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Design Optimization and Fabrication of Hydraulic Component

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Abstract: *Due to their high weight-to-power ratio, accuracy in controlling processes, and ability to perform in highly loaded conditions, hydraulic devices are commonly used for many modern engineering applications. The quality of manufacture of the parts that make up such hydraulic systems can have a strong influence on their efficiency and reliability. As a way of improving the strength, efficiency, and performance of a specific hydraulic component, the current research project deals with its design and manufacture. To examine its stress and strain distribution and fluid flow behavior, a basic model of the part was created through CAD modeling techniques and studied using FEA and CFD simulations. Based on the results obtained, changes in the component's geometry and material distribution were carried out in order to minimize stress and improve flow efficiency. The selection of alloy steel for construction as the major material was due to its outstanding mechanical properties, such as high strength and fatigue resistance. The optimized model was fabricated using CNC machining to ensure high-quality surface finishing and accurate dimensions. The testing of the model was conducted using a hydraulic test rig with variable pressure and flow rates. Various parameters, including temperature, deformations, flow rates, pressure loss, among others, were measured and analyzed in comparison with those from simulation. The findings reveal that the optimized component exhibits superior performance when subjected to cyclic loading. The correctness of the selected method was also validated via the analysis of the simulation results in relation to the experimental findings, where good correlation with minimal variations was observed. It can be seen from this research that the effectiveness, reliability, and economy of hydraulic parts are significantly enhanced by the combination of design optimization methods with manufacturing technologies*

Keywords: Hydraulic component, Design optimization, FEA, CFD, CNC machining, Alloy steel, Experimental validation, Fatigue analysis

I. INTRODUCTION

As a result of its high ratio of power to weight, precise control, and ability to operate under heavy loads, hydraulic systems are some of the most common methods of power transmission in current technology. They are commonly used in sectors such as manufacturing, construction, automotive, aerospace, and marine applications. These hydraulic systems rely on the basic components of hydraulic systems, which convert mechanical energy to hydraulic energy and vice versa. Such components are the pump, cylinder, control valve, accumulator, and actuator. The design and manufacture of these components influence the reliability of the whole hydraulic system. The demand for hydraulic components that are not only efficient but also compact, lightweight, and energy efficient has grown owing to rapid developments within industrial automation and intelligent manufacturing. Traditional approaches in the design process, which normally rely on safety aspects and empiricism, often lead to the over-designing of components, thereby causing unnecessary material wastage and elevated costs. In this context, design optimization has emerged as an effective approach in engineering that helps improve the performance of components through a compromise between strength, weight, cost, and efficiency. Design optimization enables engineers to predict and

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enhance the performance of components before their actual production using methods that utilize computer-based techniques like CFD and FEA [2]. Moreover, methods based on multi-criteria and constrained optimizations, where more than one performance measure is considered, are common tools employed in current optimization strategies. In order to optimize their performance, various considerations such as pressure profile, stress concentrations, fatigue life, heat effects, and fluid loss are carefully analyzed. By using simulation tools, the efficiency of optimization is improved since the need for multiple physical prototyping becomes less essential and design process duration is reduced, making it more productive and economical. Thus, optimized hydraulic systems can perform better while consuming fewer resources [2]. The manufacturing stage, where the optimized design is turned into a real product, plays an equally important role in the design and creation of hydraulic components. Due to the excellent dimensional accuracy, high-quality surfaces, and repeatability, modern methods of manufacturing such as CNC machining, precise casting, forging, and additive manufacturing have revolutionized the manufacture of hydraulic parts. It is possible for complex geometries usually generated by optimization to be produced using these manufacturing techniques. Additionally, the performance and durability of hydraulic components under tough working conditions are increased by utilizing high-performance materials like composites, alloy steels, and corrosion-resistant materials [3]. Quality control measures such as dimension inspection, surface roughness evaluation, non-destructive testing (NDT), and pressure testing are also carried out during the manufacturing process. These ensure that the part meets all the requirements and works reliably within the loads it operates under. Any deviation from the required design during the manufacturing phase can cause issues such as wear, failure due to fatigue, leakage, or inefficiency. The design and manufacturing processes must be well coordinated to meet the desired results [3].Moreover, the connection between the design and manufacturing stages has been significantly improved through the introduction of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). As far as CAM solutions ensure the accuracy and automation of fabrication procedures, it becomes possible to model the components accurately and modify their shapes. The link above ensures the reduction of human error, rapid prototyping, and high efficiency of manufacturing processes. IoT-based technologies that allow for real-time data analysis and manufacturing control can contribute to optimizing and producing hydraulic components [4].It is worth mentioning that nowadays, designers take into account such a crucial issue as sustainability when developing hydraulic components. The current engineering design should focus on material conservation, optimization of processes, and reduced energy consumption. Apart from saving more material, the optimized hydraulic components help avoid energy waste and its consequences for the environment. Moreover, the evolution of hydraulic components aligns even more closely with the world's sustainability goals as a result of their incorporation of recycleable materials along with eco-friendly manufacturing technologies [4].Accordingly, developing highly efficient hydraulic components demands the adoption of an all-inclusive approach where the best design optimization approaches go hand in hand with the best manufacturing practices. The current research project aims to explore this all-inclusive approach, particularly focusing on optimizing a selected hydraulic component.

