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Integrated Structural and CFD Analysis for Performance Optimization of Gear Pumps

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Abstract: Gear pumps are extensively utilized across various industries, including fluid power transmission systems, automotive applications, agricultural machinery, and aerospace, owing to their durability and efficient performance. External gear pumps, in particular, are valued for their robust design, ease of manufacturing, and relatively low production cost. Ongoing research aims to enhance the performance and reliability of these pumps. The primary objective of this study is to establish a comprehensive analysis procedure to evaluate the flow characteristics and pressure performance of an external gear pump. Analytical calculations were conducted based on a flow rate of 25 liters per minute (LPM) and an operating pressure of 150 bar. Using these parameters, a detailed 3D model of the gear pump was created in Creo Parametric CAD software. This model was then employed in Computational Fluid Dynamics (CFD) simulations to analyze fluid behavior within the pump. The CFD results were compared with the analytical calculations to assess the accuracy of the proposed methodology. Additionally, Finite Element Analysis (FEA) can be performed to investigate the structural integrity of critical components, such as the shaft, gear teeth, and casing, thereby providing further validation of the analytical results.
Keywords: Gear Pump, CFD, Flow Rate, Gear

I. INTRODUCTION

The pump can be considered as the critical part of the hydraulics system. It can be said that pump is the heart of the hydraulics system, same as a heart on human body. Hydraulics pump is used to generate a flow at required pressure level and volume. As a basic hydraulic pump, Gear pump has simple structure, robust, and has ease of manufacturing. The main reason for growth of external gear pump in mining industries, agricultural sector, and engineering industries is the low manufacturing cost, compact shape, high reliability and high performance.

A. Working of Gear Pump

External gear pump consist of two rotating gears inside a closed housing. The motion of driving gear is generated by motor power, and the motion of driven gear is generated by meshing of the teeth of two gears. When the gear starts to rotate, the teeth come into contact with each other and disengage. When the teeth leave the contact area, a vacuum is generated. The liquid entering this space to fill the vacuum must be supplied through the inlet of the pump. Once filled with fluid, the fluid enters the pocket between the teeth and is trapped in place due to the sealed housing until it reaches the outlet port of the pump.

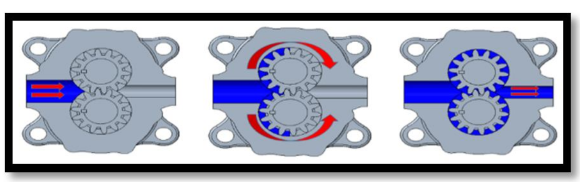

Fig 1.Working of Gear Pump

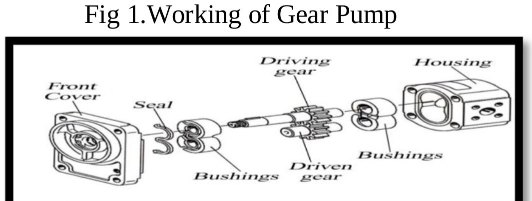

Fig 2. Exploded View of Gear Pump

B. Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) has become an integral part of modern external gear pump design. It provides valuable insights into the complex internal flow dynamics within the pump casing—phenomena that are difficult to analyze using traditional methods. By accurately simulating fluid behavior, CFD supports better-informed design decisions and significantly reduces the development cycle. As a result, it has become a widely adopted tool across the turbomachinery industry. Today, CFD is recognized as a powerful engineering resource that not only enhances design accuracy but also improves overall process efficiency and product performance.

Over the past 25 years, CFD has been increasingly used in various engineering applications. In the beginning, the use of these technologies was just a practice in the aviation and nuclear fields. Subsequently, this use has been extended to various products, physical conditions and manufacturing processes. Experimental and theoretical studies take a long time. In experiments, the actual physical model of the prototype actually needs to be manufactured, which is expensive. Due to this reason CFD analysis can also be carried out on the prototype. The CFD tool avoids every physical modelling and testing. Better and faster pump design and analysis can shorten the design cycle.

