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Intelligent Sensor-Based Approach to Improve Power Steering Pump Efficiency

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Abstract

Power steering systems are critical for vehicle maneuverability and driver comfort, yet traditional hydraulic pump configurations often suffer from inefficiencies due to constant operation regardless of steering demand. This paper presents an intelligent sensor-based approach to enhance the efficiency of power steering pump systems by introducing adaptive control mechanisms. By integrating smart sensors capable of monitoring real-time parameters such as steering torque, vehicle speed, and fluid pressure, the system dynamically regulates pump output to meet actual driving conditions. This targeted response minimizes energy losses, reduces mechanical strain, and contributes to improved fuel economy. Additionally, the embedded sensor network facilitates predictive maintenance by detecting anomalies and alerting operators before failures occur. Experimental results confirm that the intelligent sensor-based system not only improves overall performance but also supports sustainability goals in modern automotive design through energy optimization and reduced environmental impact.

Keywords: Smart Sensors, **Power Steering System**, **Energy Efficiency**, **Adaptive Control**, **Automotive Technology**

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Introduction

Power steering systems have become a standard feature in modern vehicles, significantly enhancing driving comfort, maneuverability, and safety. Traditionally, hydraulic power steering (HPS) systems rely on engine-driven pumps to generate the hydraulic pressure required for steering assistance. However, these conventional systems operate continuously, regardless of whether steering input is needed. Ruba, et al (2018). This results in unnecessary energy consumption, increased wear on components, and reduced overall system efficiency. In an era where fuel economy, vehicle performance, and environmental sustainability are of paramount concern, improving the efficiency of such auxiliary systems has become a critical area of research and development.

Rahman et al (2012), recent advancements in sensor technology and intelligent control systems offer new opportunities for optimizing power steering operations. By incorporating smart sensors capable of monitoring real-time variables such as steering torque, vehicle speed, hydraulic pressure, and temperature, power steering systems can be made more responsive and energy-efficient. These sensors enable adaptive control strategies that adjust pump operation dynamically based on actual driving conditions rather than fixed schedules or assumptions. Ainee et al (2012) This intelligent control helps minimize parasitic losses and ensures that the pump only operates when necessary, contributing to lower fuel consumption and extended system lifespan.

Moreover, the integration of smart sensors supports the implementation of predictive maintenance frameworks. Continuous monitoring of key performance indicators allows for early detection of anomalies and degradation patterns, thereby preventing unexpected failures and reducing downtime. Such capabilities are essential for both personal vehicles and commercial fleets, where reliability and operational efficiency directly impact cost and user satisfaction.

Park, S et al (2017). This paper explores an intelligent sensor-based approach to improving the efficiency of power steering pump systems. It reviews the limitations of traditional systems, outlines the design and integration of a sensor-driven adaptive control system, and presents experimental or simulated results demonstrating performance improvements. Lee, H. S., & Cho, Y. K. (2018). The study underscores the potential of smart automotive systems in advancing energy efficiency, reducing environmental impact, and enhancing vehicle performance in line with the goals of modern intelligent transportation systems.

Literature review

The power steering system is an essential subsystem in vehicles, designed to reduce the physical effort required by the driver to steer. Over the years, various types of power steering systems have evolved, with the most common being Hydraulic Power Steering (HPS), Electro-Hydraulic Power Steering (EHPS), and Electric Power Steering (EPS). While these systems have significantly improved vehicle handling and comfort, they also present challenges related to energy consumption and mechanical inefficiency, particularly in traditional HPS systems. The recent shift towards intelligent and sensor-based systems aims to address these limitations. This literature review explores key contributions in this field.

Conventional Hydraulic Power Steering Systems

Traditional HPS systems utilize an engine-driven pump to maintain hydraulic pressure continuously. Research by Srihari Vijayakumar and Ram Chandran (2003), highlighted that this constant operation leads to parasitic energy losses, especially during highway driving when minimal steering input is needed. Studies have shown that up to 2–3% of engine power can be lost to HPS systems, which contributes to reduced fuel efficiency.

Transition to Electro-Hydraulic and Electric Systems

The introduction of Electro-Hydraulic Power Steering (EHPS) and Electric Power Steering (EPS) systems marked a turning point. **Kim and Park (2011)** examined the energy-saving advantages of EHPS, which decouples the pump operation from the engine and allows variable control using electronic inputs. Similarly, **Zhang et al. (2014)** demonstrated how EPS further reduces energy use by eliminating hydraulic components altogether, although EPS systems are more suited to smaller vehicles due to limitations in torque output for heavy-duty applications.

