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Evaluation of Hydraulic Characteristics of Electrohydraulic Proportional Valve (EHPV) for an Auto-Steering Tractor Application

Yi-Seo Min [1], Yong-Joo Kim [2,3], Ryu-Gap Lim [4], Taeyong Sim [5], Taek-Jin Kim [6,*] and Wan-Soo Kim [1,7,*]

1 Department of Bio-Industrial Machinery Engineering, Kyungpook National University, Daegu 41566, Republic of Korea; msg337@gmail.com
2 Department of Smart Agriculture Systems, Chungnam National University, Daejeon 34134, Republic of Korea; babina@cnu.ac.kr
3 Department of Biosystems Machinery Engineering, Chungnam National University, Daejeon 34134, Republic of Korea
4 Department of Smart Agriculture, Korea Agriculture Technology Promotion Agency, Iksan 54667, Republic of Korea; limso@koat.or.kr
5 Department of Artificial Intelligence, Sejong University, Seoul 05006, Republic of Korea; tysim@sejong.ac.kr
6 Department of Drive System Team, TYM R&D Center, Iksan 54576, Republic of Korea
7 Upland Field Machinery Research Center, Kyungpook National University, Daegu 41566, Republic of Korea
* Correspondence: taek.kim@tym.world (T.-J.K.); wansoo.kim@knu.ac.kr (W.-S.K.)

Abstract: The performance of the electrohydraulic proportional control valve (EHPV) employed in a tractor's automatic steering system directly influences the steering performance. To develop a highly reliable EHPV, it is essential to analyze the hydraulic characteristics of the EHPV for several working conditions of tractors. This study aimed to measure and analyze the hydraulic characteristics of the EHPV according to tractor working conditions. The flow rate and pressure data of the EHPV were computed through the valve measuring system, and the required power was computed. The experimental conditions were selected based on engine rotational speed and tractor steering angle. As a result, it was discovered that the flow rate, pressure, and power all increased when the engine rotation speed and steering angle conditions increased. Furthermore, the rates of increase in flow rate, pressure, and power based on the increase in the steering angle were higher than when the engine rotation speed increased. In the regression analysis results between the two variables and the hydraulic characteristics of EHPVs, the steering angle demonstrated a higher correlation than the engine rotation speed. In conclusion, the steering angle and engine rotational speed are the major variables in the hydraulic characteristics of EHPVs, and the influence of the steering angle is greater.

Keywords: agricultural tractor; automatic steering system; electrohydraulic proportional valve; hydraulic characteristic; hydraulic system evaluation

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1. Introduction

The tractor is a major agricultural machine that performs tasks such as plowing, harrowing, fertilizing, harvesting, and hauling through attachments. Tractors account for the highest share of the global agricultural equipment market, 35%, and the tractor market size is expected to grow to $69 billion by 2029 [1]. Due to the recent high interest in automated agricultural machinery, many studies on tractor automation technology have been performed [2]. In particular, advances in communication and sensor technology have facilitated the rapid development of automation technology for agricultural machinery [3]. The utilization of these automated agricultural machines makes it possible to secure agricultural productivity and carry out highly efficient agricultural work [4]. The autonomous tractor market is expected to grow to $8.3 billion by 2028 [5].

One of the major features of autonomous tractors is auto-steering. The significance of precise steering in agricultural operations has been highlighted [6]. If steering control is not properly conducted, problems such as lowered work efficiency or deviation from the route may occur [7]. The performance of the steering system is important for precise steering of the tractor. Most tractors utilize hydraulic power steering systems, as they are more reliable than electric motor power steering (EPS), especially in agricultural machinery that is often exposed to large and fluctuating loads [8]. In such a hydraulic system, steering performance may be reduced due to factors such as fluid non-linearity and tractor vibrations. The nonlinearity in hydraulic systems arises from fluid incompressibility, friction, and hydraulic valve characteristics and significantly impacts system performance and control [9]. Additionally, tractors operating in rough road conditions generate intense vibrations, which can lead to vibration of the valve control elements such as the spool, resulting in pressure pulsation [10]. To overcome these limitations and develop a high-performance steering system, an electrohydraulic steering system has been developed. The application of electrohydraulic steering systems in agricultural and construction machinery has been extensively studied, and significant research has been conducted on the development of embedded control systems for achieving high performance [11]. The electrohydraulic steering system, employed in auto-steering tractors, determines the steering direction and flow rate using an electrohydraulic proportional directional control valve (EHPV). EHPVs have been extensively employed to implement the precise performance of agricultural machinery. The performance of the EHPV directly influences the performance of the electrohydraulic steering system [12]. Thus, the development of high-performance EHPV is important for the stability and efficiency of the automatic steering system for high-power tractors.

