

Fuel-Efficient and Low-Noise Steering Systems in Large and Heavy Vehicles using Variable Displacement Pump Technology

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ABSTRACT

A variable displacement pump (VDP) is a fuel-efficient and cost-effective technology that has been applied to steering systems in small- and medium-sized vehicles. However, it is a challenge to apply this technology to large and heavy vehicles due to marketability concerns. This study tested VDP technology in a large light truck and strived to achieve a well-balanced and high-performance steering system with regard to noise, fuel economy, and dynamic performance. Steering noise was analyzed in terms of both the source noise characteristics of the VDP and the noise attenuation characteristics of the steering system. Significant noise reduction was achieved by redesigning the VDP in its number of vanes, structure stiffness, internal component clearances, and rotor position with improved flow ripple characteristics; and by optimizing the steering system's attenuation characteristics using a design of hose-tuning cable devices with optimal pulsation transmission loss characteristics. To ensure gains in fuel economy, a new design specification was developed to control the pump's power consumption by limiting the input torque at various pump speeds. Steering dynamic performance and feel were improved by enhancing the pump's design to provide an adequate flow rate under high pressures while maintaining flow rate and torque characteristics under low pressures. As a result of the study, VDP technology was successfully applied to 2011 model year Odyssey.

1. Introduction

The automotive industry continues to face a number of business environment challenges, including a weakened global economy and severe energy crises. For automotive manufacturers and their customers, the demand for cost-effective technologies to improve fuel economy continues to increase. Electric power steering (EPS) technology is a fuel efficient steering technology that is increasingly used in small- and medium-sized vehicles; however, its high cost and capacity limitations are barriers for use in heavy vehicles. In contrast, using VDP technology in small and medium-sized vehicles has proven gains in fuel economy, with a higher benefit-to-cost ratio versus EPS. Until EPS technology becomes economically feasible to use in large and heavy vehicles, there is an opportunity to use VDP technology.

The technical challenges in applying VDP technology to heavy and large vehicles stem from the difficulties in achieving marketability, fuel economy, and vehicle performance. Due to the increased steering load, heavier vehicles demand larger displacement and higher relief pressures from power steering pumps than do smaller vehicles. The increase of displacement and pressure potentially cause a higher level of system noise, which can negatively affect marketability.

Additionally, due to the unbalanced mechanism of its unique design (see Fig. 1), a VDP inherently produces a higher level of noise than a conventional constant displacement pump (CDP)^{(1), (2)}. The VDP's output flow rate and relief pressure must be sufficient to achieve good vehicle dynamic performance; however, its displacement must be minimized to limit energy consumption and improve fuel economy.

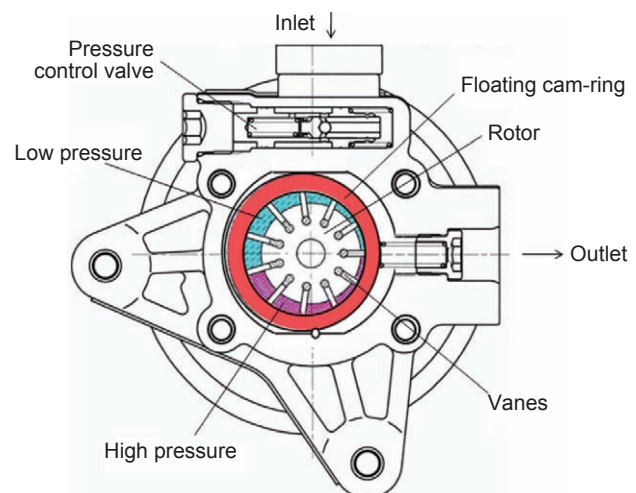


Fig. 1 Structure of variable displacement pump

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Extensive investigation was conducted to achieve a balance between steering noise performance, fuel consumption reduction, and vehicle steering performance when VDP technology is integrated into a large light truck. First, the source noise characteristics of the VDP and the noise attenuation characteristics of the steering system were analyzed by using the concepts of source flow ripple and pulsation transmission loss, and design measures were proposed to improve the noise source and attenuation characteristics. Second, to ensure benefits in fuel economy, a new design specification was proposed to control the VDP's power consumption by limiting the input torque at critical pump speeds. Finally, achieving good vehicle dynamic performance requires a high flow rate in the VDP, but this directly conflicts with noise and fuel economy requirements; therefore, appropriate flow rate characteristics were determined. This paper summarizes the achievements in steering noise reduction, fuel economy benefits, and vehicle steering performance.