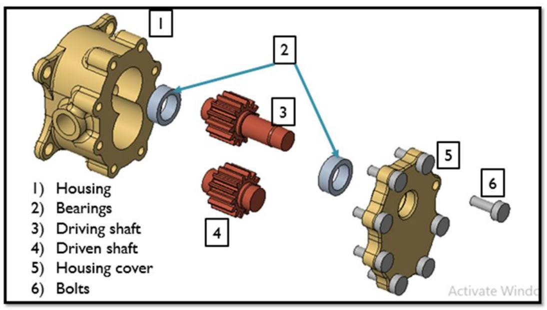

Fig 3. Creo 3D Model

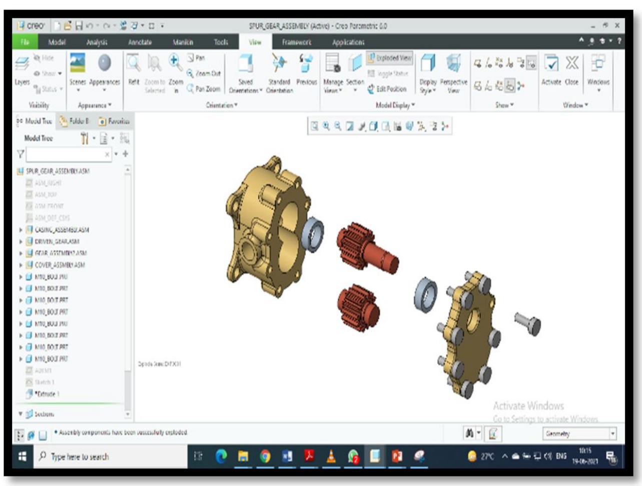

Fig 4. Exploded View of Designed Gear Pump

Creo Parametric is used as CAD tool for the preparation of Gear Pump 3D model. Here the modelling of Gear, shaft, Housing and Housing cover were done. Using the analytical calculation the CAD models were prepared and was assembled to prepare CAD model of Gear Pump.

II. COMPUTATIONAL FLUID DYNAMICS SIMULATION

The purpose of this analysis is to check the flow characteristics of Gear pump at 10 bar back pressure. Also, to validate the Analytical calculations for the performance of Gear pump (w.r.t Outlet Flowrate).

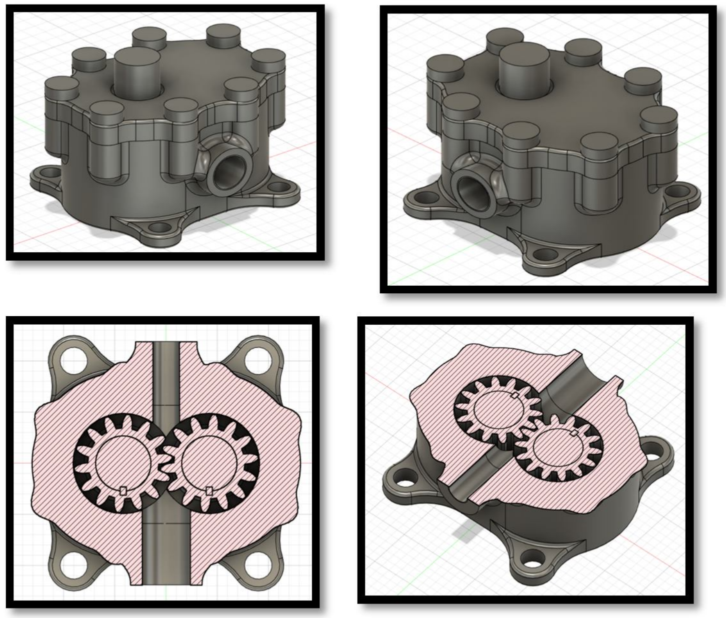

Fig 5. Gear Pump IGES imported in CFD tool

Once the CAD model is prepared it is then converted to IGES or Step format. This file then used as an input file for CFD analysis in the Autodesk CFD tool. Fig. 5 shows the solid domain imported in CFD tool.

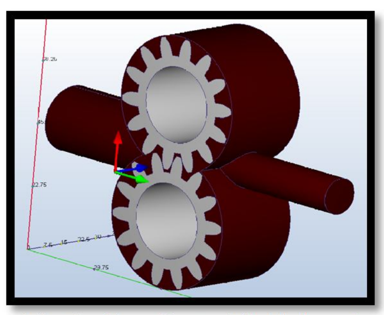

Fig 6. Gear Pump Fluid domain

Complete fluid domain is shown in the above fig 8. The brown area is the fluid inside the gear pump. This fluid domain will be used for CFD analysis.

A. Fluid Properties

Table 1. Fluid Properties

Properties	SAE Hydraulic Oil ISO VG 100
Density (kg/m3)	869
Viscosity (Pa-s)	Piecewise Linear
Conductivity (W/mK)	0.145
Specific Heat (J/g-K)	Piecewise Linear
Compressibility (MPa)	1380.19
Emissivity	1
Wall Roughness (mm)	0
Phase (Pa)	0.05

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SAE Hydraulic Oil ISO VG 100 (Viscosity Graph)	
Viscosity (Pa-s)	Temperature (Celsius)
8.08018	-45.5556
5.19353	-34.4444
3.33814	-23.3333
2.67624	-17.7778
2.14559	-12.2222
1.72015	-6.66667
1.37908	-1.11111
1.10563	4.44444
0.886399	10
0.710645	15.5556
0.570018	21.1111
0.456842	26.6667
0.36644	32.2222
0.29329	37.7778
0.188396	48.8889
0.0973033	65.5556
0.0322274	93.3333
0.00353328	148.889
0.000387833	204.444
4.25E-05	260