Research on EHPVs employed in agricultural machinery has been performed by several researchers around the world. These works include studies on the major tractor components such as a front loader [13], the power shuttle system [14], the hitch controller [15,16], and the transmission [17]. Most related studies focused on the development of valve control algorithms. The primary aim of these studies was to enhance control response speed and accuracy through the development of control algorithms. Bo et al. (2018) developed a mathematical model of EHPV considering the nonlinearity of the hydraulic system and evaluated the static and dynamic characteristics [18]. The dynamic characteristics of EHPVs are obtained under conditions such as abnormal signal input and disturbance by the tractor hydraulic system. By understanding the dynamic characteristics of EHPV, the performance of EHPV in actual tractor operation can be predicted. When EHPV is tested on an actual tractor or a test device capable of realizing actual working conditions, changes in dynamic characteristics according to the working conditions of the tractor can be analyzed. Lee et al. (2022) developed a steering algorithm through the hardware-in-the-loop (HIL) test to identify the dynamic characteristics of a tractor hydraulic system [8]. The results of the study demonstrated that the development of a steering algorithm can effectively improve the nonlinearity of EHPV. In addition, the use of the EHPV showed less steering control error and faster response compared to the use of EPS. However, prior research on the measurement of dynamic characteristics and performance evaluation of the EHPV considering various tractor working conditions is insufficient. For the development of high-performance EHPVs, it is necessary to measure the hydraulic characteristics of the EHPV mounted on an actual tractor under working conditions.

In the field of heavy vehicles, studies on the performance of EHPVs for each working condition have already been carried out. Heavy vehicles are also similar to tractors in that they apply EHPVs for stability against high loads. Xia et al. (2016) evaluated the flow rate, pressure, and spool displacement characteristics of EHPVs based on the driving speed and steering angular velocity of the vehicle [19]. EHPV performance was evaluated by developing a mathematical model of the vehicle steering system through the analyzed data. The developed model shows that application of the EHPV provides a better high-speed steering feel than using conventional hydraulic power steering. In addition, the hydraulic characteristics of valves are used as indicators for valve design optimization. Li et al. (2020)

presented optimized valve core displacement, spring stiffness, and core–shell structure so that the valve flow rate was output within the tolerance range for the design flow rate [20]. These preceding studies show that EHPV performance prediction and design optimization can be realized through EHPV hydraulic characteristics analysis.

Nevertheless, analyzing the hydraulic characteristics of EHPV during the practical agricultural operations of tractors poses significant challenges. Unlike other commercial vehicles, tractors operate on uneven soil road surfaces. The performance of tractors working in soil is influenced by various soil variables, including moisture content, soil texture, and soil strength [21]. This introduces challenges in controlling experimental conditions. Moreover, as tractors engage in tasks such as tillage that involve direct interaction with the soil, the impact of soil becomes more pronounced [22]. Therefore, in order to analyze the dynamic characteristics of the EHPV according to tractor operation, it is essential to establish a database of hydraulic characteristics that accounts for various working conditions including soil physical properties. However, since soil physical properties cannot be controlled by researchers, it is difficult to derive the exact performance of the EHPV when conducting experiments on soil condition. The hydraulic characteristics of an EHPV can be defined as real-time flow rate, pressure, and required power characteristics. The results of analyzing the hydraulic characteristics of EHPVs according to these tractor working conditions can be used for future EHPV design optimization and control strategy establishment. The performance of the hydraulic system for steering a tractor differs based on the engine rotational speed and steering angle. First, the flow rate supplied to the EHPV is identified from the hydraulic pump directly connected to the tractor engine, which varies depending on the engine rotational speed based on the hydraulic pump's displacement. Second, since the opening and closing amount of the EHPV is presented according to the steering angle of the tractor, the performance of the hydraulic system differs depending on the steering angle. Hence, it is essential to measure and analyze hydraulic characteristics such as flow rate and pressure of the EHPV in line with actual tractor working conditions so as to secure basic data for the design and development of EHPVs applicable to automatic steering tractors.