2. Marketability Improvement

2.1. Problem Identification

A vehicle operational study was conducted to identify possible noise concern areas in a large light truck equipped with a VDP. An initial prototype of a variable displacement pump, VDP1, was used to compare with a constant displacement pump, CDP0, currently used in mass production. Both pumps are similar in displacement and relief pressure, but the

vane pump design for CDP0 has 10 vanes while VDP1 has 9. Noise performance is mainly evaluated under four vehicle conditions: (1) idle engine speed and no steering input, (2) idle engine speed and continuous steering input, (3) engine speed sweep and with/without steering input, and (4) idle engine speed and steering held at rack end. Figure 2 shows a sample comparison of the cabin sound pressure spectra when the vehicle is equipped with CDP0 and VDP1 separately, and includes a basic requirement line (maximum allowable level) for the noise contributed by the steering pump.

The operational study revealed the following four major noise concern areas:

- (1) Without steering input, VDP1 induces higher levels at the 1st and 2nd harmonic frequencies than CDP0.
- (2) With steering input, VDP1 causes a much higher 2nd harmonic order than CDP0.
- (3) The 1st harmonic frequency of VDP1 is coincidentally in line with one of the engine accessory frequencies.
- (4) During engine speed sweep mode, VDP1 generates much higher noise at the 2nd harmonic frequency than CDP0.

2.2. Source Noise Characteristics

In a hydraulic power steering system, the source flow ripple generated by the steering pump interacts with the connected hose, pipes, and steering gearbox to generate pressure pulsations and excite airborne noise and mechanical vibrations. For a given pump structure and type of fluid, the source flow ripple is the key parameter representing the source

