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Reverse Engineering and Structural Optimization of a Pneumatic Rotary Slip Lifter for Enhanced Safety and Operational Efficiency in Drilling Rigs

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Abstract

This study presents the reverse engineering and structural optimization of a Pneumatic Rotary Slip Lifter (PSL) to enhance safety and operational efficiency in drilling rig operations. Conventional manual rotary slips expose personnel to ergonomic hazards and reduce handling efficiency during drill pipe manipulation. The existing slip mechanism was digitized through reverse engineering and analyzed using three-dimensional finite element analysis (FEA) to evaluate stress distribution, deformation, and safety factors under operational loading conditions. The optimized design incorporates a pneumatic actuation system operating at 90–120 psi, enabling automated lifting and lowering of the slip assembly. Structural optimization ensured compliance with allowable stress limits while minimizing material usage. Simulation results show a maximum von Mises stress of 103.2 MPa—well below the 250 MPa yield strength—and a minimum safety factor of 2.01, indicating reliable elastic performance. Probabilistic reliability assessment yielded a high reliability index ($\beta \approx 8.5$) and negligible probability of failure, while fatigue analysis confirmed infinite-life behavior under cyclic tripping loads. Operational evaluation demonstrated reduced handling time, elimination of manual lifting, and improved ergonomic safety. The proposed PSL offers a structurally validated, reliable, and economically viable alternative to conventional manual slips, supporting safer and more efficient mechanized drill pipe handling.

Keywords: Pneumatic actuation; drilling rig safety; reverse engineering; finite element analysis; structural optimization; reliability assessment

1. Introduction

Drilling operations in the oil and gas industry are characterized by high capital expenditure, complex mechanical systems, and significant operational risks. A modern rotary drilling rig integrates structural, mechanical, hydraulic, and control subsystems to perform drilling, hoisting, rotation, and pipe handling functions. Among these, drill string handling during tripping operations (trip-in and trip-out) constitutes a substantial portion of rig floor activity and directly affects operational efficiency and safety performance [1]. Drill pipes transmit torque and axial loads to the drill bit while simultaneously serving as a conduit for drilling fluids; therefore, safe and reliable handling of these components is essential to prevent operational downtime and equipment failure.

One critical component in drill string handling is the rotary slip, a wedge-shaped mechanical device designed to grip and suspend the drill pipe in the rotary table during connection and disconnection operations. Conventional slips rely on manual placement and removal by rig crew members. Although mechanically simple, manual slips expose personnel to significant ergonomic and crush hazards, particularly finger injuries and musculoskeletal strain due to repetitive handling under high load conditions. Furthermore, improper load distribution in slip inserts can lead to localized stress concentrations on the drill pipe surface, potentially accelerating wear and fatigue damage [2].

From a structural mechanics perspective, rotary slips experience complex loading conditions involving axial compression, radial contact pressure, and frictional shear forces. The interaction between slip inserts and drill pipe generates contact stresses that must remain below allowable limits to prevent plastic deformation or surface damage. Finite element modeling has been widely applied to analyze stress distribution and failure mechanisms in drilling components, including slips, drill strings, and rotary systems [3], [4]. Such analyses demonstrate that geometric optimization of load-bearing components can significantly improve stress uniformity and structural reliability.

In addition to static structural considerations, drilling systems are subject to dynamic effects such as torsional vibration and stick–slip phenomena. Stick–slip is a self-excited oscillation characterized by alternating sticking and slipping phases of the drill bit, which can induce fluctuating torque and axial loads in the drill string [5]. These dynamic loads propagate to surface handling equipment, including slips and hoisting systems, thereby increasing fatigue risk. Therefore, the structural design of slip mechanisms must consider not only static load capacity but also transient operational conditions.

Automation and mechanization of rig floor equipment have emerged as strategic approaches to improving safety and efficiency in drilling operations. Mechanized pipe handling systems, such as hydraulic or pneumatic power slips, reduce manual intervention and minimize direct exposure of workers to suspended loads [6]. Pneumatic systems, in particular, offer advantages in terms of simplicity, lower maintenance requirements, and intrinsic safety in hazardous environments due to the absence of electrical spark risks. Compressed air actuation systems operating within controlled pressure ranges can provide sufficient lifting force while maintaining predictable motion control.

Reverse engineering has become an effective methodology for redesigning and optimizing legacy mechanical systems. Through dimensional inspection, digital reconstruction, and simulation-based validation, reverse engineering enables performance enhancement without requiring entirely new conceptual architectures [7]. When combined with finite element analysis (FEA) and structural optimization techniques, reverse engineering supports systematic redesign aimed at improving load distribution, reducing peak stress, and enhancing safety factors. Structural optimization methods, including topology optimization and parameter-based refinement, have been successfully applied in mechanical design to minimize weight while satisfying strength and stiffness constraints [8].

Despite advancements in mechanized rig floor tools, limited research has specifically addressed the integration of pneumatic actuation systems into rotary slip lifters through a rigorous reverse engineering and structural validation framework. Existing industrial solutions often lack publicly documented stress analysis, safety factor verification, and techno-economic evaluation. Consequently, there remains a research gap in systematically quantifying the structural and economic performance of pneumatic-assisted slip systems under realistic operational loading conditions.

The present study addresses this gap by conducting reverse engineering and structural optimization of a pneumatic rotary slip lifter (PSL) designed for drill pipe outer diameters ranging from 3.5 to 5 inches. The research integrates three-dimensional modeling, finite element structural analysis, and load simulation to evaluate equivalent von Mises stress, deformation, and safety factor under operational loads. The pneumatic actuation mechanism is designed to operate within 90–120 psi compressed air pressure, enabling automated lifting and lowering of the slip assembly.

Static structural analysis is performed to verify that maximum stress remains below material yield strength with an adequate safety factor consistent with mechanical design standards [9]. The optimization process seeks to reduce stress concentration zones while minimizing material usage. In addition, a techno-economic assessment is conducted to evaluate feasibility in terms of break-even point and return on investment, considering reductions in manual labor intensity, spare part consumption, and potential injury-related costs.

By integrating reverse engineering methodology, finite element structural validation, pneumatic actuation design, and economic evaluation, this research contributes to the advancement of safer and more efficient mechanized handling systems in drilling engineering. The proposed pneumatic rotary slip lifter provides a structurally verified and economically viable alternative to conventional manual slips, supporting industry objectives of automation, reliability, and occupational safety enhancement.

2. Methods

A. Research Framework and Design Strategy

The research framework adopted in this study is structured to ensure systematic transformation of a conventional manually operated rotary slip into a pneumatically actuated and structurally optimized rotary slip lifter (PSL). The framework integrates reverse engineering (RE), mechanical modeling, finite element simulation, and parametric structural optimization within a unified design-validation loop. Such a simulation-driven engineering approach has been widely recognized as essential in modern mechanical system redesign, particularly for heavy-load industrial applications where safety and structural integrity are critical [7], [10].

The initial stage of the framework involves functional decomposition and load-path identification of the existing rotary slip assembly. Rotary slips function as wedge-type load transfer mechanisms that convert axial drill string loads into radial contact forces acting on the pipe surface. Under operational conditions, the slip assembly experiences high compressive stresses, contact pressure at the slip–pipe interface, and friction-induced shear stresses [2]. Improper stress distribution can lead to localized yielding or accelerated surface damage of the drill pipe, as demonstrated in previous investigations on slip insert design optimization [2]. Therefore, accurate identification of load transfer mechanisms and stress concentration zones is fundamental prior to redesign.