Therefore, the aim of this study is to analyze and evaluate hydraulic characteristics of an EHPV under various working conditions. The specific research objectives are: (1) development of a flow rate and pressure measurement system for EHPV, (2) measurement of flow rate and pressure characteristics according to working conditions, (3) required power analysis and statistical analysis based on different working conditions, and (4) evaluation of the impact of working conditions on hydraulic characteristics through regression analysis.

2. Materials and Methods

2.1. Agricultural Tractor

In this study, an agricultural tractor (PX1300, Daedong Co., Ltd., Daegu, Republic of Korea) was employed to obtain data on the hydraulic characteristics of an EHPV. The specifications of the tractor and hydraulic system are illustrated in Table 1. The tractor had dimensions of 4290 (L) × 2250 (W) × 2770 (H) mm and weighed 4070 kg. The rated power of the tractor engine was 93.2 kW at 2200 rpm. The hydraulic pump was a direct-coupled engine type, and the steering pump had a displacement of 21 cc/rev and a rated flow rate of 46.2 Lpm at an engine rotational speed of 2200 rpm. The hydraulic oil used in the steering system was UTF-55 (Daedong Co., Ltd., Daegu, Republic of Korea), with a specific gravity of 0.865 and a viscosity of 53.79 and 9.428 cSt at 40 and 100 °C, respectively.

2.2. Hydraulic Steering System

The schematic diagram of the hydraulic system employed in this study is depicted in Figure 1. The EHPV was located between the gear pump and the steering cylinder to regulate the flow rate and direction of the power steering fluid. The steering system of the tractor used in this research study was a non-load reaction type, fully hydraulic, and operated by a hydraulic system without a mechanical linkage structure. The EHPV is a developmental product designed to be attached as an add-on to existing tractors, enabling the implementation of automatic steering functionality. The flow rate of the EHPV is directly controlled through the flow control valve and the directional control valve in the valve. The flow control valve serves the purpose of regulating the discharge flow rate from the pump to achieve a specific target flow rate. The specifications of the EHPV are shown in Table 2.

Table 1. The specifications of the auto-steering tractor used in this study.

Parameters		Specifications
Dimension (length × width × height) (mm)		4290 × 2250 × 2770
Engine-rated power (kW)		93.2 (at 2200 rpm)
Engine maximum torque (Nm)		500 (at 1400 rpm)
Empty weight (kg)		4070
Steering pump	Displacement (cc/rev)	21
	Efficiency (%)	Approximately 95 (at no loads)
	The gear ratio of engine pump	1:1
Hydraulic oil	Specific gravity	0.865
	Viscosity (cSt)	53.79 (at 40 °C) 9.428 (at 100 °C)

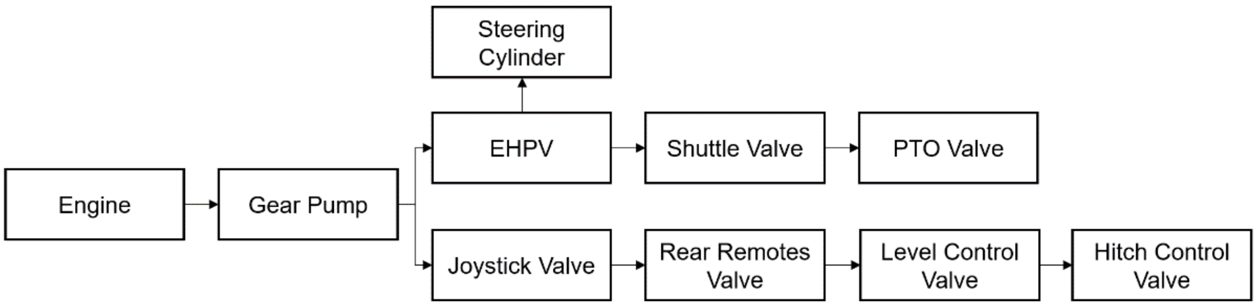

Figure 1. Schematic diagram of the tractor hydraulic system used in this study.

Table 2. The specifications of the EHPV used in this study.

Item		Specifications
EHPV	Maximum flow rate (Lpm)	60
	Control flow rate (Lpm)	25
	Maximum pressure (bar)	220

2.3. Measurement System

To attain the flow rate and pressure data of the steering system, a hydraulic characteristic measurement system of the EHPV was built utilizing a pressure sensor, a flow rate sensor, and a data acquisition system, as demonstrated in Figure 2. A pressure sensor (Hysense PR130, Hydrotechnik, Limburg an der Lahn, Germany) and a flow rate sensor (Hysense QG100, Hydrotechnik, Limburg an der Lahn, Germany) were installed in ports A and B of the EHPV, respectively. Continuous flow rate and pressure data were obtained over time through a data acquisition system (Q.brixx A107, Gantner, Nuziders, Austria). The specifications of each sensor are illustrated in Table 3.