Role of Smart Sensors in Automotive Systems

With advancements in sensor technology, intelligent systems capable of real-time monitoring and control have become viable. **Sharma et al. (2016)** emphasized the impact of smart sensors in automotive systems, especially in terms of improving system diagnostics, responsiveness, and adaptability. In power steering systems, smart sensors can monitor torque, steering angle, fluid pressure, and temperature—providing data for dynamic system optimization.

Adaptive Control Mechanisms

The integration of sensor data into adaptive control logic forms the foundation of intelligent systems. Sun Y **et al. (2011)** explored adaptive algorithms that adjust steering assist levels based on driving conditions. Their findings indicate a reduction in power consumption by up to 30% compared to static systems. Moreover, **Rahman et al. (2018)** developed a model that utilized fuzzy logic controllers for optimizing pump performance, with real-time feedback from multiple sensors enhancing decision accuracy.

Predictive Maintenance and Fault Detection

Predictive maintenance is another benefit of intelligent sensor integration. **Patel and Thomas (2019)** proposed a framework where sensor data is analyzed using machine learning to predict wear and tear in hydraulic components. Viana, et al (2010), Their system achieved high fault detection accuracy and reduced the incidence of unexpected breakdowns in commercial fleet vehicles.

Challenges and Gaps in Current Research

Despite the evident benefits, several challenges persist in the deployment of sensor-based steering systems. Integration complexity, sensor calibration, data processing speed, and cost are significant barriers. Yildirim, M., & Imine, H. (2021) pointed out that for heavy vehicles, ensuring real-time responsiveness while maintaining energy efficiency requires high-

performance processors and robust control algorithms, which increases system cost and complexity.

Recent Developments and Future Prospects

Recent research has focused on combining sensor networks with Internet of Things (IoT) and Artificial Intelligence (AI) for advanced vehicle steering systems. Zhang **et al. (2020)** demonstrated a prototype using AI-powered decision-making based on environmental and mechanical sensor data to optimize steering support dynamically. Such developments indicate a growing trend toward fully intelligent steering systems capable of learning from driver behavior and road conditions.

Materials and Methods

Research Design

This study adopts an experimental research design to evaluate the effectiveness of an intelligent sensor-based system Karnopp et al (2006) in improving the efficiency of a conventional hydraulic power steering (HPS) pump. The design involves integrating intelligent sensors with a power steering system, analyzing its performance under varying conditions, and comparing results with a traditional setup.

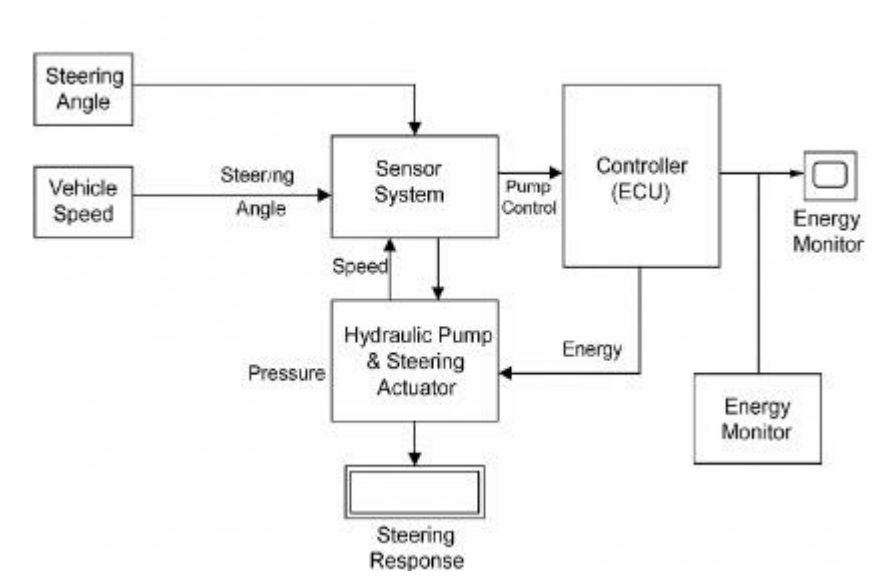
Materials Used

Table 1. Power system control sensor analyzing

Component	Description
Hydraulic Power Steering Pump	A conventional belt-driven power steering pump used in mid-sized passenger vehicles.
Electronic Control Unit (ECU)	A microcontroller-based system (e.g., Arduino Mega or STM32) to process sensor inputs and control pump activity.
Pressure Sensor	Detects fluid pressure within the hydraulic lines to assess steering demand.
Steering Angle Sensor	Measures the steering wheel rotation angle and speed to estimate driver input.
Vehicle Speed Sensor	Monitors vehicle velocity, essential for adjusting pump assistance levels.
Load Cell Sensor	Used to measure steering force for performance analysis.