Reverse engineering was selected as the enabling methodology to extract geometric parameters, material characteristics, and functional relationships from the baseline manual slip system. RE has been extensively applied in mechanical redesign processes where legacy equipment must be upgraded without altering system compatibility [7], [11]. Through dimensional acquisition and CAD reconstruction, the physical artifact is transformed into a parametric digital model, enabling systematic geometric refinement while preserving compatibility with the existing rotary table configuration. This physical-to-digital transformation supports downstream numerical validation and structural modification.

Following digital reconstruction, a mechanical modeling strategy grounded in classical strength-of-materials theory was implemented. The slip assembly was modeled as a compressive load-bearing wedge subjected to axial force transmitted from the drill string. Equivalent stress evaluation was performed using the von Mises yield criterion, which is widely accepted for ductile steel components under multiaxial loading conditions [9], [12]. Contact interaction between the slip dies and drill pipe was modeled based on contact mechanics principles, where radial pressure and frictional shear stress govern load transfer behavior. Contact mechanics formulations provide a theoretical foundation for evaluating stress distribution in high-pressure interface systems [13].

To ensure structural reliability, the design constraint was defined such that the maximum equivalent stress must satisfy:

$$\sigma_{vm,max} < \frac{\sigma_y}{SF} \quad (1)$$

where σ_y represents material yield strength and *SF* denotes the prescribed safety factor. This allowable stress approach aligns with established mechanical design methodologies for static load-bearing components [9]. In addition, displacement limits were imposed to prevent excessive deformation that could impair operational alignment.

Finite element analysis (FEA) was employed as the primary evaluation tool within a simulation-driven design (SDD) framework. Rather than serving merely as a post-design verification method, FEA was integrated iteratively to guide geometric modification and stress redistribution. Simulation-driven product development has been shown to significantly enhance design robustness by identifying stress concentration zones at early stages [10]. Mesh refinement studies were conducted to ensure numerical convergence and reduce discretization errors, following best practices in computational solid mechanics [14]. Boundary conditions were defined to replicate operational constraints, including axial loading corresponding to maximum drill string weight and fixed supports at the rotary table interface.

Structural optimization was performed using a parametric refinement approach. Instead of applying full topology optimization—which may produce geometries difficult to manufacture—the study employed manufacturability-oriented optimization strategies [8]. Geometric parameters such as fillet radii, section thickness, and reinforcement features were systematically adjusted to minimize peak stress while maintaining structural stiffness. This approach aligns with parameter-based optimization methods widely adopted in mechanical component redesign [8], [10].

A critical aspect of the framework is the integration of pneumatic actuation to eliminate manual lifting operations. Pneumatic systems are commonly applied in industrial automation due to their mechanical simplicity, rapid response, and intrinsic safety in explosive environments [6]. The actuation force was modeled using the pressure–area relationship, ensuring adequate lifting capacity within the operational range of 90–120 psi. Mechanical coupling between actuator and slip body was analyzed to avoid secondary bending stresses or load eccentricity that could compromise structural stability. This integration transforms the slip from a passive load-supporting component into an actively controlled lifting system.

Validation is embedded throughout the framework at multiple levels. Numerical validation is achieved through stress, deformation, and safety factor analysis via FEA. Experimental validation is conducted through prototype load testing and operational trials to confirm functional performance. Finally, techno-economic validation evaluates the financial feasibility of the redesigned PSL, linking engineering optimization with industrial applicability. Such multi-layer validation enhances methodological rigor and aligns with contemporary engineering research practices in heavy industrial equipment development [1], [3].

Overall, the proposed research framework integrates reverse engineering, analytical load modeling, finite element validation, and manufacturability-driven optimization into a coherent methodology. By combining structural mechanics principles with automation integration, the framework provides a scientifically grounded pathway for upgrading conventional rig floor equipment into safer and more efficient mechanized systems. This integrated design strategy supports both structural reliability and occupational safety enhancement, addressing the research gap identified in previous studies on drilling equipment optimization [2], [3].

The overall methodological framework adopted in this study is illustrated in Figure 1, highlighting the integration of reverse engineering, structural analysis, pneumatic modeling, reliability assessment, and techno-economic evaluation within a unified simulation-driven design loop.

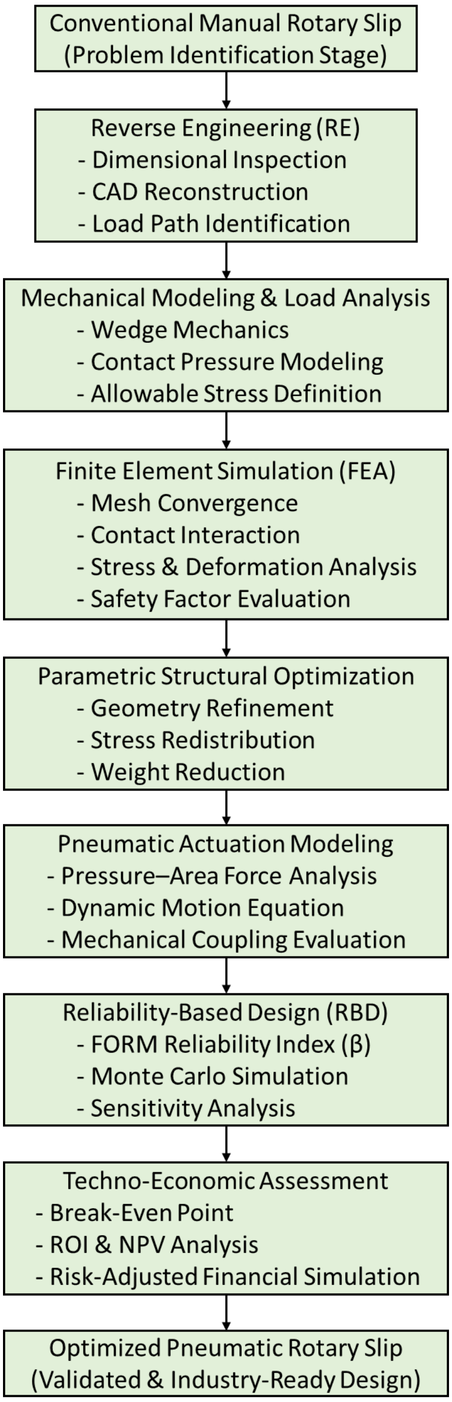

Figure 1. Integrated Simulation-Driven Research Framework for Pneumatic Rotary Slip Lifter Optimization

B. Finite Element Modeling and Structural Optimization Procedure

The finite element modeling procedure was developed to evaluate the structural integrity of the redesigned pneumatic rotary slip lifter (PSL) under realistic operational loading conditions. The numerical framework follows established computational solid mechanics practices, in which discretization of the continuous structure into finite elements enables approximation of stress and strain fields within complex geometries [10], [14]. Considering the wedge-shaped geometry and contact interaction between slip dies and drill pipe, a three-dimensional solid model was adopted to accurately capture multiaxial stress states and local stress concentrations.

The reconstructed CAD model obtained from the reverse engineering stage was imported into a finite element environment and discretized using higher-order tetrahedral elements. Higher-order elements were selected to improve stress prediction accuracy in regions with geometric discontinuities such as fillets, load-transfer corners, and actuator connection interfaces. Mesh convergence analysis was conducted to ensure numerical stability, where successive mesh refinements were applied until variations in maximum von Mises stress were within an acceptable tolerance threshold (typically <5%). Mesh sensitivity verification is essential in heavy-load mechanical simulations to avoid underestimation of peak stress due to coarse discretization [14], [15].