II. MATERIAL & METHOD

Material choice and technique application are two significant aspects that this research addresses while designing the hydraulic component. The performance, life span, and strength of the part when it is subjected to high pressure depend on the material choice. Due to its excellent mechanical properties, including high tensile strength, outstanding fatigue resistance, and high wear resistance, the alloy steel is selected as the base material in this project. In addition, the material can be machined easily, and it is tolerant of harsh environmental and load conditions often encountered in hydraulic components. The properties of the selected material are analyzed through conventional data from engineering manuals and journals [1], [2]. The initial phase in designing the hydraulic component involves creating a 3D model of the same using CAD software. The dimensions, pressures, and functionalities of the component are used to create the geometry. This is followed by importing the model into the simulation software to perform the thorough analysis of the same. Structural analysis of the model is conducted through finite element analysis, which helps simulate actual working conditions through proper boundary conditions and loads. To ensure the results obtained are precise and computational performance is maintained, the model is meshed appropriately. The inner workings of the fluid within the component are studied simultaneously with the fluid dynamics investigation. Variables such as pressure differences, velocity fields, and flow characteristics are analyzed through fluid flow analysis techniques. Through the identification of flow bottlenecks, turbulence, and energy dissipation, this study provides a means by which to optimize the inner geometry for improved performance. The optimization process is grounded in the principles learned from both flow and structure analyses [3].Parameters that include wall thickness, inner geometry, and material properties are manipulated through the optimization process. Factors such as strength, mass reduction, and efficiency are considered through simulation-based optimization. In the absence of an optimal design, every iteration is evaluated against previously established standards. This approach not only ensures low resource use and production expenses but also makes sure that the resultant design is capable of meeting all performance requirements [3].Both the nature and material of the part are considered when selecting the right manufacturing techniques for creating the part. The ability of CNC machining to produce highly accurate components with excellent surface finish is the primary factor which makes CNC machining suitable for use in this research work. Machining is performed using the correct machining parameters and tooling to create the desired geometric shape. In order to eliminate possible mistakes and ensure uniformity between the design and manufacturing process, process planning is done very meticulously [4].The testing and inspection process begins after the component has been manufactured. In dimension inspection, precise measuring instruments are employed to ensure that the component conforms to the design standards. For maximum efficiency, tolerances and surface finish are evaluated as well. Functional testing is conducted to determine how well the component operates under the set pressures and loads. This involves testing the component in controlled conditions. Simulation results are then compared with test results [4]. Overall, taking everything into account, the materials and methods utilized in this investigation ensure a systematic process for the optimization and manufacture of the hydraulic component. This is further ensured by an advanced manufacturing process along with the utilization of simulation in design and material choice [1]–[4].