Table 2. Viscosity graph for fluid

SAE Hydraulic Oil ISO VG 100 (Specific Heat)	
Specific Heat (J/g-K)	Temperature (oC)
1.8	0
1.88	20
1.964	40
2.047	60
2.219	100
2.483	160

Table 3. Specific heat for Fluid

B. *Boundary Conditions*

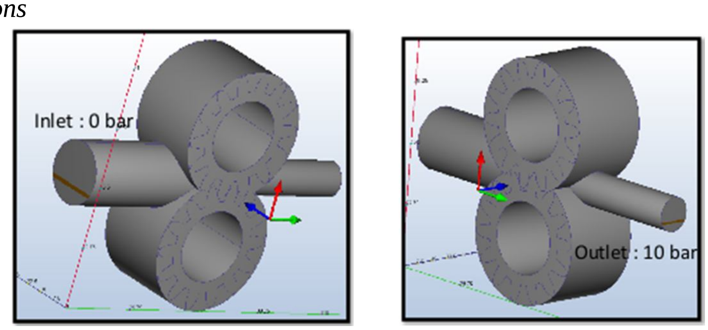

Fig. 7. I – Inlet condition II- Outlet condition

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For CFD analysis the boundary condition are given as constrains to the tool as shown in fig 9 I and II. Inlet pressure was considered as 0 bar and outlet pressure was considered as 10 bar respectively. Angular speed for the gear pump was taken as 1440 rpm and direction for rotation of gear is shown in fig 10.

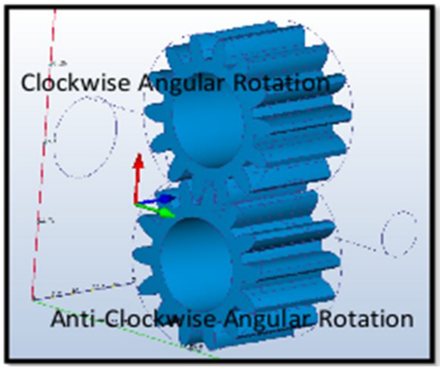

Fig 8 – Angular speed of gear pump.

C. FVM Model of Gear Pump

The Finite Volume Method (FVM) is a numerical approach used to convert partial differential equations into algebraic equations for analysis and solution. It can be readily adapted for use with unstructured meshes and is widely implemented in CFD software. The finite volume approach involves control volumes that enclose each mesh node.

Given below are details used while creating the FVM model for designed Gear Pump:

Mesh Factor: 1

Number of Nodes: 24894

Number of Elements: 109878

Maximum Wall Distance: 12.08 mm

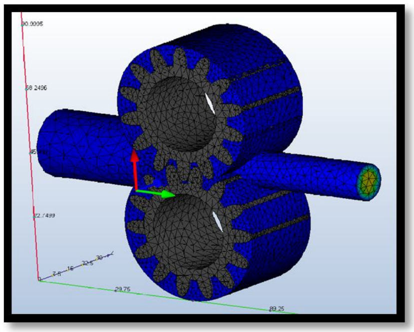

Fig 9 – FVM Model.

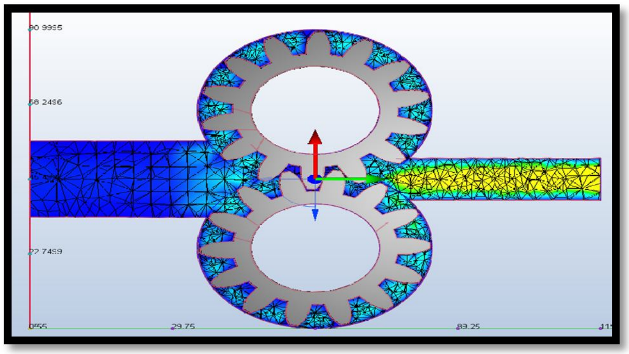

Fig 10– FVM model in 2D

III. GEAR PUMP CFD RESULT

As per the required values and the designed gear pump, given below are the results after the CFD simulation in Autodesk CFD tool.