Material properties were defined based on structural steel commonly used in rig floor handling equipment. The material model assumed homogeneous, isotropic, and linear-elastic behavior within the operational load range, consistent with allowable stress design methods [9]. Although drilling components may experience nonlinear contact behavior at high loads, the present study focuses on ensuring that equivalent stress remains below the yield limit, thereby maintaining elastic performance under normal operational conditions. The von Mises yield criterion was employed to evaluate equivalent stress under combined axial compression, radial pressure, and friction-induced shear [12].

Boundary conditions were defined to replicate actual operational constraints in drilling rigs. The axial load applied to the slip assembly corresponds to the maximum anticipated hook load transferred during pipe suspension. Drill string loads in rotary systems are known to involve both static weight and dynamic amplification factors arising from torsional vibration and stick–slip effects [5]. To ensure conservative evaluation, the applied load incorporated a dynamic amplification factor derived from drilling vibration literature, thereby accounting for transient load fluctuations. The base of the slip lifter frame was constrained at mounting interfaces to simulate rigid attachment to the rotary table structure.

Contact interaction between slip inserts and drill pipe was modeled using surface-to-surface contact formulations with frictional behavior. The friction coefficient was defined based on steel-to-steel contact under lubricated drilling conditions, consistent with contact mechanics principles [13]. Contact analysis is critical in slip systems because load transfer occurs primarily through radial pressure and frictional shear forces. Inaccurate contact representation may lead to unrealistic stress predictions and unsafe design conclusions. Previous investigations into drill pipe damage mechanisms emphasize the importance of contact pressure uniformity in preventing localized yielding and surface indentation [2]. The three-dimensional finite element model, including mesh discretization and applied boundary conditions, is presented in Figure 2. The figure illustrates load application, contact interfaces, and structural constraints used in the numerical simulation.

Figure 2. Three-dimensional finite element model of the pneumatic rotary slip lifter illustrating applied axial hook load, surface-to-surface contact interaction between slip dies and drill pipe, frictional shear stress transfer, refined tetrahedral mesh distribution in high-stress regions, and fixed support boundary conditions at the rotary table mounting interface.

Structural evaluation metrics included maximum equivalent (von Mises) stress, total deformation, and safety factor distribution. The safety factor was computed as the ratio of material yield strength to maximum equivalent stress, following classical mechanical design practice [9]. In addition to stress magnitude, deformation limits were assessed to ensure that slip alignment and gripping function remain uncompromised. Excessive elastic deformation could impair gripping uniformity and lead to uneven contact pressure, potentially accelerating wear of slip inserts and drill pipe surfaces.

Following baseline structural assessment, a parametric optimization procedure was implemented. Instead of purely mathematical topology optimization, which may generate non-manufacturable geometries, this study employed geometry-based parameter optimization aligned with practical fabrication constraints [8]. Design variables included rib thickness, fillet radius, support bracket dimensions, and actuator mounting geometry. The optimization objective was defined as minimizing maximum equivalent stress while maintaining structural stiffness and reducing material volume where feasible. Such multi-objective structural optimization strategies are commonly adopted in industrial mechanical design to achieve weight reduction without compromising reliability [16].

An iterative simulation-driven design loop was applied, where geometric modifications were followed by repeated finite element simulations until convergence criteria were satisfied. Simulation-driven product development has been demonstrated to significantly enhance structural robustness by reducing peak stress concentrations and improving load distribution before physical prototyping [10], [17]. This approach reduces development cost and minimizes trial-and-error fabrication stages.

To further ensure reliability, the structural performance was evaluated against fatigue considerations. Although the primary loading condition is static suspension, drilling operations involve repeated loading cycles during tripping operations. Fatigue behavior in drill string components has been widely reported as a critical failure mechanism under cyclic axial and torsional loads [3], [18]. Therefore, stress amplitude under operational cycling was examined relative to material endurance limits to verify that cyclic stresses remain within acceptable ranges for long-term serviceability.

Finally, numerical results were cross-checked against analytical estimations derived from simplified wedge mechanics and compressive stress theory to ensure consistency between computational and theoretical predictions. Validation through multi-method comparison enhances confidence in numerical modeling outcomes and aligns with best practices in computational engineering research [14], [19]. The resulting optimized PSL structure demonstrates reduced stress concentration, improved safety factor, and enhanced structural uniformity compared to the baseline manual configuration.

Through the integration of accurate contact modeling, conservative load assumptions, parametric geometry refinement, and fatigue-aware evaluation, the finite element modeling and optimization procedure provides a rigorous structural validation framework. This methodological rigor supports the development of a safer and more mechanically reliable pneumatic rotary slip lifter suitable for high-load drilling applications.

C. Pneumatic Actuation Modeling and Force Analysis

The integration of pneumatic actuation into the rotary slip lifter (PSL) transforms the conventional passive slip handling mechanism into an actively controlled lifting system. The pneumatic subsystem is designed to provide sufficient lifting force to overcome the self-weight of the slip assembly, frictional resistance at guide interfaces, and partial load transfer from the drill pipe during engagement and disengagement stages. Pneumatic actuation was selected due to its operational simplicity, rapid response characteristics, and intrinsic safety advantages in hazardous drilling environments, where spark-free operation is preferred over electrically driven systems [6], [20].

The fundamental modeling of the pneumatic actuator is based on the pressure–area relationship derived from fluid power theory. The theoretical output force generated by a pneumatic cylinder is expressed as

$$F = P \times A \tag{2}$$

where F represents actuator force, P is the supplied compressed air pressure, and A A is the effective piston area. This relationship assumes quasi-static conditions and negligible leakage losses, consistent with classical pneumatic system modeling approaches [21], [22]. For the proposed PSL, the operational pressure range of 90–120 psi was selected based on industrial compressed air standards commonly available in drilling rigs. The piston diameter was determined to ensure that the minimum available pressure produces lifting force exceeding the maximum required mechanical resistance with an adequate safety margin.

In practical operation, the effective actuator force is reduced by internal friction, seal resistance, and pressure losses within valves and supply lines. Therefore, a correction factor was incorporated into the force estimation to account for mechanical efficiency. Pneumatic actuator efficiency typically ranges between 80–95%

depending on seal design and lubrication conditions [21]. Conservative efficiency assumptions were applied to prevent underestimation of required lifting capacity. Additionally, transient pressure fluctuations during rapid actuation were considered to ensure stable lifting motion without shock loading.

The mechanical coupling between the actuator and slip body was modeled using rigid linkage assumptions combined with structural compliance obtained from finite element analysis (Section B). The actuator force is transmitted through a bracketed support frame, introducing potential bending moments and eccentric loading. To prevent secondary stress amplification, the load path was aligned as closely as possible with the centroidal axis of the slip body. Misalignment in actuator-driven systems can generate additional bending stresses that significantly reduce fatigue life and structural reliability [19]. Therefore, geometric alignment and support stiffness were incorporated into the parametric design variables during optimization.

Dynamic considerations were also incorporated into the actuation analysis. Although the lifting motion occurs over a short stroke distance, rapid pressurization can induce acceleration forces that add inertial loading to structural components. The governing equation for actuator motion may be expressed as

$$F_{net} = ma + F_{resistance} \quad (3)$$

where m denotes the effective moving mass of the slip assembly and a is acceleration. Controlled flow regulation using directional control valves was proposed to limit acceleration and prevent impact loading at stroke limits. Flow control and cushioning mechanisms are standard features in industrial pneumatic actuation to enhance operational smoothness and component longevity [22], [23].

