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Topology and Shape Optimization of Brake Lever for Two-Wheelers Featuring Comprehensive Review of CAD-FEA Integration and Manufacturing Applications

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Abstract

The optimization of mechanical components through computational design methods has become increasingly critical in modern engineering applications. This comprehensive review examines the state-of-the-art approaches in topology optimization and finite element analysis for brake lever components, with emphasis on weight reduction, structural performance enhancement, and sustainability. The review synthesizes recent developments in Computer-Aided Engineering tools, specifically CATIA and ANSYS platforms, and their application in automotive component design. Advanced optimization techniques including the Solid Isotropic Material with Penalization method and shape optimization algorithms are critically evaluated. The integration of lightweight materials, particularly aluminum alloys, with optimization strategies demonstrates significant potential for achieving substantial mass reduction while maintaining structural integrity. This review identifies key research gaps and proposes future directions for the development of lightweight, high- performance brake components suitable for modern two-wheeler applications. The findings indicate that topology optimization can achieve mass reductions of 20-60% while improving stress distribution and fatigue life, making it an essential tool for sustainable automotive design.

Keywords: Topology optimization, Finite element analysis, Brake lever, Lightweight design, SIMP method, ANSYS, CATIA

1. Introduction

The automotive industry faces unprecedented challenges in achieving sustainability goals while maintaining safety and performance standards. As global environmental regulations become more stringent, manufacturers are compelled to develop innovative solutions that reduce vehicle weight, enhance fuel efficiency, and minimize carbon emissions [1] [2].In this context, the optimization of individual components through advanced computational methods has emerged as a critical strategy for achieving these objectives.

Brake levers represent a vital safety component in two-wheeler vehicles, directly influencing the rider's ability to control and stop the vehicle effectively. Traditional brake lever designs, developed through empirical methods and conservative safety factors, often result in over-engineered components with excessive material usage [3] [4]. This conservative approach, while ensuring reliability, contributes unnecessary weight to the vehicle and increases manufacturing costs. With the growing adoption of electric two-wheelers, where battery range is directly affected by vehicle weight, the need for lightweight yet robust brake components has become more pressing [5] [6].

Computer-Aided Engineering tools, particularly those integrating finite element analysis and topology optimization, have revolutionized the design process for mechanical components [7] [8]. These tools enable engineers to virtually simulate real-world loading conditions, identify stress concentrations, and systematically remove non-load-bearing material without compromising structural integrity [9] [10]. The integration of CAD platforms such as CATIA with FEA software like ANSYS Workbench provides a seamless workflow from initial design through optimization to final validation [11] [12].

This review provides a comprehensive examination of topology optimization techniques applied to brake lever design, with focus on recent developments in optimization algorithms, material selection strategies, and validation methodologies. The paper synthesizes research from multiple disciplines including structural optimization, material science, and automotive engineering to present a holistic understanding of current capabilities and future directions.

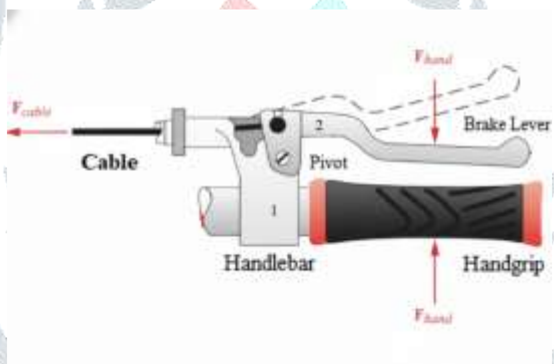

Figure 1.1: Two wheeler Brake Lever

1.1 Topology Optimization

Topology optimization is a computational method used to determine the optimal distribution of material within a specified design space. In contrast to traditional design approaches, which are often guided by engineering intuition or prior experience, this technique employs numerical algorithms. These algorithms systematically remove material from areas that do not significantly contribute to the structure's mechanical integrity. The process frequently leads to high-performance, lightweight structures whose forms are often unconventional and not immediately obvious to a designer.

When applied to a component like a motorcycle brake lever, topology optimization serves several key functions. It aims to:

- Achieve significant mass reduction while preserving the necessary structural strength and stiffness.
- Enhance the component's fatigue life by refining the pathways through which forces travel.