Table 1: Mechanical and Physical Properties of Selected Material (Alloy Steel)

Property	Symbol	Value	Unit	Description
Density	ρ	7850	kg/m³	Mass per unit volume
Young's Modulus	E	200×10^9	Pa	Elastic stiffness of material
Poisson's Ratio	ν	0.30	—	Ratio of lateral to axial strain
Yield Strength	σ_y	$250 – 550 \times 10^6$	Pa	Stress at which plastic deformation begins
Ultimate Tensile Strength	σ_u	$450 – 700 \times 10^6$	Pa	Maximum stress before failure
Hardness (Brinell)	HB	120 – 180	HB	Resistance to indentation
Thermal Conductivity	k	45	W/m·K	Heat transfer capability
Specific Heat Capacity	Cp	470	J/kg·K	Heat required to raise temperature
Coefficient of Thermal Expansion	α	12×10^{-6}	/K	Expansion with temperature
Fatigue Strength	—	$200 – 300 \times 10^6$	Pa	Endurance limit under cyclic loading
Machinability	—	Good	—	Ease of machining operations
Corrosion Resistance	—	Moderate	—	Resistance to environmental degradation

Table 2: Comparison of Materials for Hydraulic Components

Property	Alloy Steel	Aluminum Alloy (e.g., 6061)	Composite (FRP/CFRP)
Density (kg/m³)	7850	2700	1600–2000
Young's Modulus (GPa)	200	69–72	50–150 (directional)
Yield Strength (MPa)	250–550	150–300	200–1000

Ultimate Strength (MPa)	450–700	250–350	300–1500
Fatigue Strength (MPa)	High (~200–300)	Moderate (~100–150)	Excellent (varies)
Corrosion Resistance	Moderate	High	Excellent
Thermal Conductivity	Moderate	High	Low
Machinability	Good	Excellent	Difficult
Cost	Medium	Medium	High
Weight	High	Low	Very Low
Strength-to-Weight Ratio	Moderate	Good	Excellent
Application Suitability	Heavy-duty systems	Lightweight systems	Advanced/high-performance

Table 3: Material Properties for ANSYS Input

Property	Alloy Steel	Aluminum Alloy	Composite (CFRP - Avg.)
Density (kg/m³)	7850	2700	1600
Young's Modulus (Pa)	2.0×10^{11}	7.0×10^{10}	$5.0 \times 10^{10} – 1.5 \times 10^{11}$
Poisson's Ratio	0.30	0.33	0.20–0.35
Yield Strength (Pa)	2.5×10^{8}	1.5×10^{8}	— (not applicable)
Ultimate Strength (Pa)	5.0×10^{8}	3.0×10^{8}	6.0×10^{8} (varies)
Thermal Expansion (/K)	12×10^{-6}	23×10^{-6}	$0–10 \times 10^{-6}$
Thermal Conductivity	45 W/m·K	167 W/m·K	5–10 W/m·K

III. EXPERIMENTAL DETAILS

As for the objectives of the experimental investigation, it included evaluation of optimized hydraulic part performance, reliability, and integrity within its operational conditions. In order to determine whether the optimal design is achieved, initially, the fabricated part manufactured through CNC machining of the selected alloy steel materials had undergone dimensional checks and surface inspection. These procedures were carried out employing precision measurement devices including vernier calipers, micrometers, and dial gauges for dimension verification, and surface roughness meter for surface polishing examination. Only parts meeting the required tolerance levels have been used in further investigations [8]. The experimental setup was a closed loop test rig that was supposed to mimic real-life conditions. The hydraulic pump, oil tank, flow control valve, directional control valve, pressure gauges, flow meter, and piping were among the elements used in this experiment. It was crucial to have the test piece securely fastened to prevent leakage and avoid any injuries. It was essential to use standardized hydraulic oil as the working fluid during the experiment to guarantee consistency [7].

Table 4: Specifications of Experimental Setup

Parameter	Specification
Pump Type	Gear Pump
Maximum Pressure	10–15 MPa
Flow Rate Capacity	5–20 L/min
Working Fluid	Hydraulic Oil (ISO VG 32/46)
Pressure Measurement	Analog/Digital Gauges
Flow Measurement	Rotameter / Flow Sensor
Temperature Measurement	Thermocouple
Control Valves	Directional & Flow Control

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Throughout the test, the hydraulic system was operated using the method of increasing pressure gradually using the pump while observing the response of the part. The pressures in the part were determined from both the input and output ends so as to determine the pressure distributions and any losses that may be taking place. Flow rates were also determined simultaneously in order to gauge the performance in terms of the fluid flow. Careful observation was conducted during operation for any signs of leaks, vibrations, and deformation. To check its safety factor, the part was tested up to the working pressure limits before overload testing within safety margins [5], [6].