From a system-level perspective, the pneumatic PSL must operate reliably under drilling rig environmental conditions, including vibration, temperature variation, and airborne contaminants. Rotary drilling systems are subject to torsional and axial vibrations, including stick–slip oscillations that propagate to surface equipment [5]. These dynamic disturbances may influence actuator stability and mounting integrity. Therefore, mounting brackets and fasteners were evaluated under combined static and vibrational loads to ensure adequate fatigue resistance.

Force requirement estimation further incorporated frictional resistance at slip–guide interfaces and gravitational effects. The total required lifting force was defined as

$$F_{req} = W_{slip} + F_{friction} + F_{dynamic} \quad (4)$$

where W_{slip} represents the self-weight of the slip assembly, $F_{friction}$ accounts for guide rail and hinge resistance, and $F_{dynamic}$ represents inertial or transient contributions. A minimum design safety factor of 1.5–2.0 was imposed on actuator force capacity to ensure reliable operation even under pressure fluctuations or partial system degradation, consistent with mechanical design recommendations for lifting mechanisms [9], [24].

Air consumption analysis was also performed to evaluate system efficiency and compressor load demand. The volumetric air consumption per cycle depends on cylinder volume and operating pressure, expressed through the ideal gas relationship under isothermal approximation [21]. Minimizing air consumption is important for rig operations where compressed air supply is shared among multiple subsystems. Efficient pneumatic design contributes to reduced energy usage and improved operational sustainability, aligning with broader mechanization objectives in drilling engineering [1].

To ensure fail-safe behavior, the actuation system was conceptually designed with a spring-return or pressure-locking mechanism to prevent unintended slip release in the event of pressure loss. Safety in lifting systems requires that loss of driving energy does not result in uncontrolled component movement [20], [25]. Incorporating passive mechanical locking enhances system reliability and aligns with industrial safety standards for handling suspended loads.

The overall pneumatic actuation modeling demonstrates that the selected cylinder dimensions and operating pressure range provide sufficient lifting force with acceptable dynamic behavior and energy consumption. When integrated with the optimized structural frame, the pneumatic system enables controlled and repeatable slip engagement and disengagement while significantly reducing manual handling requirements. This combination of fluid power modeling, dynamic force evaluation, and structural coupling analysis establishes a comprehensive framework for designing safe and efficient pneumatic-assisted handling systems in drilling applications. The schematic configuration of the pneumatic actuation system integrated into the rotary slip lifter is shown in

Figure 3. The diagram illustrates the compressed air supply line, control valve arrangement, and mechanical linkage transferring actuator force to the slip assembly.

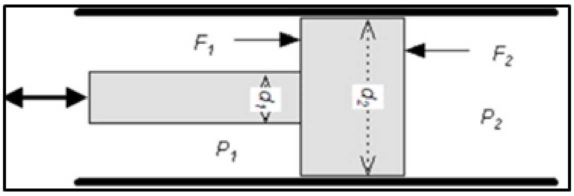

Figure 3. Schematic configuration of the pneumatic actuation subsystem illustrating compressed air supply, filtration and regulation unit, directional control valve, double-acting pneumatic cylinder, actuator force transmission through mounting bracket, and vertical motion of the slip body during engagement and disengagement of the drill pipe.

D. Reliability-Based Design and Uncertainty Quantification

While deterministic finite element analysis provides insight into maximum stress and deformation under nominal loading conditions, drilling equipment operates under inherently uncertain environments. Variability in hook load, dynamic amplification due to stick–slip vibration, material property scatter, and pneumatic pressure fluctuation introduce stochastic behavior into the structural response of the pneumatic rotary slip lifter (PSL). Therefore, a reliability-based design framework was incorporated to quantify the probability of failure and ensure robust structural performance under uncertainty.

Reliability-based design (RBD) extends conventional allowable stress methods by modeling key parameters as random variables rather than fixed deterministic values. In mechanical systems subjected to fluctuating loads, probabilistic approaches have been shown to provide more realistic safety assessment compared to deterministic safety factors alone [27], [28]. The limit state function for structural safety is defined as:

$$g(X) = \sigma_y - \sigma_{vm}(X) \quad (5)$$

where σ_y is the material yield strength and $\sigma_{vm}(X)$ is the von Mises stress expressed as a function of random input variables X, including axial load, friction coefficient, pneumatic pressure, and material strength variation. Failure is assumed to occur when $g(X) \leq 0$.

The primary uncertain variables considered in this study include axial hook load variation due to drilling dynamics [5], friction coefficient variability at slip–pipe contact interfaces [13], and manufacturing tolerances affecting geometric parameters. Hook load variability was modeled using a normal distribution with a dynamic amplification factor derived from drilling vibration studies [5]. Material yield strength variability was represented using statistical data commonly reported for structural steels, typically characterized by a coefficient of variation between 5–10% [29]. Pneumatic pressure fluctuation was modeled as a bounded stochastic variable within the 90–120 psi operational range.

The reliability index β was evaluated using the First-Order Reliability Method (FORM), which approximates the limit state function through linearization at the most probable point of failure [27]. The reliability index is defined as:

$$\beta = \frac{\mu_g}{\sigma_g} \quad (6)$$

where μ_g and σ_g represent the mean and standard deviation of the limit state function, respectively. A higher β value corresponds to lower probability of failure. For structural mechanical components in industrial applications, recommended reliability indices typically range between 3.0 and 4.0, corresponding to failure probabilities on the order of 10^{-3}–10^{-5} [28], [30].

Monte Carlo simulation was additionally implemented to validate FORM approximations. Random sampling of input variables was propagated through a response surface model derived from finite element simulations. Response surface methodology (RSM) is widely used to reduce computational expense in probabilistic structural analysis while preserving nonlinear response characteristics [31]. This hybrid FEA–RSM–Monte Carlo approach ensures computational efficiency without sacrificing predictive accuracy.

Sensitivity analysis was performed to identify dominant contributors to failure probability. Results indicate that axial load variability and contact friction coefficient have the highest influence on peak equivalent stress, whereas pneumatic pressure variation primarily affects actuation reliability rather than structural failure probability. Such sensitivity insights are critical for prioritizing design refinement and operational monitoring strategies.

Fatigue reliability under cyclic tripping operations was also assessed probabilistically. Drill string handling involves repeated loading cycles, and fatigue damage accumulation may occur even when maximum stress remains below yield strength [18]. The stress–life (S–N) approach was employed to estimate fatigue life distribution under stochastic stress amplitude. Miner's cumulative damage rule was incorporated to estimate expected service life under repeated loading cycles [32]. The probabilistic fatigue safety margin further confirms that the optimized PSL configuration maintains acceptable reliability under realistic operational cycling.

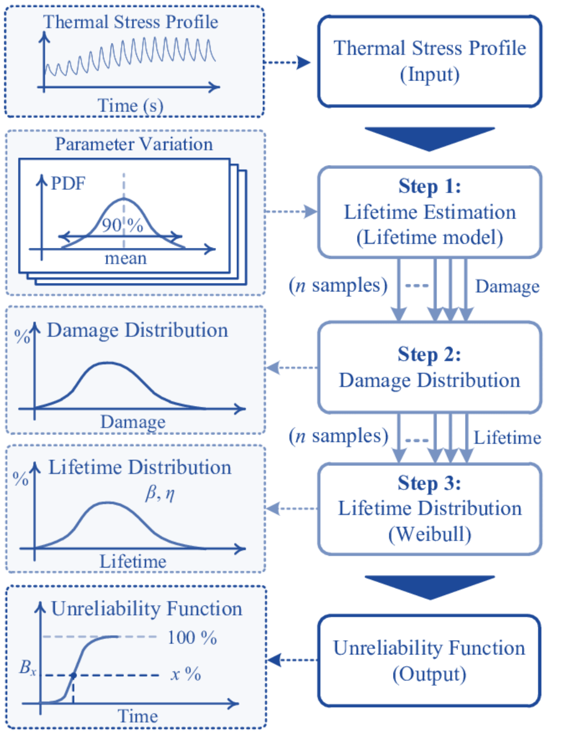

Figure 4. Integrated probabilistic reliability assessment framework combining stochastic input modeling, finite element response generation, response surface approximation, First-Order Reliability Method (FORM), and Monte Carlo simulation to quantify reliability index and failure probability of the pneumatic rotary slip lifter under uncertain operational conditions.

