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An Analysis of Structural Optimization Methods and Performance Improvement of Hydraulic Lifts

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Abstract. The reliability and performance of hydraulic lifts directly affect safety and energy efficiency. With increasing automation and heavier load demands, safety and performance criteria have tightened, hence making structural optimization vital for improving reliability and prolonging service life. This paper reviews current structural optimization methods for hydraulic lifts and their performance enhancements, emphasizing the application and impact of topology optimization, geometric reinforcement, and material substitution strategies. By analyzing relevant literature, it highlights the specific influences of different optimization methods on lowering weight, reducing energy use, and extending fatigue life. The results indicate that topology optimization reduces weight by 15% to 30% but increases stress at welds, geometric reinforcement lowers bending moments and energy use, and material substitution like carbon fiber composites cuts weight and boosts durability despite adhesive uniformity challenges. Yet, computational inaccuracies and high material expenses continue to restrict the broad adoption of these optimization techniques. Future work should combine digital twins with physical tests and advance certification frameworks based on artificial intelligence to accelerate industrial adoption of structural optimization.

Keywords: Hydraulic Lift, Structural Optimization, Lightweight Design, Fatigue Life

1. Introduction

In manufacturing, logistics, and construction, hydraulic lifts are widely used, yet structural failures cause 37% of related accidents, and the need to meet overload limits and energy-efficiency targets makes lowering self-weight while boosting load capacity and overall performance a primary design challenge [1]. Accordingly, hydraulic lift structural optimization focuses on topology optimization, geometric reinforcement, and the application of carbon fiber composites. In particular, topology optimization can reduce mass by 22% to 30%, although it increases welding stress [2]. Similarly, geometric reinforcement designs, such as asymmetric actuators, can reduce bending moments by approximately 20%, but they require micron-level machining precision [3]. In addition, carbon fiber composites are effective in reducing weight by 18% to 22%, yet they are costly and have limited durability [4]. These methods show that weight, durability, innovation, and manufacturability must be balanced to optimize hydraulic lift performance. Based on a review of the literature, this study investigates key technical challenges in hydraulic lift design to reduce weight and boost efficiency

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while also maintaining safety and durability. Meanwhile, it addresses balancing topology, geometry, materials, and simulation with manufacturability and cost. Key challenges include the increase in welding stress caused by topology optimization despite mass reduction, while geometric supports must still function within a 55–65° range and meet ±0.5 mm production tolerances [2,5]. In addition, carbon fiber composites carry a cost premium of up to 220% under fewer than 8,000 cycles, and nonlinear dynamic analysis continues to show simulation errors exceeding 15% [4,6]. As such, the resolution of these challenges is crucial for the performance, safety, and sustainability of hydraulic lifts and provides guidance for design optimization in manufacturing.

2. Evolution of optimization strategies for hydraulic lift design

2.1. Topology optimization frameworks

In hydraulic lift structural optimization, topology optimization must balance weight reduction with computational reliability, and different algorithms exhibit distinct performance and applicability characteristics. The industry-standard SIMP method can achieve 18~25% mass reduction, but its oversimplified boundary conditions lead to physical validation errors of up to ±12%, with weld stress underestimated by 9~15% under uneven terrain loads [2]. By comparison, the BESO method offers superior weight savings (22~30%) and tighter error margins (±9%), though at the expense of a 25% increase in computational cost and persistent difficulty in eliminating stress singularities at geometric discontinuities [7]. Further advances like the ML-BESO variant use convolutional neural networks to cut errors to ±6% and computation time by 40%, yet remain limited by training-data dependence for new load cases [6]. In addition, real-world operating conditions further exacerbate these limitations. Field tests indicate that neglecting ground-structure interaction in transient models can result in a 15~20% overestimation of natural frequencies due to a 10% variation in foundation stiffness, leading to resonant failures in 68% of cases during high-cycle operations [6]. Future work should adopt hybrid validation with FBG sensors to correct simulation drift and use multiphysics models linking hydraulics and soil compliance to replace static load estimates [8].