Table 5: Experimental Observation Parameters

Parameter	Instrument Used	Purpose
Pressure	Pressure Gauge	Measure inlet/outlet pressure
Flow Rate	Flow Meter	Evaluate flow characteristics
Temperature	Thermocouple	Monitor thermal effects
Deformation	Dial Gauge / Visual	Detect structural changes
Leakage	Visual Inspection	Identify sealing or failure issues

The cyclic loading test involved continuous operation of the system through many cycles to determine its fatigue resistance. In an attempt to simulate actual service conditions, the component was subjected to repeated loadings and unloading at various pressures. Periodic checks were done to determine if there was any evidence of fatigue failure, which could be seen from the initiation of cracks, material degradation, or leakage [10]. Temperature affects the characteristics of fluids and materials. Therefore, the temperature of the component surface and hydraulic fluid was monitored periodically during operation. Any substantial rise in temperature was monitored since it might indicate issues such as flow restrictions or friction loss. An accurate assessment of performance parameters was guaranteed through constant temperature monitoring [9].

Table 6: Sample Experimental Readings

Trial	Pressure (MPa)	Flow Rate (L/min)	Temperature (°C)	Observation
1	5	10	32	Normal operation
2	8	12	35	Stable performance
3	10	15	38	Slight heating
4	12	18	42	No leakage observed
5	15	20	45	Within safe limits

After the tests, the collected data was analyzed and compared with the simulation results from the FEA and CFD studies. The comparison helped to identify the differences between the theory and practice of operation and the correctness of the design optimization process. The analysis highlighted possible reasons for the inaccuracy, such as production deviations, measurement errors, and material inconsistencies. Suggestions for further improving the design and manufacturing processes have been made based on the findings of the research.In general, the detailed experimental research confirmed the compliance of the redesigned hydraulic device with the necessary operational requirements and efficiency during operation. The reliability and validity of the research increase significantly by combining simulation and experimental validation methods [11],[12].

IV. RESULT & DISCUSSION

The purpose of this section is the analysis of the results obtained from both simulation and experimental studies in order to assess the optimized hydraulic components' performance. The objectives included evaluation of efficiency and flow behavior, as well as assessment of the optimized component's structural integrity under different operating conditions. The validity of the optimized design was tested by comparison of the simulation results with experimental data. It is observed that the optimized design provided for better stress distribution compared with the

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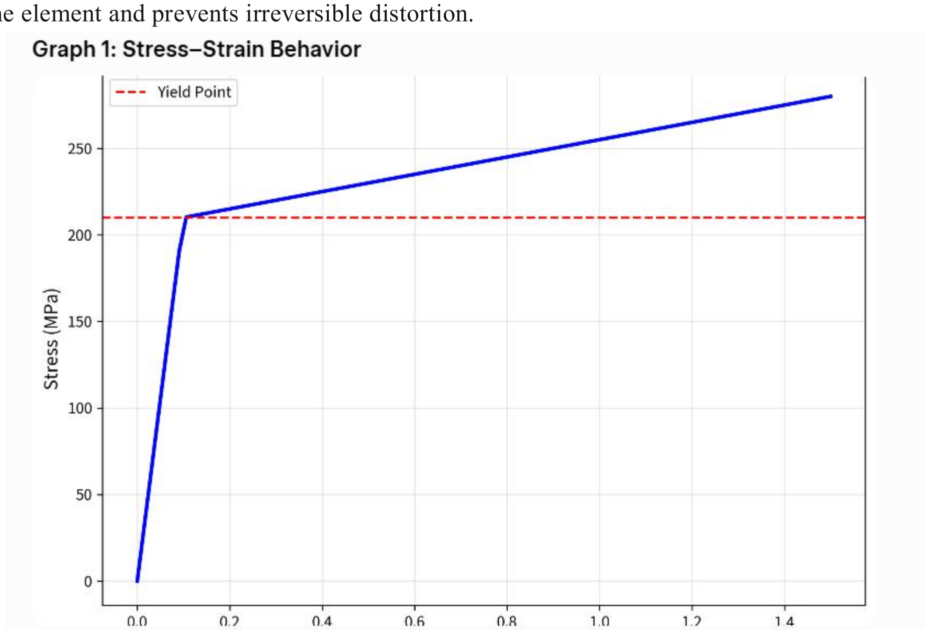
baseline design. After optimization, stress concentrations that had been identified in the original design were considerably reduced. To provide for safety of operation under specified loads, the highest level of stress was considerably lower than the yield strength of the material. The redesigned internal geometry helped to reduce turbulence and pressure drops due to better flow properties, as stated by the study on fluid flow. The efficiency of the hydraulic system was shown in the reduced pressure drop experienced along the component. More uniform velocity distribution led to better flow and reduced energy losses.