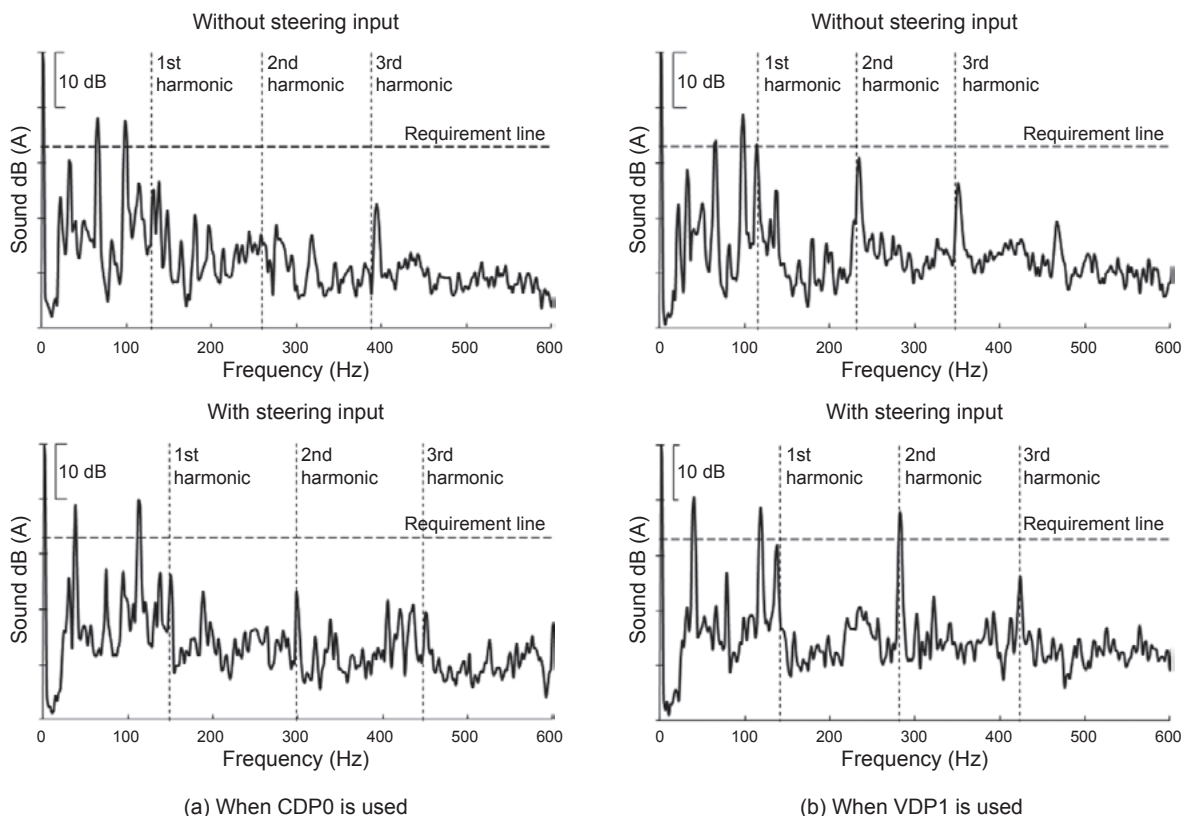


Fig. 2 Comparison of cabin noise spectra of test vehicle equipped with different pumps at engine idle speed

noise potential of the pump. The source flow ripple characteristics are evaluated through established measurement methods and systems^{(3), (4)}.

Figure 3 shows a comparison of harmonic spectra of measured source flow ripple of different pumps under two test conditions, where the first condition represents a vehicle condition at idle engine speed and without steering input, and the second represents a vehicle condition at low engine speed and with steering input. It is shown that compared with CDP0, VDP1 generates much higher levels of source flow ripple for the 1st and 2nd harmonic orders under both test conditions. This corresponds to the vehicle noise problems identified during the vehicle operational study.

To improve the source flow ripple characteristics, a proposed design (VDP2) was made that changed the following areas: the number of vanes (9 to 11), structure stiffness, the clearance among the internal components, and the position of the rotor. As shown in Fig. 3, compared to VDP1, VDP2 generates a significantly lower level of the 1st harmonic flow ripple and yields considerable reductions at the 2nd and 3rd harmonics under the 930 rpm and 5 MPa test conditions. Increasing the number of vanes from 9 to 11 also helps separate the pump's harmonic frequencies from the engine accessory frequencies.

2.3. System Pulsation Attenuation Characteristics

Noise reduction was further achieved by optimizing steering system attenuation characteristics. Typically, hose-tuning cable devices are used to attenuate the pressure pulsations and minimize the resultant audible

noise in steering systems. Figure 4 illustrates the mechanism and the corresponding quarter-wavelength side-branch resonator model of such a device. Within the side-branch resonator, standing waves of pressure and flow pulsations are excited at the fundamental resonant frequency of the quarter-wavelength and at its odd number harmonic frequencies. For such standing waves, since the pressure pulsation becomes zero at the outlet of the side-branch, the pressure pulsation is attenuated at those frequencies.

The pulsation attenuation characteristics of a hose-tuning cable can be evaluated through a pulsation transmission loss (PTL) value. It can be determined either through experimental methods^{(5), (6)} or through theoretical prediction based on analytical models of flexible hoses^{(7), (8)}. Figure 5 shows examples of PTL