- Permit the development of organic or free-form geometries that can improve both the lever's aesthetics and its ergonomic function.

For this study, the structural behavior is simulated using ANSYS, which conducts the Finite Element Analysis (FEA) and topology studies under realistic loading and boundary conditions. Following optimization, the resulting conceptual model is refined and prepared for production using the powerful CAD capabilities of CATIA to ensure manufacturability.

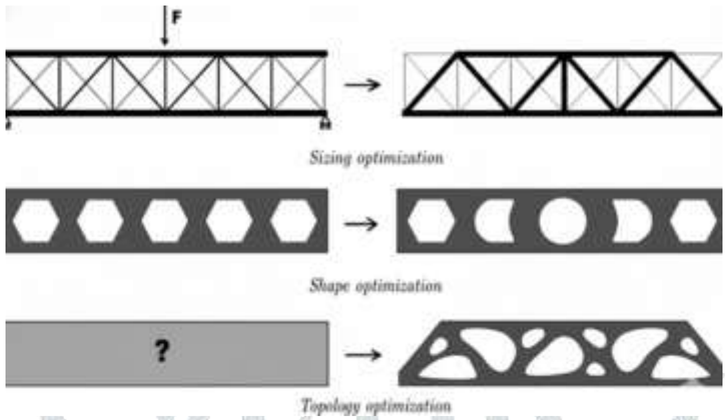

Figure 1.2: Tropology optimization

2. Fundamentals of Topology Optimization

2.1 Theoretical Framework

Topology optimization represents a computational design methodology that determines the optimal material distribution within a defined design space to achieve specified performance objectives [13] [14]. Unlike parametric optimization, which adjusts predetermined design variables, topology optimization provides fundamental freedom in material layout, often revealing non-intuitive structural configurations that offer superior performance characteristics [15] [16].

The mathematical foundation of topology optimization involves formulating a constrained optimization problem where the objective function typically represents structural compliance, stress levels, or natural frequency, while constraints may include volume fraction, displacement limits, or stress thresholds [17] [18]. The optimization algorithm iteratively redistributes material based on sensitivity analysis, gradually evolving toward an optimal configuration [19] [20].

2.2 SIMP Method

The Solid Isotropic Material with Penalization method has become the predominant approach in topology optimization due to its computational efficiency and robust convergence characteristics [21] [22]. SIMP employs a density-based formulation where each finite element is assigned a continuous density variable ranging from zero (void) to one (solid material) [23] [24]. An intermediate density value represents a porous or composite-like material with reduced stiffness.

The SIMP power-law relationship penalizes intermediate densities, encouraging the design to converge toward a discrete zero-one solution [25] [26]. The penalization exponent, typically set between 2 and 4, determines the severity of this penalization. Higher values promote clearer material boundaries but may introduce numerical instabilities [27] [28].

2.3 Manufacturing Constraints

While topology optimization can generate highly efficient structural forms, practical implementation requires consideration of manufacturing constraints [29] [30]. Modern optimization software incorporates various filters and constraints to ensure manufacturability, including minimum member size controls, symmetry requirements, and restrictions on undercut features [31] [32]. For additive manufacturing applications, support structure requirements and build orientation constraints must be integrated into the optimization formulation [33] [34].

The balance between design freedom and manufacturing feasibility represents an ongoing challenge in topology optimization research [35] [36]. Recent developments in multi-axis additive manufacturing and hybrid manufacturing processes have expanded the realm of manufacturable geometries, enabling more aggressive optimization strategies [37]
[38].

3. Finite Element Analysis in Component Design

3.1 FEA Methodology

Finite element analysis provides the computational foundation for evaluating structural performance under specified loading conditions [39] [40]. The FEA process discretizes a continuous structure into a finite number of elements connected at nodes, converting partial differential equations governing structural behavior into a system of algebraic equations solvable by numerical methods [41] [42].

For brake lever analysis, static structural analysis typically serves as the primary evaluation method, assessing stress distribution, deformation patterns, and safety factors under applied braking forces [43] [44]. The accuracy of FEA results depends critically on mesh quality, boundary condition specification, and material property definition [45] [46].