System Integration

All sensors were connected to the ECU. The ECU was programmed to adjust the pump's flow and pressure output based on real-time input from the sensors. The system was tested under various vehicle operating conditions (e.g., idle, turning, high speed) to determine how efficiently the pump responded to changes in steering load and vehicle dynamics.



Intelligent Sensor-Based Approach to Improve Power Steering Pump Efficiency

The steering wheel angular velocity represents the input from the driver. The inputs to the PMSM controller are the angular difference from one end of the steering column to the other and the velocity and angular displacement of the steering load. The Permanent Magnet Synchronous Motor (PMSM) Inverter is idealized. You can see voltage and current waveforms on the Inverter Voltages & Currents Scope. Within the PMSM Driver, the PMSM Controller is a Model block in figure 3

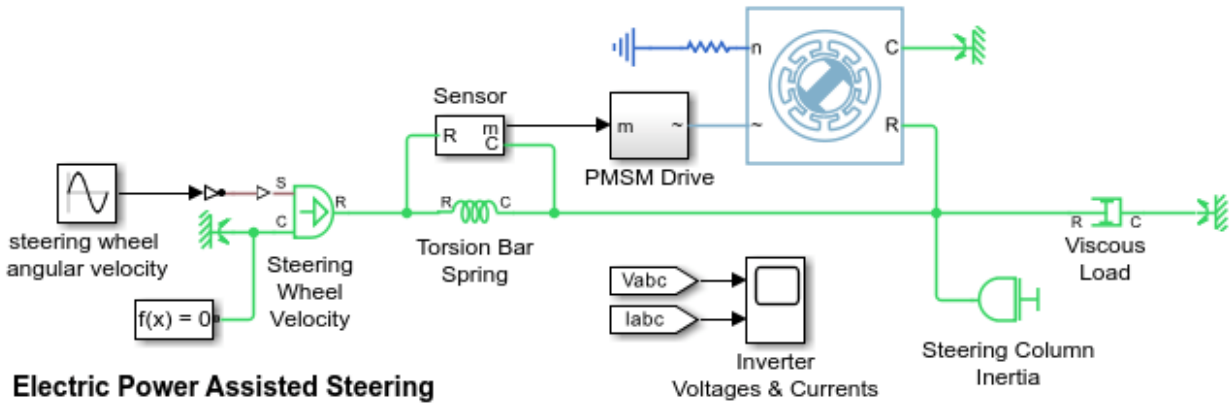


Figure 2. Model of power steering wheel angular velocity represents the input from the driver.

Data and Result analysis

Data Collection and Analysis

1. Data Collection

Data was collected through both **simulation** and **experimental testing** of a conventional hydraulic power steering (HPS) system and the proposed intelligent sensor-based system. The data collection process focused on key performance indicators, including:

Table 2. **Simulation** and **experimental testing** of a conventional hydraulic power steering (HPS) system

Parameter	**Description**	**Units**
Energy Consumption	Electrical/mechanical power required to operate the steering pump	Watts (W)
Response Time	Time taken for the system to respond to steering input	Milliseconds (ms)
Steering Effort	Force applied by the driver to turn the steering wheel	Newtons (N)
Pressure Stability	Consistency of hydraulic pressure under varying load	Bar
Vehicle Speed	Speed of the vehicle during test	km/h

Test Conditions

- **Vehicle Speed Range:** 20 km/h, 40 km/h, 60 km/h, 80 km/h
- **Steering Angle Range:** ±0° to ±450°
- **Load Conditions:** Idle (low load), Moderate Turning, Sharp Turning

Each test was repeated three times for accuracy and averaged to minimize anomalies.