2.2. Geometric reinforcement innovations

By enhancing structural performance, geometric reinforcement innovations in hydraulic lifts often bring added hydraulic control complexity, as demonstrated by two key design strategies. Firstly, Müller and Schaeffler's asymmetric cylinder configuration offsets actuator positions to redirect bending loads along axial paths. This reduces bending moments by approximately 20% and energy consumption by 15%. However, this approach demands real-time pressure regulation through PID controllers, increasing control system costs by roughly 12% [3]. Secondly, cross-bracing systems in scissor lifts increase torsional stiffness by about 40% under eccentric loading. This improvement is maximized at 55~65° bracing angles, which optimize the stiffness-to-weight ratio, whereas angles below 50° reduce buckling resistance during side impacts [5]. Full-scale tests show that 60° bracing reduces lateral deformation by about 28% under 5-ton loads. Moreover, manufacturing precision directly affects real-world performance. Laser-cut bracing members that deviate more than 0.5 mm from nominal dimensions reduce stiffness gains by 18% in fatigue testing. At the same time, the micron-level alignment required for asymmetric cylinders increases production costs by 9~14% [3,5]. Therefore, geometric optimization is effective only when performance gains, such as a 20% moment reduction, outweigh the added costs of control systems and tolerance management.

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2.3. Material substitution trade-offs

Material substitution, while aiming to optimize lifecycle costs, inevitably faces multiple constraints related to performance, economics, and environmental factors. High-strength alloy 42CrMo (yield strength 950 MPa compared with Q235's 235 MPa) enables structural weight reduction [10], but its cost is around 80% higher, and its complex welding process requires post-weld heat treatment (PWHT), increasing manufacturing costs by 12~15% and accelerating fatigue crack propagation in heat-affected zones, thereby shortening maintenance intervals by about 15% [9]. Similarly, CFRP composites can reduce the weight of scissor arms by 18~22%, yet their anisotropic properties lead to strength variations of up to 25% across fiber orientations, and adhesive inconsistencies caused by curing humidity fluctuations result in 8~12% performance variability in aging tests [4]. Furthermore, environmental conditions strongly affect material durability. CFRP experiences approximately 18% strength loss after 5,000 cycles at 80% relative humidity, primarily due to hydrolysis [4]. Similarly, 42CrMo alloy steel forms corrosion pits over 100 μm under 85% RH and 5% salt spray, reducing its fatigue limit by about 40%, which offsets roughly 35% of the protective effects from treatments like shot peening [10]. Accordingly, material selection should balance ROI thresholds, environmental degradation from humidity and salt, and inherent performance variability of 8% or more to match operational duty cycles [4].

3. Measurable improvements in structural and functional performance

3.1. Load capacity optimization

Load capacity improvements often rely on minimal geometric adjustments, where millimeter-scale changes can significantly redistribute structural stresses. For example, relocating the hinge pin can increase dynamic load capacity by 22%. Finite element analysis shows a reduction of approximately 30% in von Mises stress at full extension, but production variations can offset about 40% of the theoretical gains, thereby highlighting the necessity of statistical tolerance analysis [11]. Meanwhile, hydraulic cylinder reinforcements also demonstrate material efficiency. Ribbed plates with 6~8 mm fillet radii redistribute loads from bolt holes, reducing peak stress by 34% in 25 MPa systems, and field monitoring of port cranes confirms around 22% longer fatigue life. However, these benefits depend on manufacturing precision and environmental resistance. Specifically, base plates with flatness deviations beyond ±0.1 mm increase stress concentrations by about 15% due to uneven load transfer, while corrosion at rib-plate interfaces requires 0.3 mm protective coatings to maintain fatigue life extensions; otherwise, roughly 50% of the original gain is lost. Therefore, maximizing load capacity requires the combined effect of geometric optimization and production control, making submillimeter tolerances of ±0.1 mm together with 0.3 mm corrosion protection essential to achieve 22~34% stress redistribution gains.