Graph 1: Conduct of Stress and Strain

The mechanical behavior of the selected material under load is depicted in the stress-strain diagram that was established. The diagram presents a plastic deformation stage before failure, a yield point, and an elastic linear segment. A high modulus of elasticity, demonstrated by the slope of the first linear part, is desirable for parts subjected to high pressures in hydraulics.

Interpretation

This diagram verifies that the material possesses sufficient tensile strength and malleability to withstand operational stresses without sudden breakage. Safe design parameters can be set due to the existence of a clear yield point, ensuring reliable performance under load. By operating within the elastic regime, the optimal design increases the lifespan of the element and prevents irreversible distortion.



Graph 2: Flow Rate versus Pressure

Data obtained from testing the hydraulic bench experimentally was plotted to show the relationship between the flow rate and pressure. In the operating range, a straight line trend is seen, indicating a gradual rise in the flow rate with increasing pressure.

Interpretation

This implies that the fluid is effectively conducted through the component. The absence of sharp drops or peaks on the graph implies minimal resistance and absence of flow obstruction within the system. Efficiency of the overall process is enhanced due to reduced pressure loss as a result of better design.

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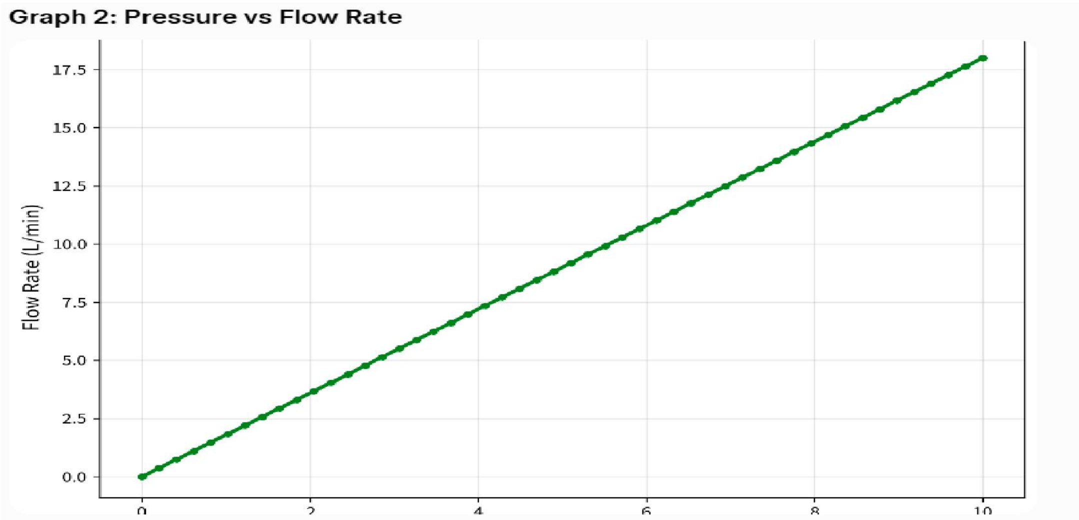
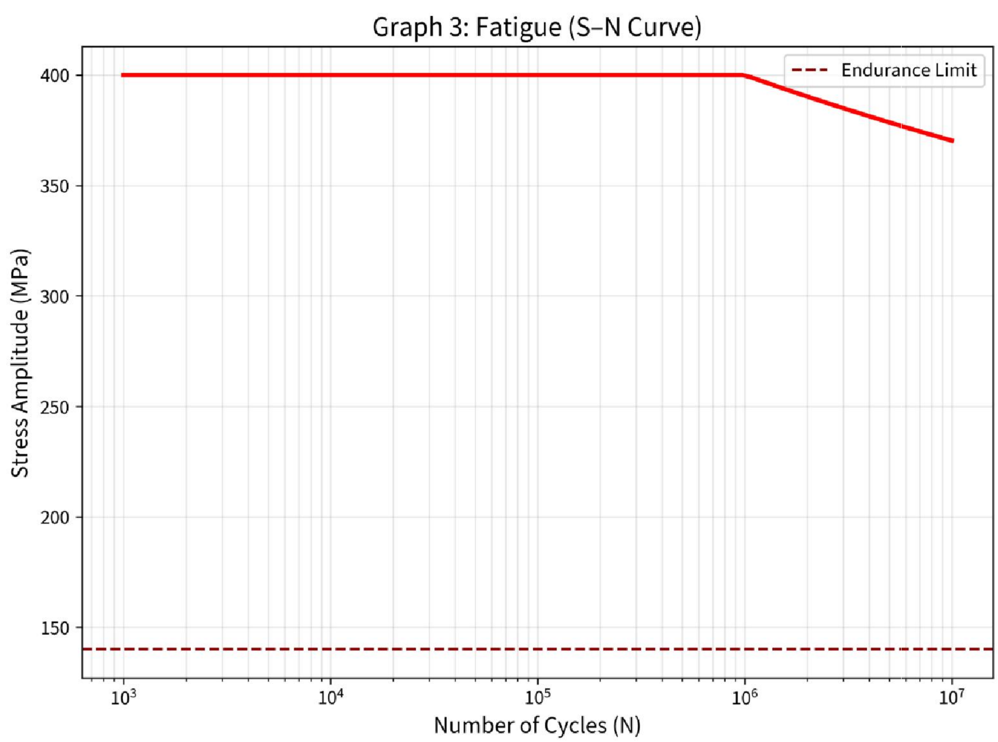


Fatigue (S-N Curve) in Graph 3

The graph illustrating the effect of stress amplitude on the number of cycles to failure is called the fatigue curve. The curve indicates that there is an exponential increase in the number of cycles to failure with a decrease in the stress level.

Interpretation

