

Three-dimensional wheel models were developed in SolidWorks using a parametric, feature-based workflow. The rim cross-section was sketched and converted into a solid using the Revolve Boss/Base feature, after which spoke profiles were generated with the Extruded Boss/Base feature and replicated using Circular Pattern. Fillets were applied at all spoke–rim and spoke–hub junctions to reduce stress concentration. The straight-

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spoke wheel (Fig. 2) served as the reference geometry, from which the inclined, Y-shaped (Fig. 3), and spiral configurations were derived by modifying only the spoke region while keeping the rim and hub geometry unchanged. For each spoke pattern, models with 4, 5, and 6 spokes were generated.



Fig. 2. Straight-spoke alloy wheel CAD model (4-spoke).

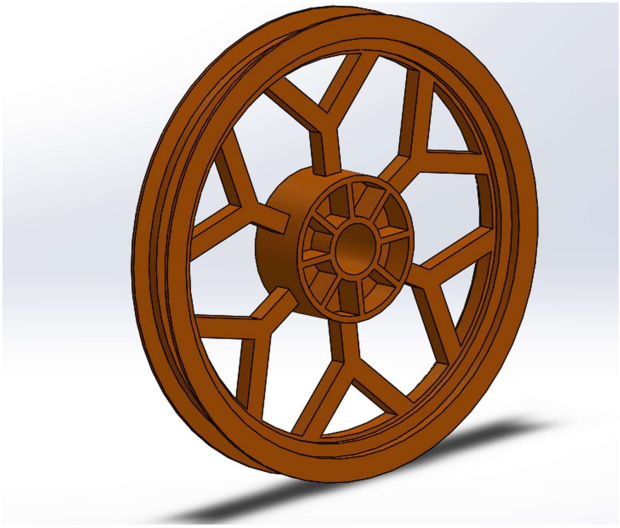


Fig. 3. Y-shaped alloy wheel CAD model.

B. Materials

Five materials were evaluated: Aluminum Alloy, Magnesium Alloy, Titanium Alloy, Glass, and PEEK (polyether ether ketone). Their mechanical properties are summarized in Table I.

TABLE I. MATERIAL PROPERTIES

Material	E (GPa)	ν	ρ (kg/m³)	σy (MPa)
Aluminum Alloy	71	0.33	2770	280
Magnesium Alloy	45	0.35	1800	160
Titanium Alloy	110	0.34	4500	830
Glass	70	0.22	2500	120
PEEK	3.6	0.40	1320	100

C. Finite Element Analysis

The SolidWorks geometry was imported into ANSYS Workbench, cleaned of insignificant features, and discretized using tetrahedral elements (Fig. 4), with mesh refinement applied at the spoke–hub and spoke–rim junctions where high stress gradients were expected. A frictionless support was assigned at the hub mounting surface to represent the axle connection, together with a displacement constraint on the hub side face to eliminate rigid-body motion.

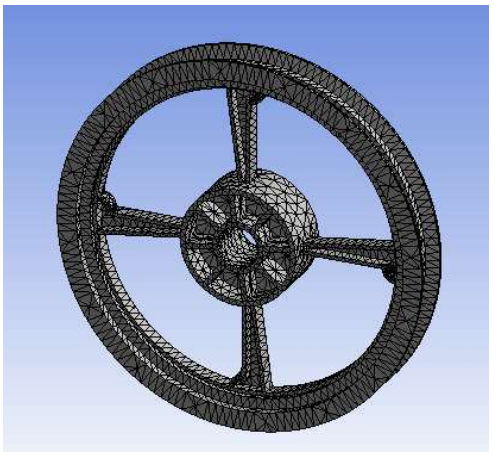


Fig. 4. Tetrahedral mesh of the alloy wheel.

D. Loading Conditions

Static structural analysis applied three simultaneous loads representative of normal service conditions: a tire inflation pressure of 0.46 MPa on the rim surface, a vertical load of 2000 N applied to the rim to represent vehicle and rider weight, and a rotational velocity corresponding to 650 RPM (approximately 60 km/h) to capture centrifugal effects. These conditions were held constant across all spoke geometries, spoke counts, and materials to ensure a consistent basis for comparison. Modal analysis of the optimized design was subsequently performed

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with the same boundary conditions but without external loads, to extract the first five natural frequencies and mode shapes.

IV. Results and Discussion

A. Effect of Spoke Geometry (Aluminum Alloy)

Table II compares the total deformation, equivalent (von Mises) stress, equivalent strain, and shear stress obtained for the four spoke geometries with six spokes under the combined loading condition. Results for the 4- and 5-spoke variants followed the same trend and are omitted here for brevity.