Inlet Pressure: 0.00019 bar

Inlet Flowrate: 11.85 lpm

Outlet Pressure: 10 bar

Outlet Flowrate: 25.47 lpm

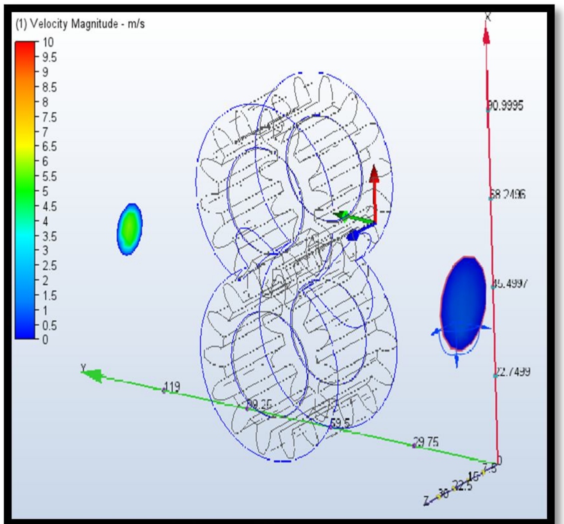

Fig 11 – Inlet and outlet port condition

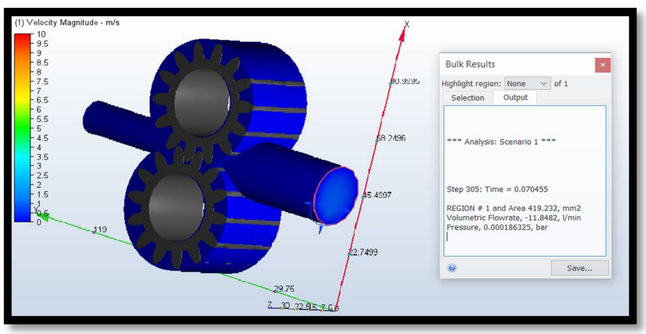

Fig 12 – Inlet pressure and flow rate

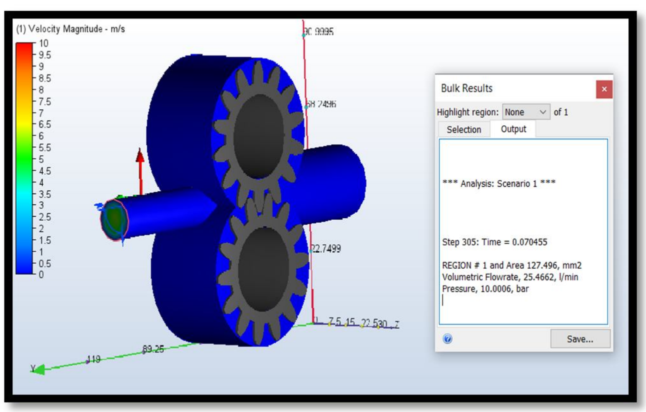

Fig 13 – Outlet pressure and flow rate

Velocity at Inlet and Outlet Ports

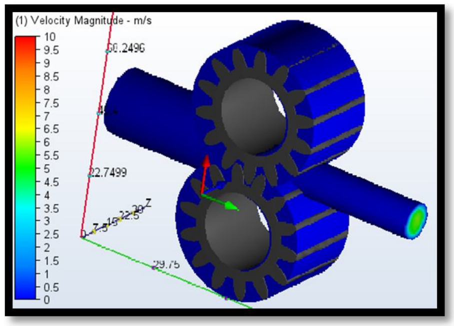

Fig 14 – Gear Pump Velocity Contour

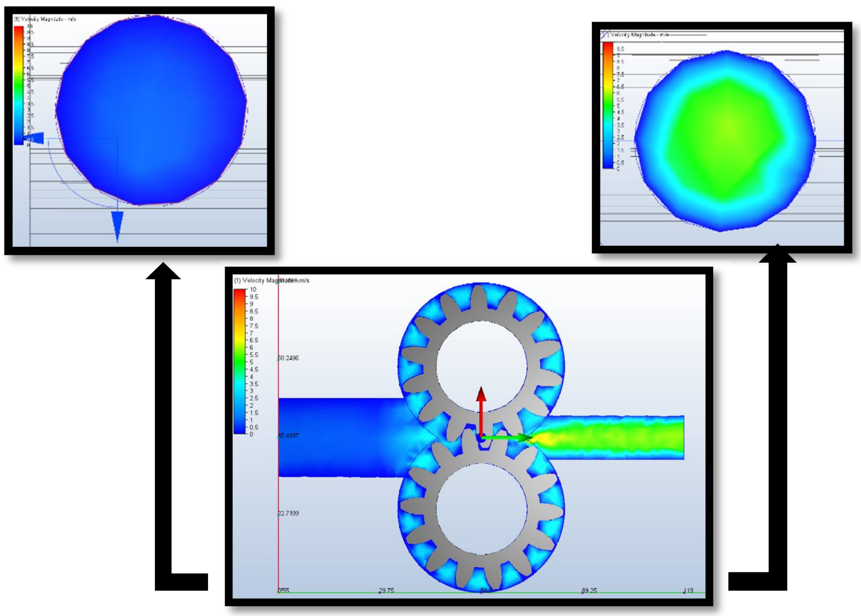

Fig 15 – Inlet and Outlet Port

VELOCITY		
	INLET	OUTLET
Area	419.2 mm^2	127.5 mm^2
Flow Rate	11.85 lpm	25.47 lpm
Velocity	0.47 m/s	3.3 m/s