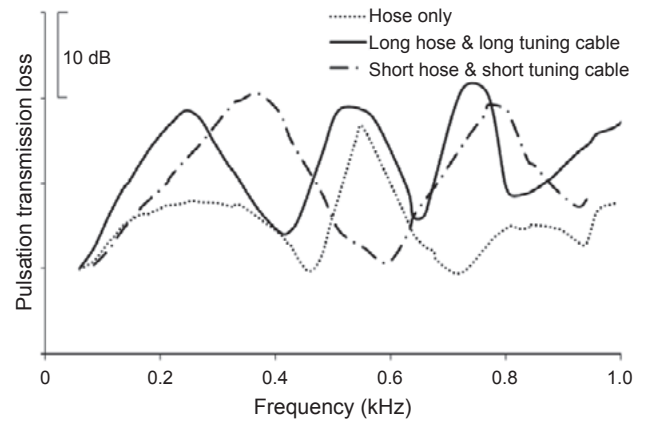
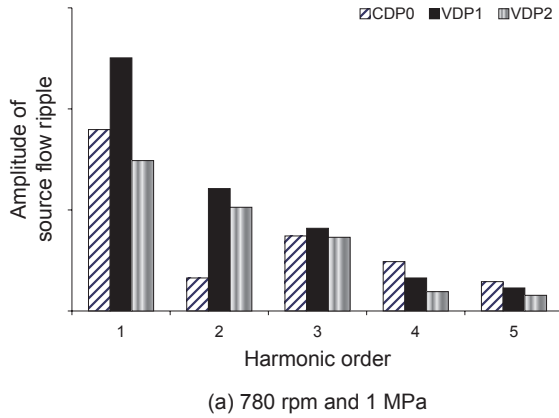
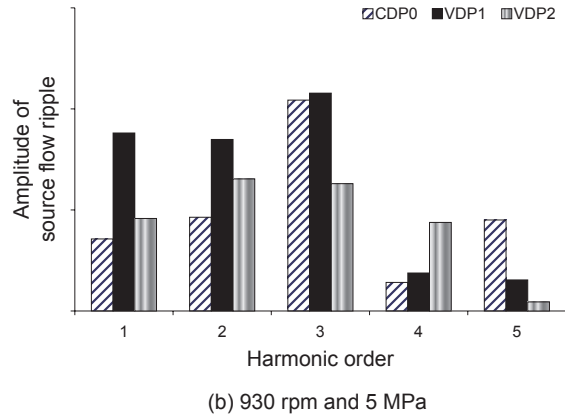


Fig. 5 Examples of measured pulsation transmission losses of different hose-tuning cable systems