TABLE II. STATIC RESULTS FOR 6-SPOKE CONFIGURATIONS (ALUMINUM ALLOY)

Spoke Type	Def. (mm)	Stress (MPa)	Strain	Shear (MPa)
Straight	0.154	16.85	0.000260	6.48
Inclined	0.079	13.60	0.000225	5.62
Y-Shaped	0.148	12.80	0.000198	4.85
Spiral	1.310	122.50	0.001780	8.95

Across all spoke counts (4, 5, and 6), the inclined-spoke wheel consistently produced the lowest total deformation (e.g., 0.079 mm for the 6-spoke variant, a 48.7% reduction relative to the straight-spoke baseline), reflecting the improved bending resistance provided by angled load paths. However, the Y-shaped configuration consistently achieved the lowest equivalent stress, equivalent strain, and shear stress of all four geometries — for the 6-spoke case, 24.0% lower stress, 23.9% lower strain, and 25.2% lower shear stress than the straight-spoke wheel, while keeping deformation close to the inclined-spoke result. This is attributed to the branched load path of the Y-shaped spoke, which distributes load over two paths between the hub and rim and reduces localized stress concentration. The spiral-spoke design performed worst overall, with deformation, stress, strain, and shear stress 6–8 times higher than the straight-spoke baseline, indicating that the curved load path is structurally inefficient under the applied combined loading despite its aesthetic appeal. Increasing the spoke count from 4 to 6 progressively reduced deformation and stress for every geometry, consistent with improved load distribution as more load paths are added between hub and rim. On the basis of this combined evaluation, the 6-spoke Y-shaped configuration was selected as the optimum geometry for further material-level analysis.

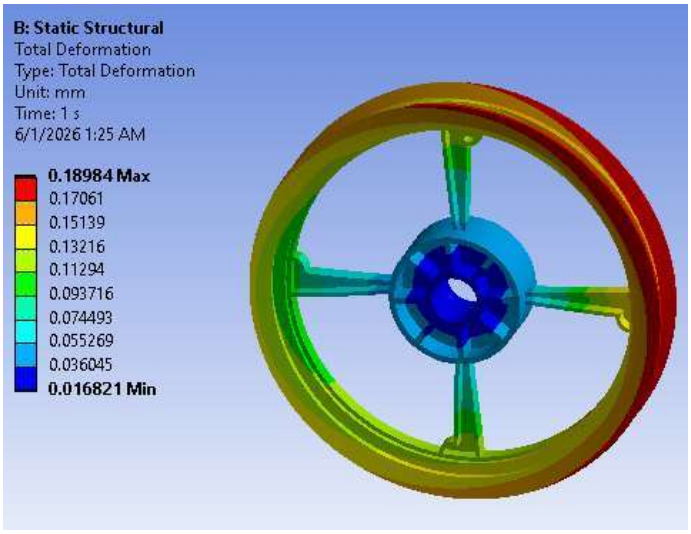


Fig. 5. Equivalent (von Mises) stress contour, straight-spoke wheel.

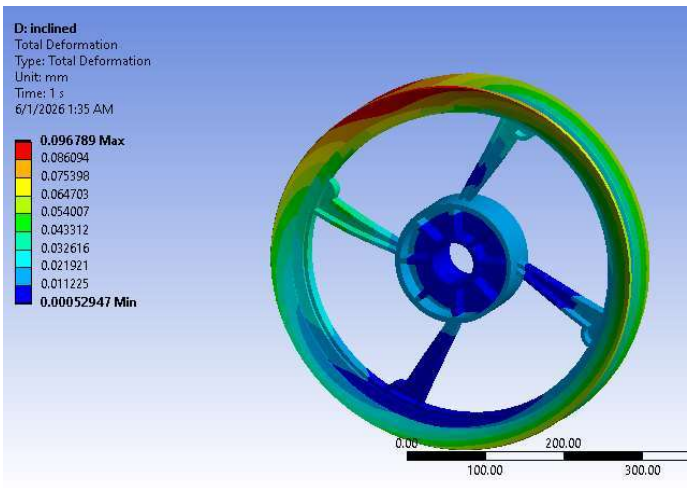


Fig. 6. Deformation contour, Y-shaped spoke wheel.

B. Effect of Material (6-Spoke Y-Shaped Wheel)

With geometry and loading held fixed, the five candidate materials were compared; results are summarized in Table III. Because the applied loads and geometry are identical, the equivalent stress and shear stress obtained from the linear-elastic solution (12.8 MPa and 4.85 MPa, respectively) are the same for every material, while deformation, strain, and factor of safety vary with material stiffness and strength.