Table 4. Inlet and Outlet Port Results

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Statics Pressure at Inlet and Outlet

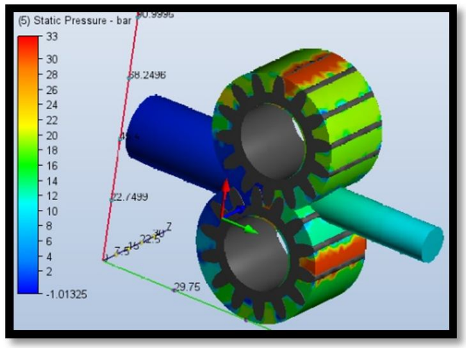

Fig 16 – Gear Pump Static Pressure Contour

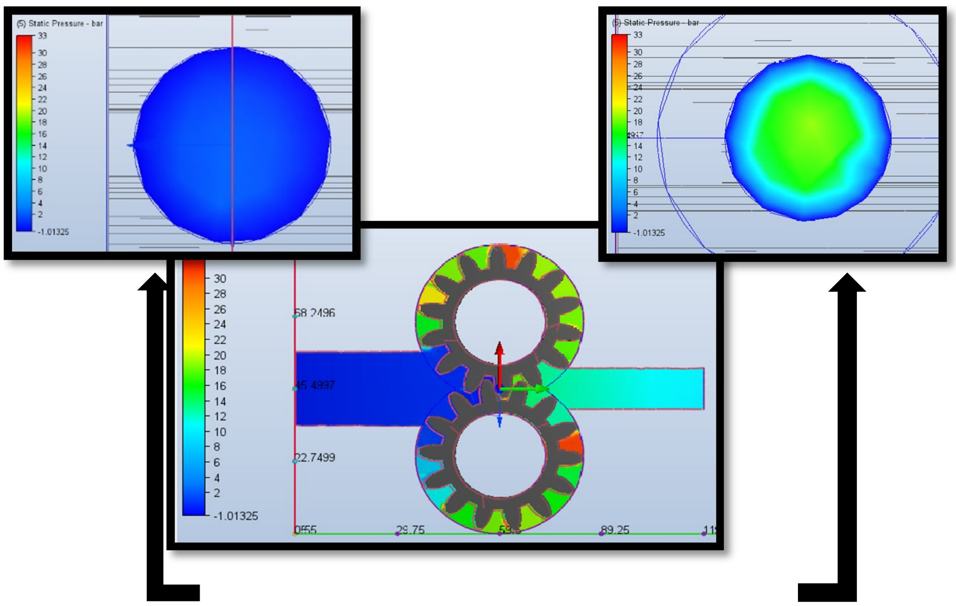

Fig 17 – Inlet and Outlet Port

STATIC PRESSURE		
	INLET	OUTLET
Pressure	0.00019 bar	10 bar

Table 4. Inlet and Outlet Port Results

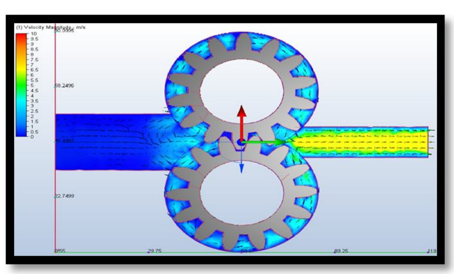

Fig 18 – Velocity Vector Plot

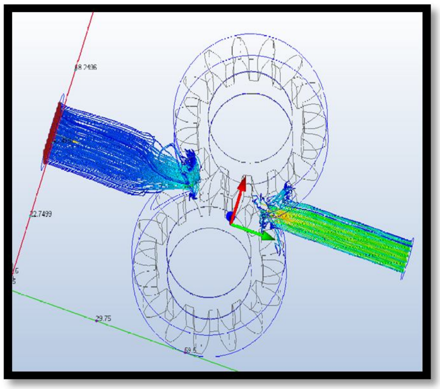

Fig. 19 Streamline Flow Contour

Material Properties

Shaft and Gear Material – 40Ni2Cr1Mo28	
Density	7.85 g/cc
Hardness	321
Tensile strength, ultimate	1175 MPa
Tensile strength, yield	880 MPa
Modulus of Elasticity	205 GPa
Poison’s Ration	0.29

Casing Material - GCI 25	
Density	7.20 g/cc
Hardness	120-550
Tensile strength, ultimate	310MPa
Tensile strength, yield	265MPa
Modulus of Elasticity	128 Gpa
Poison’s Ration	0.26

IV. CONCLUSION

The integration of the steering pump and hydraulic steering gear is a significant development in the automotive industry, offering a range of technical and operational benefits. In hydraulic systems, particularly in automotive power steering mechanisms, the steering gear pump plays a crucial role in ensuring that the hydraulic fluid moves with adequate pressure and flow to assist with steering movements. The data provided for the pump's inlet and outlet areas, flow rates, and velocities allows us to analyse the performance of the steering gear pump and its impact on system efficiency. This report evaluates these parameters, discusses their implications, and suggests areas for system improvement.