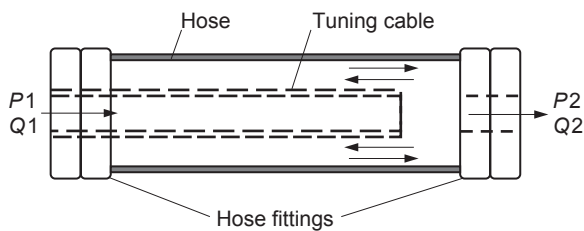


(a) 780 rpm and 1 MPa

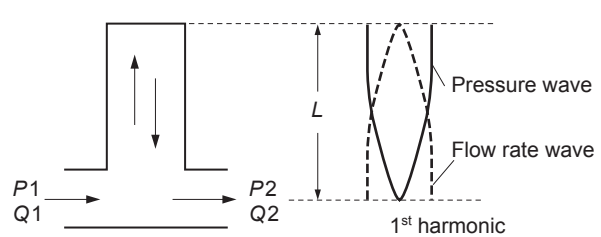


(b) 930 rpm and 5 MPa

Fig. 3 Comparison of measured source flow ripple spectra of different pumps



(a) Hose - tuning cable mechanism



(b) Conceptual quarter-wavelength side-branch

Fig. 4 Pulsation attenuation mechanism used in hydraulic power steering system

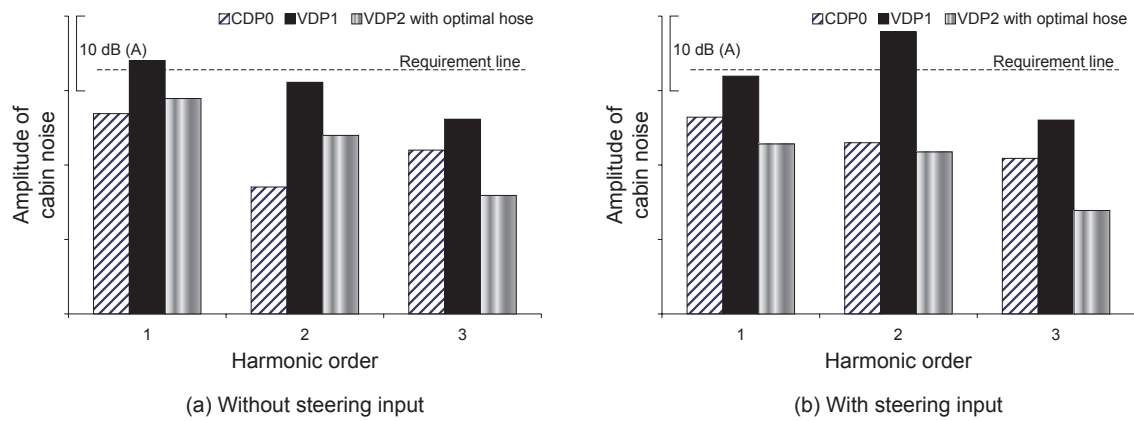


Fig. 6 Comparison of cabin steering noise harmonic spectra when different pumps are used

measurement results and how it can be tuned to target different frequencies.

In this study, two hose-tuning cable devices were combined. The design was optimized to provide a maximum PTL value targeting primarily at the 2nd harmonic order and secondly at the 1st and 3rd harmonic orders of the pump at engine idle speed.

2.4. Noise Performance

Steering noise performance of the vehicle equipped with VDP2 and optimal hose design was confirmed under various driving conditions. Figure 6 shows the measured cabin noise harmonic spectra at engine

idle speed with and without steering input conditions. The final setting has achieved overall levels similar to or slightly better than CDP0, and the noise levels are within the requirement line (i.e., the maximum allowable line) within substantial margins.

Using a 10-point rating system, with 1 representing extremely poor performance and 10 being excellent performance, the noise was subjectively evaluated under both normal and extreme steering usage modes, such as the steering wheel held at rack end during engine sweeping. Figure 7 illustrates that VDP2 with optimal hose design has achieved the noise performance slightly better than CDP0 for both normal steering and extreme steering conditions.

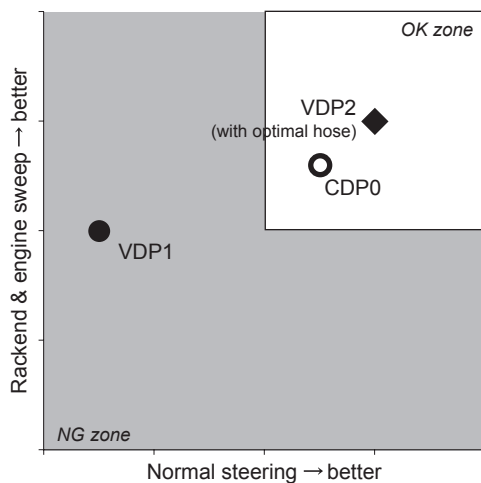


Fig. 7 Subjective evaluation results for vehicle equipped with different pumps

3. Gains in Fuel Economy

3.1. Mechanism of Lower Fuel Consumption

The VDP's unique flow-speed characteristics yield improvements in fuel economy. A typical constant displacement pump (CDP) has a fixed displacement that produces a flow rate almost linear to pump speed. Conversely, the VDP has a floating cam-ring mechanism (Fig. 1) so that the cam-ring's position can be regulated with pump speed. When the pump speed reaches a preset rpm, the cam-ring is repositioned toward the rotational center of the pump shaft, thereby reducing the flow rate.

As shown in Fig. 8, the pumped flow rate of a CDP is usually much higher than what is needed for the flow rate tuned for vehicle performance, while the pumped

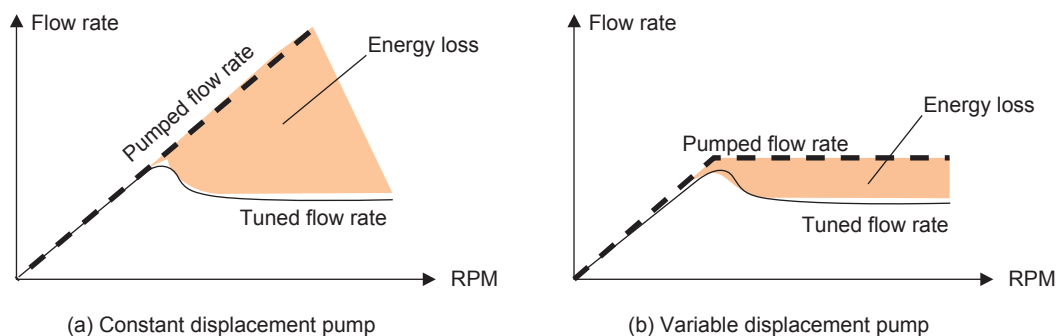


Fig. 8 Conceptual flow rate-speed characteristics of CDP and VDP

flow rate of a VDP can be much closer to the flow rate curve needed. Consequently, the VDP has less internal bypass flow and less energy loss than a CDP.