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TABLE III. MATERIAL COMPARISON — 6-SPOKE Y-SHAPED WHEEL

Material	Def. (mm)	Strain	σy (MPa)	F.o.S.
Aluminum	0.148	0.000198	280	21.9
Magnesium	0.172	0.000285	160	12.5
Titanium	0.085	0.000110	880	68.8
Glass	0.235	0.000410	150	11.7
PEEK	0.620	0.002350	100	7.8

Titanium Alloy delivered the best raw structural performance, with 42.6% lower deformation and 44.4% lower strain than Aluminum Alloy, and the highest factor of safety (68.8) due to its high stiffness-to-weight ratio and 830 MPa yield strength. However, titanium's high raw-material and machining cost limits its practicality for mass-produced motorcycle wheels. PEEK and Glass, by contrast, exhibited substantially higher deformation and strain than the metallic alloys owing to their low stiffness, making them less suitable despite their low density. Aluminum Alloy offered a favorable compromise: a factor of safety of 21.9, 13.9% lower deformation and 30.5% lower strain than Magnesium Alloy, together with good corrosion resistance, availability, and manufacturability. Considering both structural performance and economic feasibility, Aluminum Alloy was selected as the optimum material for the final wheel design, and the 6-spoke Y-shaped Aluminum Alloy wheel was carried forward to modal analysis.

C. Modal Analysis of the Optimized Design

Modal analysis of the 6-spoke Y-shaped Aluminum Alloy wheel, performed with the same hub boundary conditions but without applied loads, yielded the first five natural frequencies listed in Table IV.

TABLE IV. NATURAL FREQUENCIES OF THE OPTIMIZED WHEEL

Mode	1	2	3	4	5
Frequency (Hz)	216.3	308.3	308.7	321.9	699.7

The fundamental mode occurs at 216.3 Hz and corresponds to overall bending deformation of the rim and spoke assembly, with the highest displacement observed at the outer rim (Fig. 7). Modes 2 and 3 occur at nearly identical frequencies (308.3 Hz and 308.7 Hz), reflecting the rotational symmetry of the six-spoke Y-shaped geometry, while modes 4 and 5 (321.9 Hz and 699.7 Hz) show progressively higher stiffness and more localized deformation patterns. Because these natural frequencies lie well above the typical excitation frequencies generated by engine vibration, road irregularities, and wheel rotation at normal operating speeds, the risk of resonance during service is low, confirming that the optimized wheel possesses adequate dynamic stability.

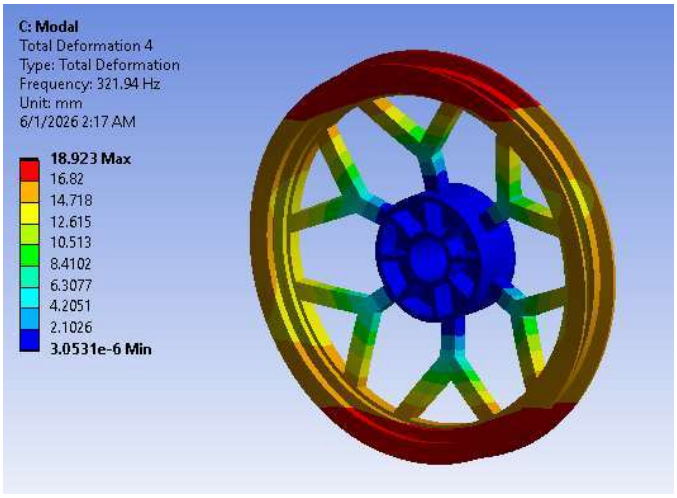


Fig. 7. Fifth-mode shape of the optimized 6-spoke Y-shaped Aluminum Alloy wheel (699.7 Hz).

V. Conclusion

Finite element analysis of four spoke geometries (straight, inclined, Y-shaped, and spiral) for a Bajaj Pulsar 150 cc alloy wheel, under combined tire pressure, vertical load, and rotational speed, showed that spoke geometry strongly influences deformation and stress distribution. The Y-shaped configuration

achieved the best overall balance of stress, strain, and shear stress among the geometries tested, while the spiral-spoke design was structurally the least efficient. Increasing the spoke count from 4 to 6 consistently improved structural performance for all geometries. Among five candidate materials evaluated for the optimized Y-shaped geometry, Titanium Alloy provided the highest raw structural performance, but Aluminum Alloy was selected as the practical optimum considering its combination of adequate strength (factor of safety of 21.9), low weight, corrosion resistance, and manufacturability. Modal analysis of the resulting 6-spoke Y-shaped Aluminum Alloy wheel confirmed a fundamental natural frequency of 216.3 Hz, sufficiently separated from typical service excitation frequencies to avoid resonance. These findings support the 6-spoke Y-shaped Aluminum Alloy wheel as a lightweight, structurally reliable design for motorcycle applications. Future work should extend this analysis to fatigue and crack-propagation behavior under cyclic loading, experimental validation through prototype testing, and topology optimization of the spoke geometry to further reduce mass while preserving stiffness and vibration resistance.

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