Important performance metrics in hydraulic systems consist of flow rate, velocity, and the cross-sectional area of the pipes that carry the fluid.. These factors directly impact the efficiency, responsiveness, and longevity of the pump and the overall system. In this analysis, we focus on how the system operates, based on the given flow rate, velocity, and area data at the pump's inlet and outlet.

Data Overview and Observations

The steering gear pump operates based on the principle of converting mechanical energy into hydraulic energy, where the fluid is pumped through the system to assist steering. The data provided shows:

Inlet:
Area: 419.2 mm²
Flow Rate: 11.85 LPM (liters per minute)
Velocity: 0.47 m/s

Outlet:
Area: 127.5 mm²
Flow Rate: 25.47 LPM
Velocity: 3.3 m/s

This data indicates a notable rise in both the flow rate and velocity from the inlet to the outlet, which is a key characteristic of a well-designed pump that accelerates the fluid through a smaller outlet, typically to ensure quicker and more responsive fluid movement for the steering mechanism.

V. FUTURE SCOPE

Integration of Steering Pump and Hydraulic Steering Gear As automotive technology continues to evolve, the integration of the steering pump and hydraulic steering gear is set to undergo significant advancements. The future of these systems will see developments driven by electrification, autonomy, sustainability, and improved user experiences. Below is a detailed exploration of the areas where future advancements in steering pump and hydraulic steering gear integration are likely to occur.

A. Electrification of Steering Systems

The move toward electric and hybrid vehicles is reshaping the landscape of automotive design, particularly in steering technologies. Traditionally, steering systems rely on hydraulic pumps that are driven by the engine, consuming power and affecting fuel efficiency. Future steering systems will focus on the full electrification of steering pumps, making them entirely independent of the engine and allowing for a direct connection between the motor and the steering system.

B. Electric Power Steering (EPS)

Electric steering pumps, already present in many modern vehicles, will evolve to become even more efficient, with increased precision and responsiveness. This eliminates the need for hydraulic fluids, resulting in a reduction in maintenance and environmental impact. The integration of electronic components will also allow for better customization of steering response based on driving conditions and vehicle requirements.

C. Brushless Motors

The future of EPS will likely incorporate brushless motors, which are more efficient and durable than traditional motors. These motors will allow the steering pump to be more compact, with reduced energy consumption and increased longevity, making them well-suited for electric vehicles that require minimal power loss.

D. Vehicle-Level Integration

Full integration with the vehicle’s overall powertrain management system will optimize the steering system’s performance. For instance, the steering system could adjust based on the battery state of charge, energy recovery during braking, or driving modes like eco or sport.

E. Improved Efficiency and Reduced Power Consumption

The drive for more fuel-efficient and environmentally friendly vehicles will push the need for highly efficient steering systems. The integration of advanced materials, innovative fluid dynamics, and improved design will enhance the energy efficiency of both hydraulic and electric steering pumps.

- Hydraulic Efficiency: Future hydraulic systems will incorporate pumps that are smaller, lighter, and more efficient. New materials, such as advanced polymers or lightweight metals, will reduce the weight of the pump without sacrificing performance. Additionally, the hydraulic fluid itself may be improved for better flow dynamics, reducing friction and power loss.
- Variable Displacement Pumps: These pumps can adjust the flow of fluid based on steering demand, reducing energy consumption when steering effort is low. By automatically modulating the pump's output, variable displacement pumps will ensure that the system only uses the energy necessary for steering, improving overall efficiency.
- Integrated Heat Management: As electric vehicles (EVs) require optimized thermal management, steering pumps and hydraulic systems will integrate heat exchange mechanisms to maintain optimal operating temperatures. This will further boost the efficiency of the system by preventing overheating, which can reduce power efficiency.

F. Active and Adaptive Steering Systems

As the automotive industry pushes toward more advanced driving technologies, steering systems will evolve to become more adaptive and capable of providing an optimized driving experience.

Active steering systems will rely on sophisticated algorithms to adjust the steering characteristics in real-time, offering a more intuitive driving experience.