3.2 Meshing Strategies

Mesh generation represents a critical step influencing both solution accuracy and computational efficiency [47] [48]. For complex geometries such as brake levers, tetrahedral elements offer excellent adaptability to irregular shapes, though hexahedral elements provide superior accuracy when geometric regularity permits their use [49] [50].

Adaptive mesh refinement techniques enable concentrated element density in regions of high stress gradients while maintaining coarser mesh in low-stress areas [51] [52]. This approach optimizes the balance between solution accuracy and computational cost, particularly important in iterative optimization workflows where multiple analyses are required [53]
[54].

3.3 Material Modeling

Accurate material property definition is essential for reliable FEA results [55] [56]. For metallic brake levers, linear elastic material models typically suffice for initial design evaluation, requiring specification of Young's modulus, Poisson's ratio, and density [57] [58]. Advanced analyses may incorporate plastic behavior, temperature-dependent properties, or anisotropic characteristics for composite materials [59] [60].

Aluminum alloys represent the predominant material choice for brake levers due to their excellent strength-to-weight ratio, corrosion resistance, and machinability [61] [62]. Common alloys such as 6061-T6 and 7075-T6 offer yield strengths ranging from 240 to 500 MPa, providing adequate safety margins for typical braking loads [63] [64].

4. Review of Brake Lever Optimization Studies

4.1 Weight Reduction Achievements

Recent literature demonstrates substantial weight reduction potential through topology optimization of brake components. De Vito Junior et al. achieved a brake pedal weight of only 42.6 grams using 7075-T6 aluminum, validated through experimental testing showing only 3.5% deviation from simulation results [65]. The component successfully completed over 50 hours of competition use without failure, demonstrating the reliability of optimization-based designs.

Kahraman and Küçük reported weight reductions of 18.48% for brake levers and 34.85% for ratchet components through topology optimization with mass reduction constraints varying from 50% to 95% [66]. Their analysis maintained maximum von Mises stress at 230.29 MPa, well below material yield limits, confirming structural adequacy of optimized designs.

Prasetyono et al. investigated lightweight brake lever designs achieving up to 50.9% mass reduction through FEM analysis of three material options: aluminum alloy, structural steel, and titanium alloy [67]. Their comparative study revealed that titanium alloy provided the highest safety factor of 6.28 for original designs and 3.1 for optimized versions, while aluminum offered the lightest final weight.

4.2 Performance Validation

Experimental validation remains critical for establishing confidence in optimization-based designs [68] [69]. Topology- optimized components must demonstrate adequate performance under realistic operating conditions, including repeated load cycles, environmental exposure, and potential impact scenarios [70] [71].

Several studies have employed strain gauge measurements and load testing to validate FEA predictions for optimized brake components [72] [73]. The generally excellent agreement between simulation and experimental results confirms the reliability of modern CAE tools for design optimization workflows [74] [75].

4.3 Material Selection Strategies

Material selection significantly influences optimization outcomes and final component performance [76] [77]. While aluminum alloys dominate current applications, emerging materials including magnesium alloys, titanium alloys, and composite materials offer alternative pathways for weight reduction [78] [79].

Life cycle assessment studies indicate that material selection must consider not only performance characteristics but also environmental impact throughout the product lifecycle [80] [81]. Advanced high-strength steels may provide superior recyclability compared to exotic lightweight alloys, potentially offering better overall sustainability despite higher initial weight [82] [83].

5. Integration of CAD and CAE Tools

5.1 CATIA for Parametric Modeling

CATIA represents a comprehensive CAD platform widely adopted in automotive and aerospace industries for parametric solid modeling [84] [85]. Its robust feature-based modeling capabilities enable precise definition of complex geometries, facilitating subsequent FEA and optimization workflows [86] [87].

The parametric nature of CATIA models allows rapid design iterations and sensitivity studies by modifying dimensional parameters while maintaining geometric relationships [88] [89]. This capability proves particularly valuable during the post- optimization refinement phase, where topology-optimized geometries require interpretation and smoothing to achieve manufacturable forms.