Figure 2. Data measurement system for collecting the flow rate and pressure data of tractor EHPVs.

Table 3. Specifications of the sensor system used to measure hydraulic characteristics in this study.

Item	Specifications
Flow rate sensor (Hysense QG100)	Measuring principle: displacement Viscosity range: 10–500 mm^2/s (cSt) Output signal: 4–20 mA Range: 0.7–70 Lpm Supply voltage: 12–24 VDC Environmental temperature: max. +80 °C Accuracy: 0.4%
Pressure sensor (Hysense PR130)	Measuring principle: piezo-resistive Pressure type: relative pressure Output signal: 4–20 mA/0–10 VDC Range: 250 bar Weight: 85 g Accuracy: 0.5%
Data acquisition (Q.brixx A107)	4 universal analog input channels Fast, high-accuracy digitalization 24-bit ADC, 10 kHz sample rate per channel Power supply: 10–30 VDC Environmental temperature: −20 °C–60 °C Accuracy: 0.01% typical

2.4. Experiment Method

To assess the hydraulic characteristics of the EHPV, experiments were conducted to collect flow rate and pressure data during steering operations. The study focused on the influence of engine rotational speed and steering angle, which directly impact the performance of EHPVs. To measure the stable hydraulic characteristics, the tractor remained stationary under urethane road surface conditions. The EHPV controlled the valve opening through an integrated control unit. A control signal was applied to rotate the tractor wheel from 0° to the target steering angle and back to 0°. Steering sensors (424A, Elobau, Leutkirch, Germany) were installed on the right wheel of the tractor to measure the steering angle. The experiments involved categorizing the steering direction (left and right) and were conducted under a total of 18 working conditions, considering variations in steering direction, engine speed (900, 1400, and 2200 rpm), and steering angle (16°, 38°, and 54°). The selected engine speed levels represented idle, maximum torque, and maximum power conditions, respectively, corresponding to different operational scenarios of the tractor. The engine speed was consistently maintained at a fixed level using the tractor's throttle lever. Furthermore, 3 steering angle conditions of 16°, 38°, and 54° were chosen, representing approximately 30%, 70%, and 100% of the maximum steering angle of 54°, respectively. The steering angle is a crucial parameter in assessing the steering ability of a tractor, and multiple steering angle conditions were selected to comprehensively evaluate the steering performance across diverse working conditions. Each experiment was performed in 2 repetitions under the same working conditions displayed in Figure 3.