- Steering Feedback Adjustment: In the future, the steering system will be capable of dynamically adjusting the feedback, responsiveness, and torque based on real-time data about road conditions, vehicle speed, and driving behaviour. For example, when driving at high speeds, the system could offer more resistance, enhancing stability and reducing the risk of oversteering. Conversely, during low-speed manoeuvres, such as parking, the system would provide lighter steering for ease of use.
- Autonomous Driving Integration: For fully autonomous vehicles, steering systems will be fully integrated with the vehicle's self-driving technology. Hydraulic and electric pumps could become more versatile, allowing for completely hands-off driving with minimal effort required from the driver, thus increasing vehicle manoeuvrability in tight spaces or during emergency situations.
- Real-Time Adjustments: Future systems may adjust in real time to match changes in driving conditions, such as road quality, slope, and vehicle load. For example, when driving on rough roads or uneven terrain, the steering system could increase steering assistance, while on smooth highways, it could reduce assistance to allow for a more stable, controlled ride.

G. Integration with Advanced Driver Assistance Systems (ADAS)

Advanced Driver Assistance Systems (ADAS) are increasingly common in modern vehicles, and future steering systems will need to integrate smoothly with these technologies to improve safety and driving comfort.

- Lane Keeping Assist (LKA): Steering systems will become tightly integrated with LKA and lane-centering technologies. Hydraulic and electric steering pumps will respond to steering corrections made by these systems, providing active adjustments when the vehicle is drifting from its lane or needs steering intervention.
- Automatic Parking: With the growing prevalence of automated parking features, steering pumps and hydraulic systems will play a crucial role in enabling precise steering during parking maneuvers. Future systems will provide quicker, more precise steering adjustments to make parking in tight spaces easier and more accurate.
- Collision Avoidance: Steering systems could become more sophisticated in avoiding obstacles by providing automated steering inputs based on data from the vehicle's radar, cameras, and sensors. This could involve automatic steering assistance to avoid obstacles or assist in emergency braking.
- Enhanced Safety Protocols: In addition to providing safety features like lane-keeping and automatic parking, the steering system will become more reactive in emergencies. For example, the steering system might automatically adjust during a collision or prevent oversteering in hazardous weather conditions.

H. Weight Reduction

A significant focus in the automotive industry is reducing vehicle weight to improve efficiency, especially for electric vehicles where every kilogram counts towards range. Steering pumps and hydraulic steering gears are prime candidates for miniaturization and weight reduction.

Lightweight Materials: The future of steering components will rely on lightweight materials such as carbon fiber or aluminum alloys, which can reduce the overall weight of the steering pump and hydraulic gear. These materials will also improve durability and resist corrosion, which is essential for systems exposed to high-pressure environments.

Compact Design: The design of the steering pump and hydraulic gear will become more compact. With the help of innovative pump configurations and more efficient hydraulic circuits, future systems will take up less space, providing manufacturers with more room to incorporate other essential vehicle components.

Space Efficiency: Reducing the size of hydraulic steering systems can also result in more flexible vehicle designs. This can be particularly beneficial for electric vehicles, where space optimization is key for battery placement and maximizing interior space.

I. Self-Diagnosis and Predictive Maintenance

As automotive technologies advance, the integration of smart technologies into steering systems will enable real-time monitoring and self-diagnosis capabilities. Predictive maintenance could prevent costly breakdowns and enhance vehicle reliability.

- Sensors and Diagnostics: Future steering systems will likely incorporate a network of sensors that monitor critical parameters like fluid pressure, temperature, and pump performance. These sensors will relay data to Onboard diagnostic systems are capable of notifying drivers about potential issues early, helping to improve vehicle uptime and reduce maintenance costs.
- AI-Driven Predictive Maintenance: Machine learning algorithms could predict when certain components of the steering system are likely to fail or require maintenance based on historical data and real-time performance metrics. By analysing usage patterns, the system could notify the driver or fleet operators when it’s time for maintenance, thus reducing downtime and preventing unexpected failures.
- Remote Diagnostics: Manufacturers may offer remote diagnostics for steering systems, allowing technicians to access performance data remotely and recommend necessary service or software updates. This could make maintenance faster, more accurate, and less disruptive.

J. Sustainability and Environmental Impact

As the automotive industry faces growing pressure to reduce its environmental footprint, steering systems will need to evolve in a way that minimizes their impact on both the environment and the vehicle’s overall energy consumption.

- Recyclable Materials: The future of steering components will include an emphasis on using recyclable or biodegradable materials. By reducing the use of non-recyclable fluids and materials, manufacturers can make hydraulic steering systems more eco-friendly. Similarly, electric power steering pumps will need to use environmentally friendly materials and reduce the amount of rare-earth materials used in motors.
- Energy Recovery: As electric vehicles move towards more energy-efficient systems, the integration of energy recovery technologies into the steering system could help harvest energy during steering adjustments. This recovered energy could be used to power other vehicle systems or recharge the battery, contributing to overall energy efficiency.
- Zero-Emission Fluids: For hydraulic systems, future steering pumps may use zero-emission or biodegradable hydraulic fluids, which would significantly reduce their environmental impact if leaks or spills occur.