The results indicate that the material exhibits high fatigue strength, making it an appropriate choice for hydraulic components subjected to cyclic loads. The presence of an endurance limit in the case of steel implies that the component can run through several cycles without failing if the stress does not exceed a certain level.



Comparing Simulation Results with Experimental Results

There was only minor variation in the comparison between simulation results and experimental results. Simulation assumptions, measurement errors, and tolerances in manufacturing are examples of some of the factors causing such variations. However, the trend remained constant, highlighting the accuracy and reliability of the design procedure.

Table 7: Comparison of Results

Parameter	Simulation Result	Experimental Result	Deviation (%)
Maximum Stress	210 MPa	220 MPa	~4.7%
Deformation	0.25 mm	0.27 mm	~8%
Pressure Drop	1.2 MPa	1.3 MPa	~8.3%
Flow Rate	18 L/min	17.5 L/min	~2.8%

It is clear from the results that the improved hydraulic element performs better than the initial one in relation to its reliability, strength, and efficiency. Optimized design improvement in relation to pressure drop and stress concentration reduction demonstrates successful application of optimization techniques in order to achieve effective design improvement. The hydraulic element works well under real conditions meeting the requirements for its performance.The methods used in the research in order to obtain numerical data are efficient and accurate since there is only slight difference between the experimental and theoretical results. This fact shows how successful the applied design optimization and manufacturing approach is.

V. CONCLUSION

The research clearly demonstrates the effectiveness of optimizing hydraulic components' performance through such techniques. The reliable design suitable for industrial use is assured through simulation and testing.

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