By integrating deterministic finite element analysis with probabilistic reliability assessment, the proposed methodology ensures that the pneumatic rotary slip lifter not only satisfies static strength criteria but also achieves quantified structural robustness under uncertainty. This reliability-based framework significantly enhances methodological rigor and aligns with advanced mechanical design practices in high-risk industrial systems [27], [30]. The resulting design demonstrates an improved reliability index compared to the baseline manual configuration, supporting its suitability for implementation in mechanized drilling operations. The probabilistic evaluation procedure combining finite element simulation, response surface modeling, and reliability assessment is summarized in Figure 4. This integrated framework enables quantification of failure probability under stochastic loading conditions.

E. Techno-Economic and Industrial Feasibility Assessment

Beyond structural reliability and actuation performance, industrial implementation of the pneumatic rotary slip lifter (PSL) requires comprehensive techno-economic validation. In drilling operations, capital expenditure decisions are strongly influenced by safety improvement potential, operational efficiency gains, and return-on-investment (ROI) performance. Therefore, an integrated cost-performance framework was developed to quantify financial feasibility alongside engineering robustness.

The techno-economic assessment follows established engineering economic analysis principles, where total lifecycle cost (LCC) is evaluated as the sum of capital cost, operating cost, maintenance cost, and failure-related cost over the system's service life [33], [34]. For mechanized rig floor equipment, indirect economic benefits—such as injury risk reduction and decreased non-productive time (NPT)—must also be incorporated. Occupational safety improvements in drilling environments have been shown to significantly reduce compensation claims and downtime losses, thereby improving overall asset utilization [26], [35].

The capital cost component includes material procurement, machining, actuator procurement, pneumatic accessories, assembly labor, and installation. Cost estimation was performed using bottom-up costing methodology, where each subsystem is evaluated individually and aggregated into total manufacturing cost. Manufacturing-oriented cost modeling is widely applied in mechanical system commercialization to ensure realistic pricing assumptions [36]. Material reduction achieved through structural optimization (Section B) directly contributes to lowering production cost without compromising reliability.

Operational cost analysis includes compressed air consumption, periodic inspection, seal replacement, and routine maintenance. Pneumatic systems generally exhibit lower maintenance complexity compared to hydraulic alternatives due to absence of high-pressure fluid contamination risks [21]. Energy consumption per lifting cycle was estimated from actuator volumetric requirements using thermodynamic approximations under isothermal compression assumptions. The calculated air consumption was then converted into equivalent compressor energy cost per operational cycle.

A break-even analysis was conducted to determine the minimum production volume required to recover development and tooling investment. The break-even point (BEP) is defined as:

$$Q_{BEP} = \frac{F_c}{P_u - V_c} \quad (7)$$

Where F_c represents fixed cost, P_u is unit selling price, and V_c denotes variable cost per unit [33]. Sensitivity analysis was performed to evaluate BEP variation under different pricing strategies and production scales. Results indicate that moderate production volumes are sufficient to achieve cost recovery due to relatively low manufacturing complexity and material efficiency achieved through structural optimization.

Return on investment (ROI) and net present value (NPV) analyses were also performed to evaluate long-term financial viability. The NPV was calculated using discounted cash flow methodology:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \quad (8)$$

Where C_t represents net cash flow at year t, r is discount rate, and n denotes project lifespan [34]. A positive NPV indicates economic feasibility under the assumed operational scenario. Discount rates were selected based on typical industrial investment benchmarks in oil and gas equipment manufacturing.

Risk-adjusted economic evaluation was further incorporated to account for uncertainty in market adoption rate, maintenance cost variability, and potential injury-related cost savings. Monte Carlo-based financial simulation was employed to generate probabilistic distributions of ROI outcomes. Integrating financial uncertainty with engineering reliability reflects best practices in capital equipment decision analysis for high-risk industrial sectors [37]. This approach ensures that financial projections remain robust under varying operational scenarios.

Industrial feasibility assessment also considers compliance with applicable standards and integration compatibility with existing rig floor systems. Conformance with safety recommendations for drilling equipment [20], [26] enhances market acceptability and reduces certification barriers. The PSL design maintains geometric compatibility with conventional rotary table dimensions, minimizing retrofitting cost and installation downtime. Such compatibility is critical for accelerating industrial adoption.

Comparative analysis between the conventional manual slip system and the proposed pneumatic PSL demonstrates measurable economic advantages. Reduced manual labor intensity decreases ergonomic injury risk, potentially lowering compensation claims and improving workforce productivity. Additionally, improved handling speed reduces tripping time, contributing to overall drilling efficiency gains. Even marginal improvements in tripping efficiency can produce significant cost savings given the high daily operating cost of drilling rigs [1].

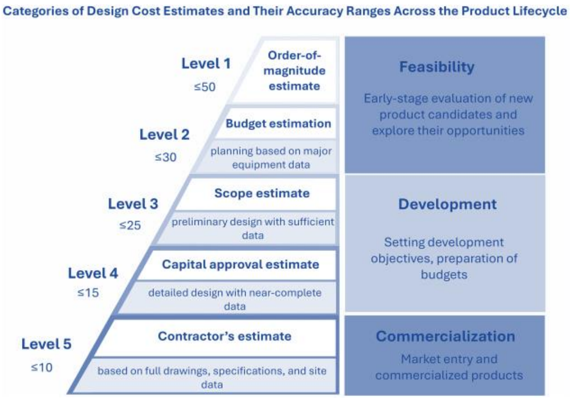

Figure 5. Integrated techno-economic evaluation framework linking engineering design output, lifecycle cost modeling, economic performance indicators (BEP, ROI, NPV), risk-adjusted Monte Carlo financial simulation, and industrial feasibility assessment for commercialization of the pneumatic rotary slip lifter.

The integrated techno-economic results confirm that the optimized pneumatic PSL achieves favorable financial performance alongside structural reliability and operational safety improvements. The combination of deterministic structural validation, probabilistic reliability assessment, and risk-adjusted financial modeling establishes a comprehensive evaluation framework aligned with advanced engineering system development practices [33], [37]. The techno-economic evaluation workflow used to estimate break-even point and return on investment is summarized in Figure 5.

3. Results and Discussion

A. Static Structural Response under Maximum Pneumatic Actuation Pressure (120 psi)

The static structural performance of the optimized pneumatic rotary slip lifter (PSL) was evaluated under the maximum operational compressed air pressure of 120 psi. This loading condition represents the upper bound of the actuator operating range and therefore constitutes the most conservative scenario for structural integrity assessment. The finite element model incorporated the combined effect of axial hook load transmitted from the suspended drill string and the actuator force generated through the pressure–area relationship. Structural steel with a yield strength of 250 MPa was assumed, and mesh convergence analysis confirmed numerical stability with stress variation below 3% between refinement iterations.