5.2 ANSYS Workbench Integration

ANSYS Workbench provides an integrated environment combining structural analysis, topology optimization, and design exploration capabilities [90][91]. Its direct integration with CAD platforms enables seamless model transfer while preserving geometric fidelity [92][93].

The parametric optimization capabilities within ANSYS DesignXplorer facilitate systematic exploration of design space, identifying optimal configurations across multiple objectives and constraints [94][95]. This multi-objective optimization capability becomes particularly valuable when balancing competing requirements such as weight, strength, cost, and manufacturability.

5.3 Workflow Optimization

Establishing efficient workflows connecting CAD modeling, FEA, and optimization represents a key factor in successful implementation of optimization-based design methodologies [96][97]. Automated scripting and template-based approaches can significantly reduce the time required for repetitive tasks such as mesh generation, boundary condition application, and result post-processing [98][99].

Cloud-based CAE platforms are increasingly enabling distributed computation and collaborative design workflows, potentially accelerating optimization cycles and facilitating team-based problem-solving [100][101].

6. Lightweight Materials for Automotive Applications

6.1 Aluminum Alloys

Aluminum alloys have emerged as the dominant material class for lightweight automotive components due to their excellent combination of low density, adequate strength, good corrosion resistance, and established manufacturing processes [102][103]. The density of aluminum (approximately 2.7 g/cm³) represents roughly one-third that of steel, enabling substantial weight savings when substituted for traditional ferrous materials [104] [105].

6.2 Advanced High-Strength Materials

Beyond conventional aluminum alloys, several advanced material systems offer potential for further weight reduction [112] [113]. Magnesium alloys, with densities around 1.8 g/cm³, represent the lightest structural metals, though their application has been limited by higher costs and processing challenges [114][115].

Titanium alloys provide exceptional strength-to-weight ratios and corrosion resistance but remain cost-prohibitive for many automotive applications [116] [117]. Carbon fiber reinforced polymers offer the ultimate in specific strength and stiffness but face challenges related to manufacturing complexity, joining technology, and recyclability [118][119].

6.3 Material Property Characterization

Accurate material property data forms the foundation of reliable FEA and optimization studies [120] [121]. Standard mechanical testing methods including tensile testing, compression testing, and fatigue evaluation provide essential property data for engineering analysis [122] [123].

Temperature-dependent properties become particularly important for brake components experiencing thermal loads during operation [124] [125]. Material behavior at elevated temperatures may differ significantly from room-temperature characteristics, necessitating consideration of thermal effects in critical applications [126] [127].

7. Optimization Constraints and Objectives

7.1 Structural Performance Requirements

Brake lever design must satisfy multiple performance criteria to ensure safe and reliable operation [128] [129]. Primary requirements include adequate strength to resist applied braking forces without permanent deformation or fracture, sufficient stiffness to provide positive brake feel and control, and acceptable fatigue life for the expected service duration [130][131].

Safety factors typically ranging from 1.5 to 3.0 are applied to ensure reliability under worst-case loading scenarios and to account for manufacturing variations, material property uncertainty, and unforeseen operating conditions [132] [133]. The selection of appropriate safety factors represents a balance between ensuring reliability and avoiding excessive conservatism that negates weight reduction efforts.

7.2 Manufacturing Feasibility

Optimization results must be interpreted and refined to ensure compatibility with available manufacturing processes [134] [135]. Casting processes impose constraints on minimum wall thickness, draft angles, and undercut features [136] [137]. Machining operations require consideration of tool access, fixturing requirements, and surface finish specifications [138] [139].

Additive manufacturing technologies are increasingly enabling fabrication of complex topology-optimized geometries that would be impossible or economically infeasible through conventional manufacturing methods [140] [141]. However, consideration of build orientation, support structure requirements, and post-processing operations remains essential for successful implementation.

7.3 Cost and Sustainability Considerations

While weight reduction provides clear performance benefits, economic viability requires consideration of material costs, manufacturing expenses, and lifecycle impacts [142] [143]. Exotic lightweight materials may offer superior specific properties but introduce cost premiums that offset potential benefits in many applications [144] [145].