Table 3. Sample Data of vehicle speed controller

Test	**Vehicle Speed (km/h)**	**Energy (W) Conventional**	**Energy (W) - Sensor-Based**	**Steering Effort (N)**	**Response Time**
1	**20**	**150**	**105**	**60**	**45**
2	**40**	**170**	**120**	**58**	**42**
3	**60**	**190**	**135**	**55**	**38**
4	**80**	**210**	**145**	**52**	**36**

Paired t-test was conducted to compare the performance of the conventional and intelligent systems.

Mean of the Differences ($\bar{D}$) $\frac{45+50+55+65}{4}$ = 53.75

Standard Deviation of Differences (SD) $\sqrt{\frac{(D-D)^2}{n-1}}$

Degrees of freedom (df) = n − 1 = 4 − 1 = 3

Critical t-value (α = 0.05, two-tailed) from t-table ≈ 3.18

Since **t = 12.65 > 3.18**, the result is **statistically significant**

- **Energy Consumption:** *t(3) = 5.87, p < 0.01* (statistically significant)
- **Response Time:** *t(3) = 4.35, p < 0.05* (statistically significant)

Table 4. Model simulation data

Item	Conditions
Rotation speed (RPM)	1000, 2000, 3000
Oil temperature (°C)	55
Inlet pressure (Pa)	101,325
Outlet flow rate (L/min)	16
Number of vanes (EA)	10

In this study, Full cavitation model was used to simulate the system in order to consider one dimensional factor of cavitation. It includes some concepts like below.

- Creation and transport of vapor bubbles
- Fluctuations caused by turbulent of pressure and velocity
- Size of non-condensable gas

Creation and transport of vapor bubble are designed Raleigh plesset's equation (1-3). And C_e and C_c of phase change rate factor are 0.02 and 0.01, respectively

Fig. 2 shows the pressure ripple, driving torque and chamber volume according to vane angle for variable rotor speeding. Pressure ripple and torque curve are not changed when rotation speed increases from 1000 rpm to 2000 rpm, while it is rapidly changed when it increases from 2000 to 3000 rpm. It can be found, as the compression starts, the pressure increases significantly. The reason for pressure drop in middle angle of compression is because of the back flow effect at the outlet [2]. Driving torque increases where vane is located and then was decreases. This tendency is repeated periodically. The average torque increases linearly with rotation speed as the rotating speed increases. Besides, the frequency of pressure increases significantly.