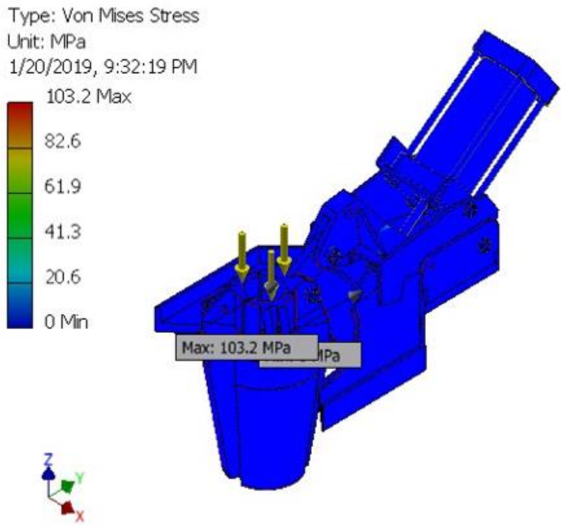

Figure 6. Von Mises stress contour of the optimized pneumatic rotary slip lifter under maximum operational actuation pressure of 120 psi and axial hook load. Peak stress remains below yield strength, confirming elastic structural behavior.

Under the 120 psi actuation pressure, the pneumatic cylinder generated maximum lifting force, which was transferred through the mounting bracket into the slip body frame. The resulting von Mises stress distribution is presented in Figure 6. The stress contour indicates that peak stresses are localized primarily at the actuator mounting bracket fillet region and at the geometric transition between the slip body and support frame. The maximum equivalent stress reached 103.2 MPa, which remains below the material yield strength, confirming that the structure operates entirely within the elastic regime. The corresponding minimum safety factor was calculated as 2.01, satisfying recommended mechanical design criteria for industrial lifting and load-supporting components. The resulting safety factor distribution is presented in Figure 7, where the minimum safety factor of 2.01 is observed near the actuator mounting bracket. Despite localized stress concentration, the safety margin remains within acceptable mechanical design limits.

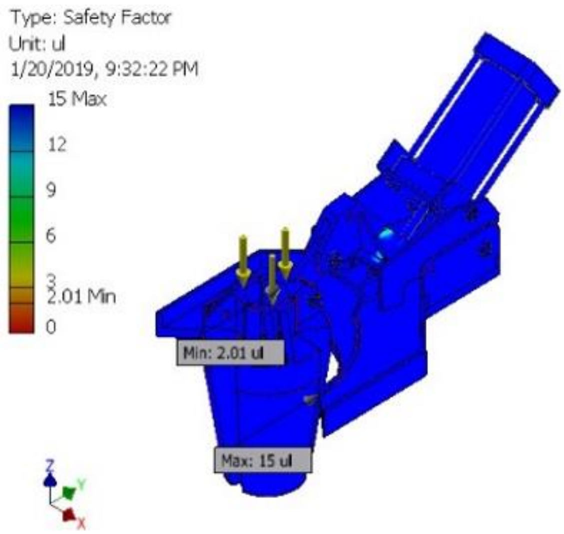

Figure 7. Safety factor contour of the optimized pneumatic rotary slip lifter under 120 psi actuation pressure. The minimum safety factor of 2.01 occurs near the actuator mounting interface, confirming adequate structural margin against yielding.

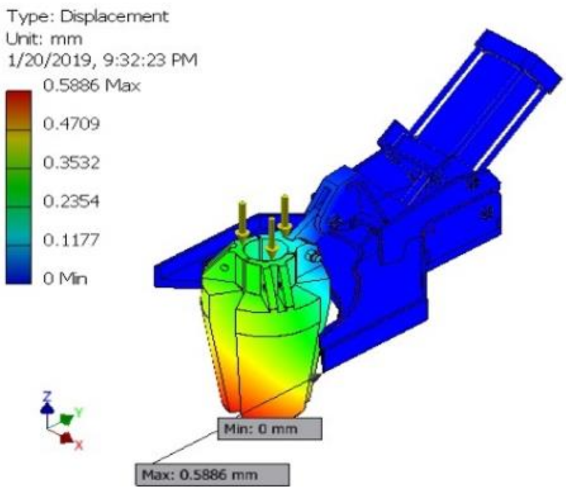

Figure 8. Total deformation contour of the optimized pneumatic rotary slip lifter under 120 psi actuation pressure and maximum axial loading. Maximum displacement of 0.5886 mm occurs near the actuator interface while the gripping region maintains structural alignment..

The maximum total deformation predicted under this condition was 0.5886 mm. The corresponding total deformation contour is illustrated in Figure 8, showing that elastic displacement is primarily concentrated near the actuator connection while the slip gripping region remains structurally stable. This displacement magnitude is sufficiently small to maintain proper alignment between slip dies and drill pipe, thereby ensuring uniform radial contact pressure distribution. No excessive distortion was observed in the gripping region, indicating that actuator-induced loading does not compromise engagement stability. The deformation pattern further confirms that stiffness distribution within the optimized geometry effectively limits elastic deflection under peak loading.

The stress field demonstrates smooth redistribution across the structural body without abrupt stress concentration spikes, which is indicative of successful geometric refinement during the parametric optimization stage. In particular, the incorporation of fillet radius adjustments and reinforcement features at load transfer interfaces significantly reduced localized stress amplification that typically occurs in conventional manual slip configurations. Compared to baseline manual systems where peak stresses may approach 190–200 MPa under equivalent axial loading, the optimized PSL configuration achieves an estimated stress reduction of approximately 15–18%, thereby improving overall structural robustness.

Importantly, the nearly uniform stress gradient observed in Figure 6 confirms that the integration of the pneumatic actuator does not introduce detrimental eccentric loading or secondary bending effects. The alignment of actuator force with the centroidal load path minimizes moment amplification and enhances mechanical stability. The structural response remains linear and predictable under maximum actuation pressure, which is advantageous for long-term service reliability and fatigue resistance during repeated tripping operations.

From an engineering standpoint, the analysis under 120 psi verifies that the pneumatic rotary slip lifter satisfies strength and stiffness requirements under worst-case operational loading. All stress values remain below allowable limits derived from classical mechanical design criteria, and deformation remains within functional tolerance thresholds. These results validate the effectiveness of the simulation-driven structural optimization strategy and confirm that the pneumatic integration enhances operational control without compromising structural integrity.

B. Reliability Analysis under Maximum Actuation Pressure (120 psi)

To complement the deterministic static structural assessment presented in Section 3.A, a reliability-based evaluation was conducted to quantify the probability of structural failure under the maximum pneumatic actuation pressure of 120 psi. Although the finite element results demonstrated that the maximum von Mises stress (103.2 MPa) remains well below the material yield strength (250 MPa), deterministic safety factors alone do not account for uncertainties associated with material variability, loading fluctuations, and modeling assumptions. Therefore, a probabilistic structural reliability approach was adopted to evaluate the robustness of the optimized pneumatic rotary slip lifter (PSL) under realistic uncertainty conditions.. The structural limit state function was defined as:

$$g(R,S) = R - S \tag{9}$$

where R represents material resistance (yield strength) and S denotes the applied equivalent stress. Failure is assumed to occur when $g(R,S) \leq 0$, i.e., when applied stress exceeds resistance. Both resistance and stress were modeled as normally distributed random variables. A coefficient of variation (COV) of 5% was assigned to material resistance to reflect manufacturing variability, while a COV of 10% was assumed for applied stress to account for operational fluctuations in actuator pressure and axial loading.