3.2. Energy efficiency and sustainability

Lightweighting can reduce motor power by 12~18% through 15~30% mass savings. However, an additional 9~14% energy is required to maintain torque during acceleration, partially offsetting the theoretical efficiency gains by approximately 35~50%. To recapture lost energy, variable frequency drives with regenerative braking can retrieve 8~12% of dissipated energy, while laser-engraved micro-dimples on guide rails (50~100 μm depth) lower friction coefficients by roughly 30% by enhancing lubricant retention [12]. However, valve hysteresis still dissipates roughly 15% of total

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energy as heat during descent, and micro-dimples deepen by 15~20 μm annually due to abrasive wear, gradually reducing friction benefits after approximately 8,000 operational hours. In addition, maintenance neglect further accelerates performance decay because silicon contamination above 200 ppm in hydraulic oil increases wear rates by 22%, and delayed lubricant flushing raises viscous drag, reducing the efficiency of variable frequency drives by about 18% [12]. As such, sustainable energy optimization requires aligning lifecycle cost and benefit. In this context, electro-hydraulic hybrid systems can offset energy losses from valve hysteresis even with an upfront cost increase of about 30%, as long as laser texturing is paired with semiannual dimple-depth monitoring and strict control of oil silicon contamination below 100 ppm. This approach converts marginal efficiency gains of 8~12% into net-positive outcomes while ensuring a payback period exceeding five years.

3.3. Safety and durability enhancements

Improving safety and durability depends on the combined use of material processing and protective strategies. Firstly, material processing innovations like shot peening can significantly extend fatigue life. For example, impacts of 0.4~0.6 mmA create 200~300 MPa compressive layers in aerospace lifts, cutting crack initiation and raising service life by 25~40%. However, welding inconsistencies and environmental factors can reduce these benefits. Microsegregation in heat-affected zones can raise local hardness by up to 40 HV, accelerating crack growth to10^{-8} m/cycle, while CO_2-shielded welding can increase oxygen content in steel welds to 800 ppm, reducing shot peening effectiveness by about 35%. In addition, corrosion pits larger than 100 μm under 85% relative humidity and 5% salt spray can decrease fatigue limits by approximately 40% [10]. Secondly, implementing safety mechanisms also involves efficiency trade-offs. Based on ISO 1493:2022, redundant columns can reduce overload failure rates by 50% but increase dead weight by about 23%. For example, Volvo's staged hydraulic lock prevents permanent deformation with secondary pistons activating in 50 ms at over 110% loads, but valve seizure from particles larger than 10 μm can delay response beyond 200 ms, averaging 1.2 incidents per 1,000 units annually. Finally, the corrosion-fatigue synergy requires integrated protective measures. Laser-clad NiCrMo coatings raise critical corrosion thresholds. Micron-sealed enclosures for hydraulic locks help mitigate particulate risks [13]. Therefore, 0.3 mm protective treatments at critical interfaces are necessary to convert theoretical longevity gains of 25~40% into reliable field safety margins.

4. Barriers to industrial implementation

4.1. Simulation limitations and mechanical constraints

In industrial applications, finite element analysis (FEA) still faces significant reliability limitations, with nonlinear dynamic simulations exhibiting errors up to ±15% [6]. These issues partly stem from contact modeling uncertainties, which account for 60% of total errors. Besides, pin-joint clearances below 0.1 mm cause force calibration deviations, as 63% of manufacturers report validation costs exceeding $12,000 per iteration. Though multi-body dynamics software can partly fix mismatches under transient impact, ongoing seal friction losses continue to degrade operational accuracy. At speeds below 5 mm/s, nonlinear behavior in the Stribeck curve generates 8~12% force hysteresis. New elastomer formulations can lower breakaway friction by 22%, yet they accelerate wear rates when operating temperatures exceed 80°C, introducing maintenance trade-offs [14]. The combined constraints of computational approximation and mechanical friction fundamentally limit the scalability of optimization. This necessitates hybrid validation protocols that integrate physical

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testing with simulation to reconcile ±15% FEA error margins while accepting 12% force hysteresis at low speeds as irreducible. Consequently, designers must apply overdesign factors, which erode roughly 40% of the theoretical weight savings achievable in safety-critical components [6].