3.2. Specification for Controlling Power Consumption

Since the operating torque of a VDP in relation to operating speed (pulley RPM) is directly related to power consumption, an operating torque specification must be established to guarantee gains in fuel economy.

Figure 9 illustrates how the maximum operating torque is related to the fuel economy gain under different driving modes. The gain is quantified as the mileage difference between the test vehicle equipped with VDP versus CDP0. It is clearly shown that the fuel economy gain has a linear relationship to the operating torque. Figure 10 shows a comparison of the operating torque curves between CDP0 and VDP2. In a VDP, the maximum operating torque occurs around the engine idle speed and reduces as speed increases. In a CDP, the maximum operating torque occurs at the same engine idle speed, but remains roughly constant as speed increases. As shown in Fig. 8, this corresponds to the different flow rate characteristics between variable and constant displacement pumps.

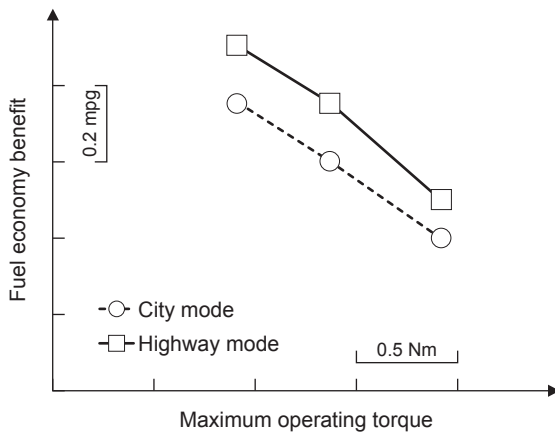


Fig. 9 Fuel economy benefits in relationship to pump's maximum operating torque

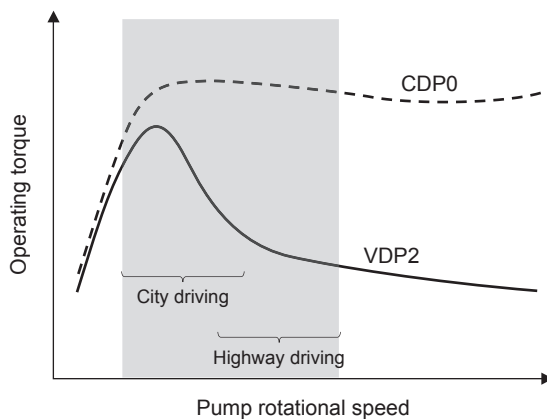


Fig. 10 Comparison of operating torque curves between VDP2 and CDP0

A new specification to control the VDP's operating torques was established so that the operating torque curve is constrained by a boundary curve (Fig. 11) for maximum allowable torque. During typical customer usage, operating the vehicle with steering inputs is a small portion of total usage; therefore, the operating torque specification focuses on the lower operation pressure condition of the VDP.

In this specification, three different pump speeds are used to define the boundary curve. The first point is set at the engine idle speed at which the VDP is near its maximum flow output and thus its maximum operating torque. This point is very important to control since it reflects the engine speed conditions in a typical city driving mode. The second point is set at the average engine speed for highway cruising. The last point is set at a high pump speed to capture driving conditions during accelerated engine speeds. It was confirmed that VDP2 meets the requirements of this new specification.