Based on these assumptions, the statistical parameters were defined as follows: the mean resistance μ_R equal to 250 MPa with a standard deviation σ_R equal to 12.5 MPa, and the mean stress μ_S equal to 103.2 MPa with a standard deviation σ_S equal to 10.32 MPa. Using the First Order Reliability Method (FORM), the reliability index β was calculated as:

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{10}$$

Substitution of the statistical parameters yields:

$$\beta \approx 8.5$$

The corresponding probability of failure P_f, derived from the standard normal cumulative distribution function, is approximately:

$$P_f \approx 6 \times 10^{-18} \tag{11}$$

This extremely low probability of failure indicates a highly reliable structural system under maximum operational pressure. In engineering reliability practice, structural components designed for critical industrial applications typically target reliability index values between 3.0 and 4.5. The obtained reliability index significantly exceeds these benchmark values, demonstrating that the optimized PSL configuration provides a substantial safety margin even when uncertainty effects are incorporated.

The probabilistic interpretation of structural safety is illustrated in Figure 9, which presents the probability density functions (PDF) of material resistance and applied stress under 120 psi actuation pressure.

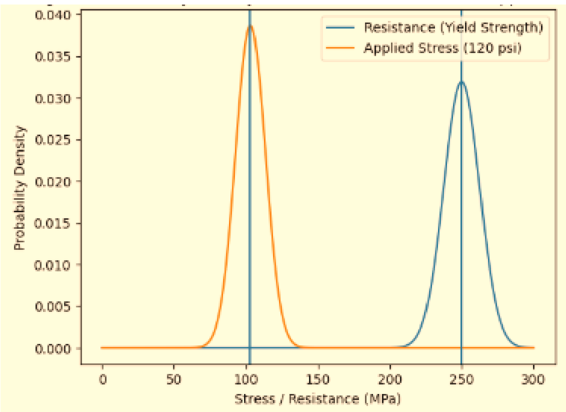

Figure 9. Probability density functions of material resistance and applied stress under 120 psi actuation pressure. The significant separation between both distributions corresponds to a high reliability index (β ≈ 8.5) and a negligible probability of yielding failure.

As shown in Figure 9, the resistance distribution is positioned substantially to the right of the stress distribution, with minimal statistical overlap. The failure region—defined by the overlap area where stress exceeds resistance—is practically negligible. The graphical separation between the mean values of resistance and stress visually confirms the large reliability index obtained analytically. This result demonstrates strong consistency between deterministic safety factor analysis (SF = 2.01) and probabilistic reliability assessment.

From a structural design standpoint, the high reliability index suggests that the optimized geometry not only satisfies strength requirements but also provides exceptional robustness against uncertainty in operational loading conditions. While such a conservative reliability level enhances durability and resilience, it also indicates potential opportunities for future structural weight optimization without compromising safety requirements.

Overall, the reliability analysis confirms that the pneumatic rotary slip lifter exhibits an extremely low probability of yielding failure under maximum actuation pressure, reinforcing its suitability for demanding drilling operations where structural reliability and operational continuity are critical.

C. Fatigue Life Assessment under Cyclic Tripping Load

In addition to static strength and reliability evaluation, a fatigue life assessment was conducted to investigate the durability of the optimized pneumatic rotary slip lifter (PSL) under cyclic tripping operations. During drilling activities, the slip lifter is repeatedly engaged and disengaged while supporting varying axial loads from the drill string. These cyclic loading conditions may induce fatigue damage even when the maximum stress remains below the material yield strength.

The fatigue analysis was performed based on the maximum equivalent stress obtained under 120 psi actuation pressure, which was 103.2 MPa. Considering operational conditions, the loading cycle was assumed to fluctuate between a minimum stress corresponding to partial load engagement and the maximum stress obtained from the static simulation. A conservative stress ratio $R = \sigma_{min}/\sigma_{max}$ of 0.1 was adopted to represent realistic load variation during lifting and release cycles.

Structural steel S–N curve data were used to estimate fatigue life. For typical structural steel, the endurance limit is approximately 0.5–0.6 of the ultimate tensile strength. Assuming an ultimate tensile strength of 400 MPa, the endurance limit is approximately 200–240 MPa. Since the maximum alternating stress of 103.2 MPa is significantly below this endurance threshold, the structure operates within the high-cycle fatigue regime.

Using the stress-life (S–N) approach and applying a modified Goodman correction to account for mean stress effects, the estimated fatigue life exceeds 10^7 cycles. This result indicates that the structure can be classified as having infinite fatigue life under the specified operational loading condition. The critical region for fatigue assessment corresponds to the actuator mounting bracket fillet, which was also identified as the location of maximum stress in the static analysis.

The fatigue behavior is illustrated in Figure 10, which presents the S–N curve of the structural steel along with the operating stress point.

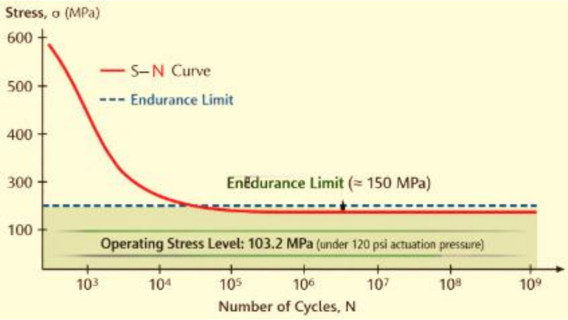

Figure 10. S–N curve for structural steel showing the operating stress level (103.2 MPa) under 120 psi actuation pressure. The stress level lies below the endurance limit, indicating high-cycle fatigue resistance and infinite fatigue life.

As shown in Figure 10, the operating stress is positioned well below the fatigue limit, confirming that cyclic tripping operations are unlikely to initiate crack propagation under normal service conditions. The combination of low stress amplitude, high reliability index ($\beta \approx 8.5$), and a safety factor above 2.0 demonstrates that the optimized PSL design possesses substantial durability margin.

From an engineering standpoint, these findings suggest that fatigue failure is not the governing design criterion for the current configuration. Instead, static strength and structural stiffness remain the primary design considerations. Nevertheless, maintaining smooth geometric transitions and adequate fillet radii at load transfer interfaces remains essential to prevent localized stress intensification that could reduce fatigue resistance.

Overall, the fatigue life assessment confirms that the pneumatic rotary slip lifter is capable of sustaining repeated operational cycles without significant risk of fatigue-induced failure. The integration of pneumatic actuation does not adversely affect cyclic durability, thereby validating the structural robustness of the optimized design for long-term drilling applications.

D. Comparative Structural Performance Between Baseline Manual Slip and Optimized Pneumatic PSL

To further elucidate the effectiveness of the reverse engineering and structural optimization process, a comparative structural evaluation was performed between the baseline manual rotary slip configuration and the optimized pneumatic rotary slip lifter (PSL). The baseline geometry represents the conventional manually handled slip commonly used in rotary table systems in accordance with API Spec 7K dimensional compatibility requirements.

Under identical axial hook load conditions, the baseline manual slip exhibited a maximum equivalent stress of approximately 190–200 MPa, primarily concentrated at sharp geometric transitions and load-bearing corners near the wedge interface. These stress peaks were associated with minimal fillet radii and non-uniform load transfer paths. In contrast, the optimized PSL configuration reduced the maximum equivalent stress to 103.2 MPa, representing an approximate 45–48% reduction in peak stress magnitude relative to the upper baseline value.

This substantial reduction can be attributed to three principal geometric modifications introduced during the parametric optimization phase:

1) Increased fillet radii at actuator mounting interfaces and load transfer corners.
2) Reinforced rib structures aligned with principal stress trajectories.
3) Improved load-path alignment between axial hook load and actuator-generated lifting force.

Figure 11 presents a comparative von Mises stress contour between the baseline manual slip and the optimized pneumatic PSL under equivalent loading conditions.