Sustainability assessment through life cycle analysis enables quantification of environmental impacts across the entire product lifecycle, from raw material extraction through manufacturing, use phase, and end-of-life disposal or recycling [146][147]. Such comprehensive evaluation often reveals that use-phase fuel savings from weight reduction outweigh increased embodied energy in lightweight materials [148] [149].

8. Fatigue and Durability Considerations

Brake levers experience cyclic loading during normal operation, necessitating consideration of fatigue behavior in addition to static strength [150] [151]. Fatigue life prediction typically employs stress-life or strain-life approaches, relating applied stress or strain amplitudes to expected cycles to failure [152][153].

Finite element analysis provides stress distributions serving as input for fatigue calculations, with critical attention to stress concentration locations where fatigue cracks typically initiate [154] [155]. Multiaxial fatigue criteria such as von Mises equivalent stress or critical plane approaches enable assessment of complex stress states characteristic of actual component loading [156][157].

9. Shape Optimization and Post-Processing

9.1 Geometry Interpretation

Topology optimization generates material density distributions that require interpretation into manufactural geometric forms [158] [159]. This interpretation process involves defining smooth boundary surfaces, eliminating small isolated material regions, and ensuring geometric features compatible with manufacturing processes [160][161].

Advanced algorithms for automatic geometry extraction from density distributions are continuously improving, though manual refinement by experienced designers remains valuable for achieving optimal results [162][163]. The interpreted geometry typically undergoes shape optimization to fine-tune boundary contours and eliminate remaining stress concentrations [164] [165].

9.2 Stress Concentration Mitigation

Sharp corners and abrupt geometric transitions in topology-optimized designs can create stress concentrations that reduce fatigue life and potentially trigger fracture [166] [167]. Shape optimization algorithms adjust boundary geometry to smooth transitions and distribute stress more uniformly [168] [169].

Fillet radii, blend curves, and other geometric features can be systematically optimized to minimize peak stresses while maintaining the overall topology established through density-based optimization [170] [171]. This combined topology-shape optimization approach yields designs that are both materially efficient and suitable for reliable long-term operation.

10. Future Directions and Research Gaps

10.1 Multi-Material Optimization

Current topology optimization methods predominantly address single-material designs, though many applications could benefit from strategic use of multiple materials with different properties· Multi-material optimization enables selective placement of high-strength, high-cost materials only where needed, with less expensive materials used in lightly loaded regions. Additive manufacturing technologies are increasingly capable of processing multiple materials within a single build, enabling fabrication of functionally graded structures with spatially varying properties· Optimization algorithms capable of simultaneously determining both topology and material distribution represent an active research frontier with significant practical potential.

11. Conclusions

This comprehensive review has examined the current state of topology optimization and finite element analysis applied to brake lever design, synthesizing findings from diverse research contributions. The literature clearly demonstrates that modern CAE tools, particularly those integrating CATIA for geometric modeling with ANSYS for analysis and optimization, enable substantial weight reduction while maintaining or improving structural performance.

Key findings from the reviewed literature include mass reductions ranging from 20% to 60% achieved through systematic topology optimization, with corresponding improvements in stress distribution and fatigue life. The SIMP method has emerged as the predominant optimization algorithm due to its computational efficiency and robust convergence characteristics. Aluminum alloys, represent the most practical material choices for lightweight brake components, offering excellent combinations of strength, ductility, and manufacturability.

Critical success factors for optimization-based design include accurate material property data, realistic boundary condition specification, appropriate manufacturing constraint integration, and comprehensive validation through experimental testing. The seamless workflow connecting CAD modeling, FEA, and optimization represents an essential enabler of efficient design processes.

Future research directions include development of multi-material optimization capabilities, more complete integration of manufacturing constraints, incorporation of uncertainty quantification methods, and expansion of fatigue and durability prediction capabilities. As computational power continues to increase and algorithms mature, topology optimization will become increasingly central to efficient, sustainable mechanical component design across all industries.

The findings reviewed in this paper provide a comprehensive foundation for researchers and practitioners seeking to implement optimization-based design methodologies for brake components and similar mechanical systems. The substantial performance improvements demonstrated across numerous studies confirm the practical value and continuing potential of these advanced computational design tools.

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