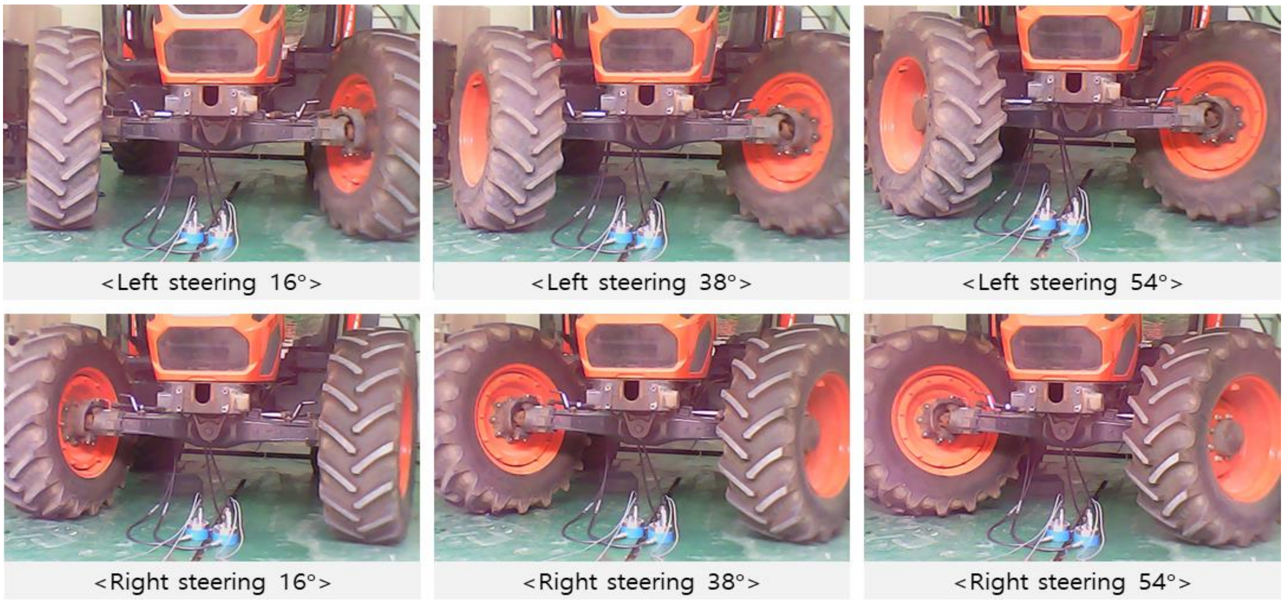

Figure 3. The experiments for measuring EHPV hydraulic characteristics according to the steering angle.

2.5. Data Analysis Method

In this research, the hydraulic characteristics of the EHPV based on engine rotational speed and steering angle were evaluated. Hydraulic power was computed through Equation (1) employing the collected flow rate and pressure data to assess the power needed for tractor steering. The hydraulic efficiency was applied as 90% in consideration of the results of previous studies [23]. To analyze the variability of the obtained data, the coefficient of variation (CV) was examined through Equation (2).

$$P_t = \eta_v \times \frac{p \times Q}{0.6}, \tag{1}$$

where P_t is the hydraulic power requirement (W); η_v is the hydraulic efficiency (−); p is the pressure (bar); and Q is the flow rate (Lpm).

$$CV = \frac{SD}{Average} \tag{2}$$

where CV is the coefficient of variation; and SD is the standard deviation.

To analyze the effect of engine rotational speed and steering angle on the hydraulic characteristics of the tractor hydraulic system, a one-way analysis of variance (ANOVA) and post hoc analysis employing least significant difference (LSD) were carried out using IBM SPSS Statistics (SPSS 25, SPSS Inc., New York, NY, USA). The analysis approach referred to prior research [24]. Two groups were judged to display statistically significant differences when $p < 0.05$ was satisfied.

Additionally, regression analysis was carried out to assess the effect of steering angle and engine rotational speed on hydraulic characteristics. Through Equation (3), the coefficient of determination (R^2) of the hydraulic characteristics of the EHPV were attained.

$$R^2 = \frac{\sum(\hat{y}_i - \overline{y})^2}{\sum(y_i - \overline{y})^2} \tag{3}$$

where R^2 signifies the coefficient of determination; $\hat{y}_i$ represents the estimated value; $\overline{y}_i$ is the average of value; and y_i denotes the measured value.

3. Results

3.1. Profile of the Hydraulic Characteristics for Auto-Steering Tractor EHPV

3.1.1. Flow Rate

Figure 4 shows the flow rate profile of the EHPV under three steering angles, three engine rotational speeds, and two steering directions. The hydraulic characteristics of the EHPV exhibit different outcomes for each condition, and it was observed to be affected by the steering angle condition and engine rotational speed condition. The flow rate increased as the steering angle increased at the same engine rotational speed, and, likewise, the flow rate increased as the engine rotational speed increased at the same steering angle. Moreover, a higher flow rate was demonstrated in right steering (Figure 4D–F) compared to left steering (Figure 4A–C). The flow rate at steering angles of 16°, 38°, and 54° under an engine rotational speed of 900 rpm during left steering was found to fluctuate in the range of 0.02–6.69, 0.01–7.72, and 0.01–9.47 Lpm, respectively. According to the same steering angle conditions, the flow rates ranged from 0.01 to 8.81, 0.01 to 8.62, and 0.10 to 10.48 Lpm at an engine rotational speed of 1400 rpm, and ranged from 0.01 to 8.58, 0.01 to 9.93, and 0.13 to 10.95 Lpm at an engine rotational speed of 2200 rpm. Additionally, the flow rate at steering angles of 16°, 38°, and 54° under an engine rotational speed of 900 rpm during right steering ranged from 0.01 to 7.81, 0.01 to 9.22, and 0.60 to 10.21 Lpm, respectively. Under the same steering angle conditions, the flow rates ranged from 0.01 to 8.77, 0.01 to 9.78, and 0.30 to 10.63 Lpm at an engine rotational speed of 1400 rpm, and ranged from 0.01 to 10.40, 0.01 to 10.14, and 0.64 to 12.95 Lpm at an engine rotational speed of 2200 rpm, respectively.