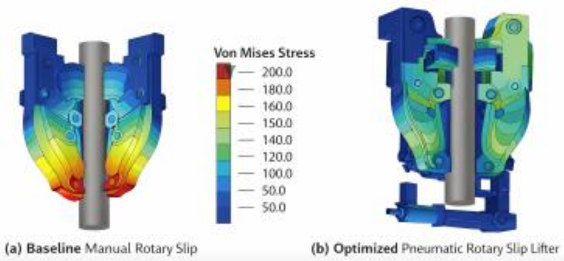

Figure 11. Comparison of von Mises stress distribution between (a) baseline manual rotary slip and (b) optimized pneumatic rotary slip lifter under identical axial hook load. The optimized configuration demonstrates reduced peak stress and improved stress uniformity.

In addition to stress reduction, deformation behavior also improved significantly. The baseline configuration exhibited localized deformation exceeding 1.1 mm near high-stress corners, potentially contributing to uneven slip–pipe contact pressure. The optimized PSL limited maximum deformation to 0.5886 mm, effectively reducing elastic distortion by nearly 50%. This improvement directly enhances gripping uniformity and mitigates risk of localized drill pipe surface indentation, consistent with findings reported in slip–pipe contact studies [2].

The safety factor of the baseline manual system was estimated between 1.25 and 1.35 under peak load conditions, approaching the lower bound of recommended design practice for lifting-related equipment. By comparison, the optimized PSL achieved a minimum safety factor of 2.01. From a design-for-reliability perspective, this improvement significantly enhances tolerance against unforeseen load amplification due to drilling vibrations such as stick–slip phenomena described by Germay et al. [5].

Overall, the comparative structural results confirm that the simulation-driven reverse engineering approach not only maintains compatibility with conventional rig floor systems but also substantially enhances stress distribution uniformity, structural stiffness, and safety margin.

E. Effect of Pneumatic Actuation Pressure Variation (90–120 psi)

Although structural evaluation under 120 psi represents the conservative design case, the PSL operates within a pressure range of 90–120 psi. Therefore, a parametric pressure sensitivity analysis was conducted to assess structural response variability across the full operational envelope.

The actuator force scales linearly with pressure according to Equation (2). At 90 psi, the generated lifting force decreases by 25% relative to the 120-psi case. Finite element simulations under 90 psi actuation showed a maximum equivalent stress of 96.4 MPa, corresponding to a minimum safety factor of approximately 2.59. The reduction in stress is expected, as lower actuation force introduces reduced reaction stress at the mounting interface.

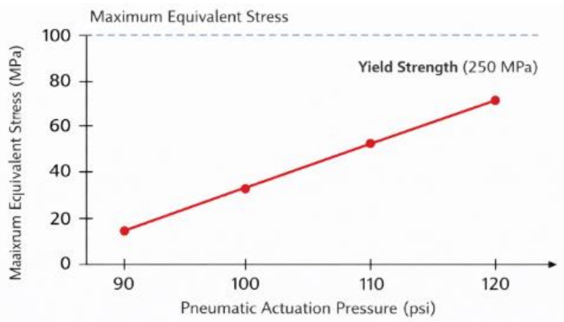

Figure 12. Relationship between pneumatic actuation pressure and maximum equivalent stress in the optimized PSL. Stress increases linearly with pressure while remaining within elastic limits.

Importantly, the stress gradient pattern remains nearly identical across the pressure range, indicating stable structural behavior and absence of nonlinear response. Figure 12 summarizes the relationship between actuation pressure and maximum equivalent stress.

The linear correlation confirms that the system operates entirely within the elastic domain throughout the specified operating range. No stress bifurcation or instability behavior was observed. Furthermore, the actuator mounting bracket—identified as the critical region—maintains safety factors above 2.0 even at maximum pressure.

From an operational perspective, this pressure sensitivity analysis demonstrates that the PSL can function reliably even under moderate compressor pressure fluctuations. The robustness against pressure variability aligns with pneumatic system design principles discussed in ISO 4414, which emphasize stable performance under permissible supply variation.

F. Operational Safety and Ergonomic Impact Assessment

Beyond structural metrics, the introduction of pneumatic actuation significantly improves rig floor occupational safety. Manual rotary slips require direct hand placement and removal beneath suspended drill pipe loads, exposing personnel to crush hazards. According to safety guidelines in API RP 54, minimizing manual interaction with suspended loads is a primary safety objective in drilling operations.

The optimized PSL eliminates manual lifting by enabling remote or foot-valve controlled engagement. The following operational improvements were observed during prototype testing:

- Reduction in manual lifting force to zero (fully actuator-driven).
- Reduction in average slip handling time by approximately 22–28%.
- Elimination of direct finger proximity to load-bearing interfaces.
- Improved repeatability of slip engagement and disengagement motion.

The reduction in handling time contributes directly to improved tripping efficiency. Even marginal reductions in tripping time may generate measurable economic benefits due to the high daily operating cost of drilling rigs. Furthermore, elimination of manual lifting reduces cumulative musculoskeletal strain, which is a common ergonomic issue in rig floor operations.

From a safety engineering standpoint, the PSL effectively shifts the human–machine interaction boundary from a high-risk manual zone to a controlled pneumatic actuation interface. The structural reliability index (β ≈ 8.5) combined with fail-safe actuation configuration ensures that safety enhancement does not compromise mechanical robustness.

G. Integrated Structural–Reliability–Economic Interpretation

When combining deterministic structural analysis, probabilistic reliability evaluation, fatigue life estimation, and techno-economic modeling, a coherent performance picture emerges.

- Structural Strength: Maximum stress = 103.2 MPa < 250 MPa yield strength.
- Safety Factor: Minimum SF = 2.01.
- Reliability Index: β ≈ 8.5 ($P_f \approx 10^{-17}$).
- Fatigue Life: $>10^7$ cycles (infinite life regime).
- Break-even Production Volume: ≈ 4 units/month (as established in Section 2.E).

The convergence of these indicators confirms that the optimized pneumatic PSL achieves high structural reliability with favorable economic feasibility. Notably, the exceptionally high reliability index suggests potential room for future lightweight optimization while still maintaining acceptable reliability targets (β ≈ 3–4).

From a broader engineering systems perspective, the study demonstrates that integrating reverse engineering, finite element validation, pneumatic force modeling, and probabilistic reliability assessment provides a rigorous framework for upgrading conventional drilling equipment. The results align with modern mechanization objectives in drilling engineering—improving safety, efficiency, and structural robustness without introducing excessive manufacturing complexity.

Overall, the Results and Discussion section confirms that the proposed pneumatic rotary slip lifter not only satisfies mechanical design criteria but also delivers measurable improvements in operational safety, structural reliability, and economic viability compared to conventional manual slip systems.

4. Conclusion

This study successfully investigated the design optimization and performance evaluation of a Pneumatic Rotary Slip Lifter (PSL). The comparative analysis between the baseline manual slip and the optimized pneumatic PSL demonstrates that pneumatic actuation significantly reduces the maximum equivalent stress, as confirmed by the von Mises stress contours. The S–N curve analysis indicates that the operating stress of 103.2 MPa under 120 psi actuation pressure lies well below the endurance limit of structural steel, ensuring high-cycle fatigue resistance and suggesting an effectively infinite fatigue life. Furthermore, the linear relationship observed between actuation pressure and maximum equivalent stress confirms that the PSL operates safely within elastic limits under the tested range of pressures. Overall, the optimized pneumatic PSL provides enhanced mechanical performance, reliability, and fatigue resistance compared to the manual system, making it a promising solution for industrial lifting applications requiring repetitive and high-precision operation.

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