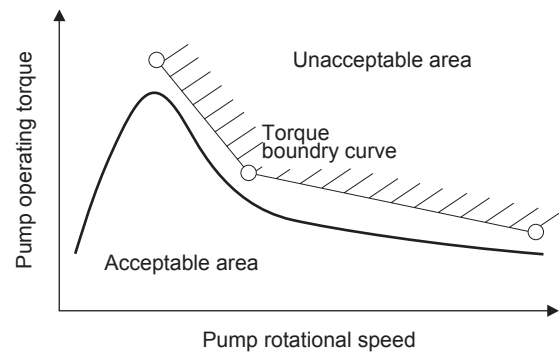


Fig. 11 VDP torque control specification

4. Vehicle Steering Performance

4.1. High Steering Rate Catch-up Performance

Many areas of vehicle dynamic performance are affected by the characteristics of the power steering pump, such as flow rate and pressure characteristics. The design of VDP2 was confirmed to yield satisfying results in these performance areas. As two examples, high steering rate catch-up performance and steering feeling performance are described herein.

High steering rate catch-up performance (also referred to as "catch-up") is described as the effort in turning a steering wheel at a high steering angular rate. The steering angular rate can reach a critical point, called the "maximum assisted steering rate," at which the fluid entering the rack cylinder is not supplied fast enough to provide full power steering assist. As shown in Fig. 12, beyond the maximum assisted steering rate, the steering effort increases at a significantly greater ratio, called the "catch-up effort ratio," compared to the steering angular rate. Therefore, better catch-up performance requires a higher maximum assisted steering rate and a lower catch-up effort ratio.

To achieve satisfying vehicle catch-up performance, the design of VDP2 was enhanced to provide an adequate flow rate under high pressures while maintaining the flow rate and torque characteristics under low pressures. Various tolerances of the internal components of the pump were carefully designed to reduce internal fluid leakage under high pressures. Additionally, the design of the steering gearbox was also refined to minimize the fluid leakage inside the gearbox. As shown in Fig. 12, the final enhanced system with VDP2 provides much better catch-up performance.

4.2. Steering Feel

Steering feel is another important vehicle performance area for VDP use in large and heavy vehicles. At lower speeds, the steering effort should feel light and easy to operate, while at higher speeds, the steering effort should feel solid and secure.

To achieve these steering feel characteristics, VDP2 is designed with a drooping flow rate, that is, the flow rate decreases as the pump speed increases. Consequently, sufficient power assisting force is provided for parking and low-speed maneuvers and less force at high speeds or highway cruising. In addition, the drooping flow rate also has a fuel economy benefit because as less fluid is being pumped with increasing pulley speeds, the power consumption is less.

This study confirmed that the vehicle steering effort characteristics with VDP2 and CDP0 are very similar. With VDP2, the test vehicle achieved a nimble steering feel at low speeds and a secure and natural steering feel at high speeds.

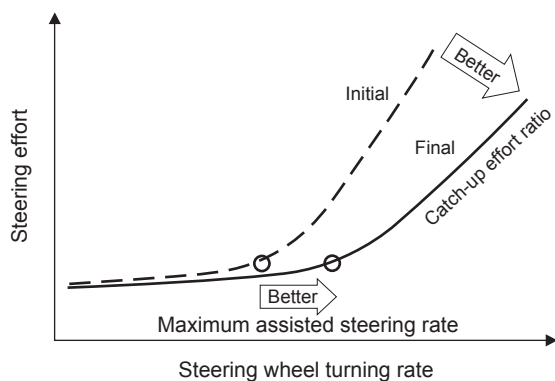


Fig. 12 High steering rate catch-up performance

5. Conclusion

A systematic investigation has been conducted to integrate VDP technology in a large light truck and achieve a well-balanced system with regard to steering noise, fuel economy, and steering performance. The steering noise has been analyzed in terms of both the source noise characteristics of the VDP and the noise attenuation characteristics of the steering system. Design measures were proposed and significant noise

reduction was achieved. To ensure sufficient fuel economy gains with the VDP, a new specification to control the input torque characteristics of the pump has been developed. Finally, high steering dynamic performance has been achieved by the appropriate setting of the pump's flow rate characteristics.

This research proves that VDP technology can be applied to large and heavy vehicles to obtain both good fuel economy and a high level of steering performance. As a result of the study, VDP technology has been successfully applied to 2011 model year Odyssey.

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