The flow rate distribution at LS (left steering) and RS (right steering) exhibits temporal fluctuations due to real-time adjustments of the spool position through the steering controller in the EHPV's electrical control unit. In the case of steering angle conditions of 16°, the control unit initially sets the spool to open the valve by 30%. The actual steering of the wheel is influenced by various factors such as tire characteristics, road surface conditions, fluid viscosity, and hysteresis. To ensure stable steering, the control unit continuously adjusts the spool position and compensates for any deviations in input. Consequently, the flow rate rapidly increases, undergoes fluctuations, and gradually decreases, resulting in varying outcomes across experiments.

A noteworthy observation is that while the flow rate distribution shows differences between experiments, the average and maximum values consistently exhibit similar results within a ±10% margin of error across the two repeated experiments. This highlights the stability and reproducibility of the collected data and reinforces the reliability of the data collection method.

3.1.2. Pressure

The pressure profile of the EHPV under three different steering angles, three engine rotational speeds, and two steering directions is displayed in Figure 5. The operating pressure, which is the absolute difference between the port pressures on both sides of the EHPV, was obtained. The pressure was amplified as the steering angle increased at the same engine rotational speed, and, likewise, the pressure increased as the engine rotational speed increased at the same steering angle. The maximum value of the pressure characteristic at the same engine rotational speed varied according to the steering angle. Specifically, at the maximum steering angle of 54 degrees, the pressure of the EHPV increased to a level similar to the operating pressure of the relief valve. Furthermore, higher pressure was demonstrated when steering right (Figure 5D–F) compared to when steering left (Figure 5A–C). The pressure at steering angles of 16°, 38°, and 54° under an engine rotational speed of 900 rpm when steering left was observed to fluctuate in the range of 10.0 to 41.7, 9.4 to 54.5, and 2.1 to 143.1 bar, respectively. Based on the same steering angle conditions, the pressure ranged from 17.6 to 40.9, 7.7 to 50.3, and 0.9 to 147.2 bar at an engine rotational speed of 1400 rpm, and ranged from 13.6 to 49.4, 15.9 to 62.3, and 12.3 to 156.1 bar at an engine rotational speed of 2200 rpm. Additionally, the pressure at steering angles of 16°, 38°, and 54° under an engine rotational speed of 900 rpm when steering right ranged from 14.1 to 43.2, 0.1 to 56.2, and 15.2 to 145.2 bar, respectively. Under the same steering angle conditions, the pressure ranged from 16.4 to 43.1, 6.4 to 56.3, and 10.4 to 150.6 bar at an engine speed of 1400 rpm, and ranged from 15.2 to 50.5, 2.7 to 56.6, and 15.5 to 161.1 bar at an engine speed of 2200 rpm.