K. Customization and Adaptive User Experience

Future steering systems will provide a highly personalized driving experience, allowing drivers to customize the steering feel based on their preferences and driving conditions.

- Customizable Steering Sensitivity: Drivers will be able to adjust the steering response, sensitivity, and feel based on their personal preferences or driving mode. For example, in a sport mode, the system may provide more direct feedback and firmer resistance, while in comfort mode, it would be lighter and more responsive.
- Feedback-Based Adjustments: The system could adjust steering resistance in response to environmental factors, such as wind conditions or road irregularities, providing a more comfortable and stable driving experience.

- Haptic Feedback: For improved road feel and vehicle control, steering systems could incorporate advanced haptic feedback, allowing drivers to sense road conditions or potential hazards through vibrations in the steering wheel.

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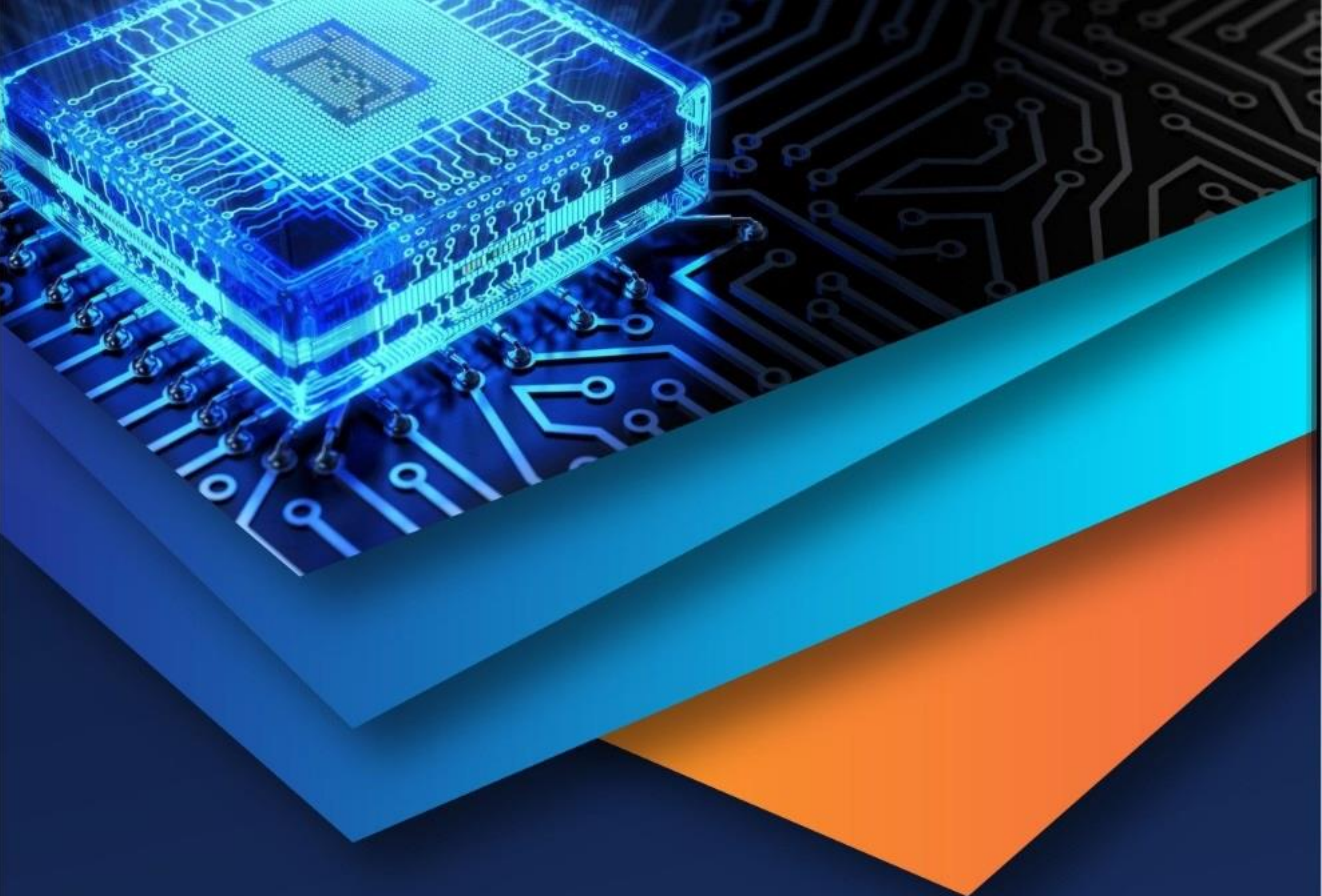

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