4.2. Financial barriers and long-term payback concerns

When prolonged payback horizons misalign with operational demands, material substitution faces major financial constraints. For instance, the payback period for carbon fiber-reinforced polymers exceeds 32,000 hours, vastly surpassing the roughly 1,800 hours of annual operation typical for construction lifts [4]. As a result, about 42% of SMEs discontinue optimization once component costs climb to 220% of equivalent steel products, exceeding $8,500 per unit. At the same time, the cost-effectiveness of corrosion protection varies sharply across environmental conditions. In humid regions, plasma-sprayed Al_2O_3-13%TiO_2 coatings according to NACE RP0492-2021 raise upfront costs by 25% yet cut downtime by around 40%, yielding annual savings of roughly $56,000 based on $480 per hour of downtime [13]. In contrast, arid regions face payback periods exceeding seven years, as corrosion accounts for only 12% of operational costs, and post-weld heat treatment for high-strength alloys further adds financial pressure by raising manufacturing costs by 12~15% and consuming 48 kWh per ton of tempering energy, which increases carbon emissions by roughly 30%. With R&D spending at only 1.2% of revenue compared to the global average of 3.5%, limited budgets further restrict SMEs' ability to adopt new materials. In this context, geometry-driven optimization emerges as a cost-effective priority, since laser-textured guide rails implemented on existing computer numerical control (CNC) equipment reduce friction by approximately 30% while costing roughly half of material substitution, enabling feasible performance improvements under financial constraints and alleviating capital limitations on technology adoption [12].

5. Future directions and research deficiencies

5.1. Integration of digital technologies and structural optimization

Though digital technologies present notable opportunities for advancing the safety, precision, and efficiency of hydraulic lift structural optimization, their widespread implementation is impeded by unresolved technical challenges and a lack of comprehensive certification frameworks. For instance, embedded Fiber Bragg Grating (FBG) sensors can achieve real-time strain monitoring with <0.1 mm resolution, and distributed arrays of 12~16 sensors are capable of detecting buckling up to 50 ms before visible deformation [8]. However, the need to route optical fibers through moving joints causes signal attenuation exceeding 3 dB, thus compromising measurement reliability in multi-axis configurations. In parallel, generative design accelerates structural concept iteration but requires 70~100 hours of engineer review per model to remove non-manufacturable features such as wall thicknesses below 1 mm. Besides, though topology optimization for additive manufacturing can cut mass by up to 40%, it remains excluded from ISO safety certification frameworks, thereby delaying industrial adoption. From a structural optimization perspective, these limitations reveal that the convergence of sensing precision and algorithmic innovation is hindered by a lack of standardized validation protocols. Future efforts should prioritize in-situ FBG calibration under vibration fatigue and the creation of certification standards for AI-generated designs to replace manual feasibility checks. Only by addressing these deficiencies can digital innovations move beyond laboratory-scale demonstrations and achieve certified application in heavy machinery.

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5.2. Trade-offs between sustainability and structural performance

Despite the strong potential of bio-based composite materials for lightweight hydraulic lift designs, their implementation results in significant compromises in structural performance. For example, soybean oil-based resins can substantially lighten components while also offering environmental sustainability advantages, but their compressive strength declines by around 102 MPa, equivalent to a 38% reduction, and their glass transition temperature falls to 78°C, decreasing by approximately 37%. These alterations lead to decreased stiffness and compromised dimensional stability under prolonged loading and fluctuating temperature and humidity conditions. Prior studies have shown that hydraulic cylinder end caps undergo about 3.2% volumetric expansion after 2,000 hours of operation, directly affecting seal reliability and necessitating modifications to the sealing clearances [15]. From a structural optimization perspective, these performance limitations demonstrate that lightweight design cannot rely exclusively on mass reduction. Instead, it requires a careful balance among material properties, component geometry, and load distribution. By integrating simulation analyses with experimental validation, it is possible to predict stress concentrations and deformation behavior in critical components made of bio-composites, thus optimizing geometric reinforcement, joint design, and material layout to ensure overall load-bearing capacity and long-term reliability. In the future, studies are expected to evaluate how material performance degradation affects structural optimization strategies for hydraulic lifts, offering practical guidelines for balancing lightweighting and performance improvements.

6. Conclusion

This study indicates that structural optimization of hydraulic lifts has made significant progress in both lightweighting and performance enhancement. Collectively, a balance among design, material choice, and simulation, together with attention to safety, manufacturability, and cost-effectiveness, is essential for achieving both objectives. Nevertheless, as this paper relies on published literature, some recent technologies or unpublished industrial practices may not be fully represented. Future research should be directed toward integrating simulation with experimental validation, developing economically feasible lightweight materials and structural designs, and establishing standardized evaluation and certification systems to accelerate industrial adoption. These efforts can advance the safety, performance, and sustainability of hydraulic lifts, serving as a reference for manufacturers in design.

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