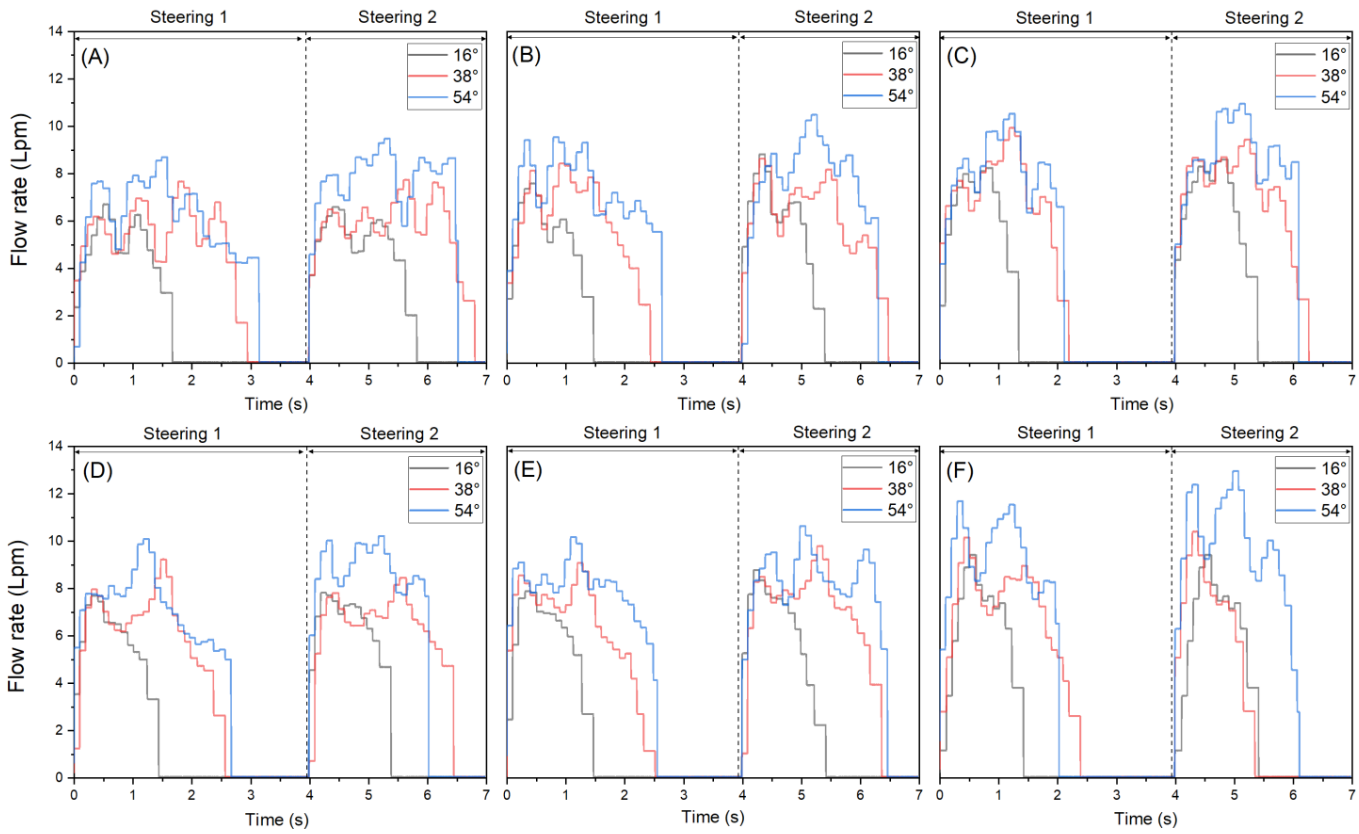

Figure 4. Representative results of flow rate measurement for the EHPV based on each working condition case (**A**–**F**): Case (**A**) = left steering, engine speed 900 rpm; Case (**B**) = left steering, engine speed 1400 rpm; Case (**C**) = left steering, engine speed 2200 rpm; Case (**D**) = right steering, engine speed 900 rpm; Case (**E**) = right steering, engine speed 1400 rpm; and Case (**F**) = right steering, engine speed 2200 rpm.

The distribution of pressure is shown to be similar to the shape of the distribution of flow rate. However, it is slightly different in that the pressure rises gradually as the flow rate is supplied. Additionally, except for the case where steering is performed up to the maximum steering angle, fluctuations in pressure are not more severe than fluctuations in flow rate. This is because, in the ideal case, the pressure of a fluid passing through a pipe is proportional to the square of the flow rate. This can be confirmed by the fact that the pressure has a lower CV value than the flow rate under the same conditions, except for the case of 54° in Section 3.2. In the pressure distribution, it can be seen that the pressure is applied even after the flow rate supply is stopped. This phenomenon is caused by oil remaining inside the steering cylinder. In particular, under maximum steering angle conditions, the steering cylinder becomes full of oil and causes a rapid increase in pressure.

Fluids in bodies with no free volume develop high pressures due to their incompressibility. This accounts for the pressure surge at the maximum steering angle.