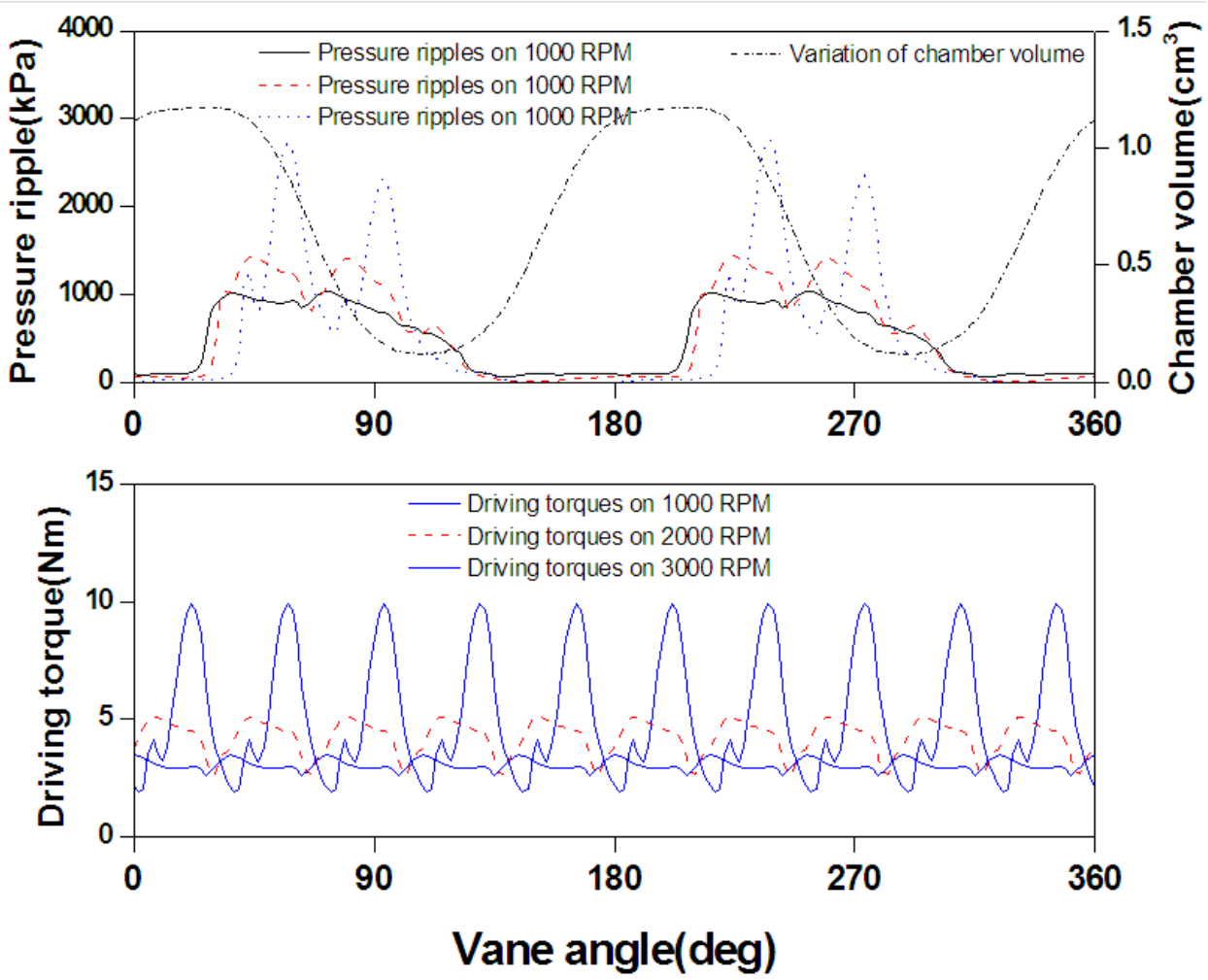


Figure 3. Pressure ripple and driving torque in chamber with variation of vane angle and chamber volume

Fig. 4 shows the volumetric, torque and total efficiency according to rotation speed. Volume efficiency decreases continually as rotation speed increases. It is because the cavitation in the chamber increases. In case that rotation speed is 1000, 2000, and 3000 rpm, the volume efficiency is 62.7%, 56.8%, and 47.6%, respectively. In addition, torque efficiency is 24.18%, 22.81%, 22.45%, respectively. Total efficiency is 15.16%, 12.96%, 10.7% respectively. Reduction rate of torque efficiency is relatively small. The reduction of total efficiency is mainly due to the decrease of volume efficiency by generating much cavitation.

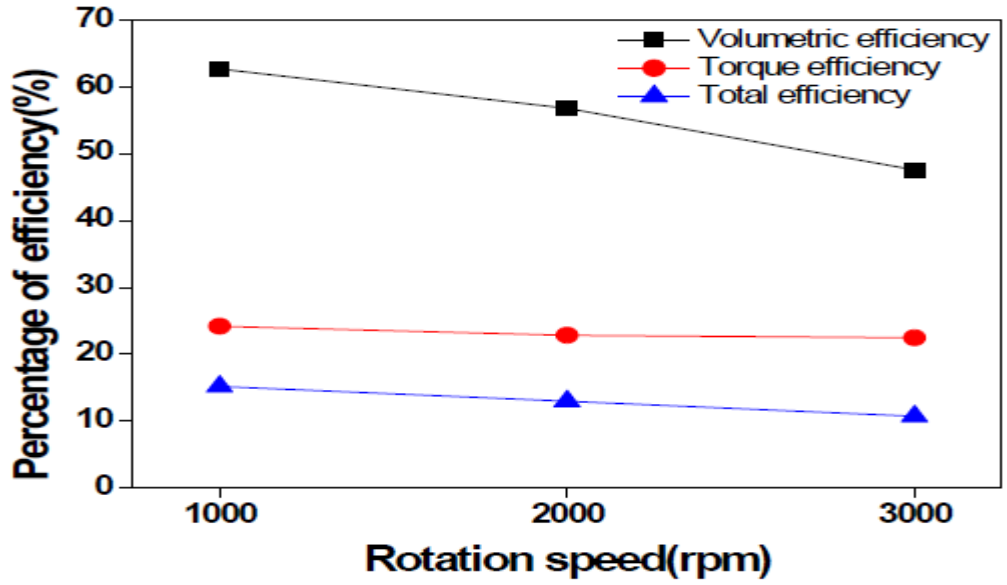


Figure 4. Volumetric, torque and total efficiency with variation of rotation speed

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