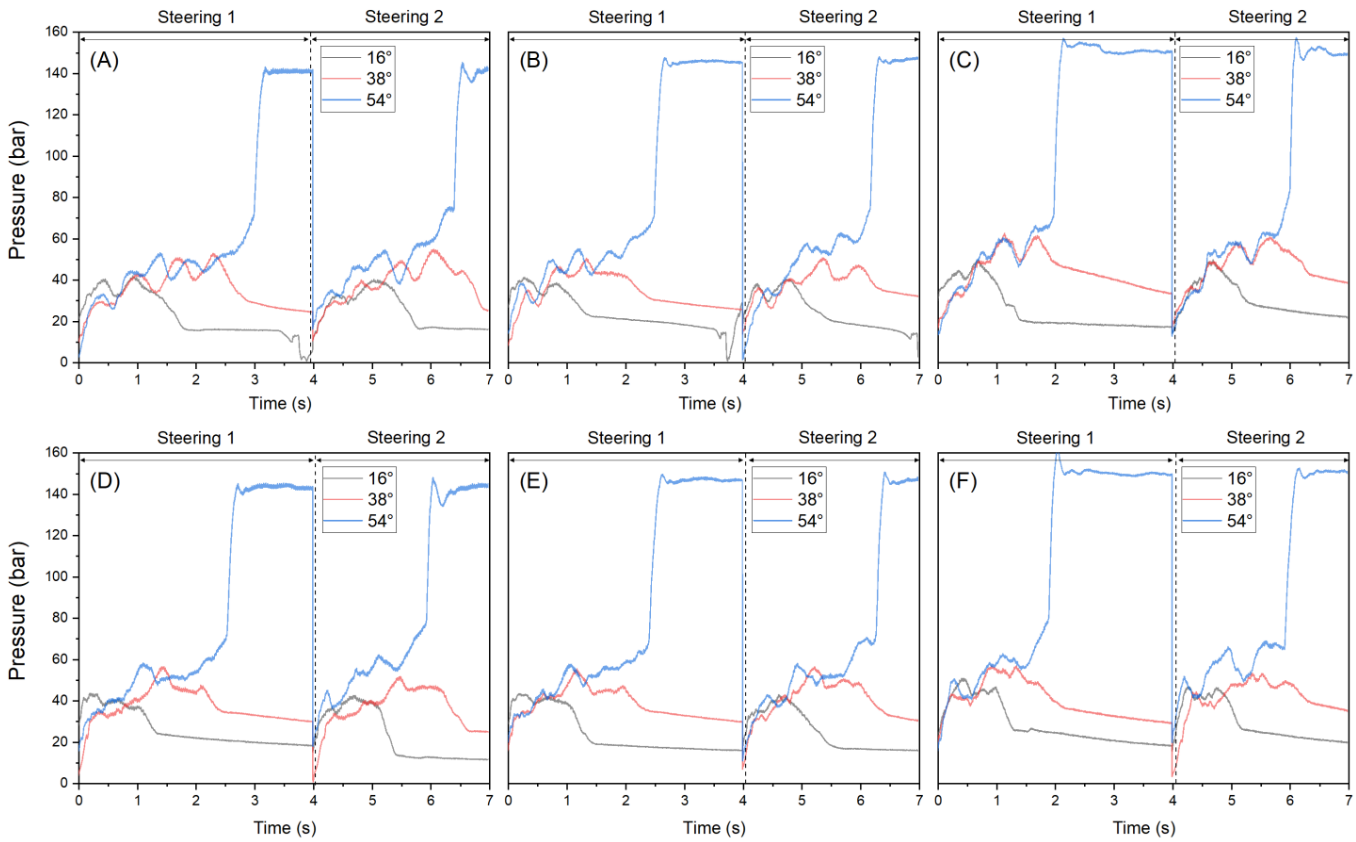

Figure 5. Representative results of pressure measurement for the EHPV based on each working condition case (**A**–**F**): Case (**A**) = left steering, engine speed 900 rpm; Case (**B**) = left steering, engine speed 1400 rpm; Case (**C**) = left steering, engine speed 2200 rpm; Case (**D**) = right steering, engine speed 900 rpm; Case (**E**) = right steering, engine speed 1400 rpm; and Case (**F**) = right steering, engine speed 2200 rpm.

3.1.3. Required Power

Figure 6 demonstrates the power profile of the EHPV under three steering angles, three engine rotational speeds, and two steering directions. The power was amplified as the steering angle increased at the same engine rotational speed, and, likewise, the power increased as the engine rotational speed increased at the same steering angle. At the same engine rotational speed, the maximum value of the power characteristic varied based on the steering angle. In particular, the maximum output of the EHPV at the maximum steering angle of 54 degrees was very high, owing to the pressure. Furthermore, a higher power was demonstrated when steering right (Figure 6D–F) compared to when steering left (Figure 6A–C). The power at steering angles of 16°, 38°, and 54° under an engine rotational speed of 900 rpm when steering left was observed to fluctuate in the range of 1 to 378, 0 to 615, and 0 to 1684 W, respectively. Under the same steering angle conditions, the power ranged from 0 to 470, 0 to 598, and 0 to 1351 W at an engine rotational speed of 1400 rpm, and ranged from 0 to 629, 0 to 914, and 3 to 1980 W at an engine rotational speed of 2200 rpm. Additionally, the power at steering angles of 16°, 38°, and 54° under an engine rotational speed of 900 rpm when steering right ranged from 0 to 495, 0 to 767, and 14 to 1665 W, respectively. Based on the same steering angle conditions, the power ranged from 0 to 502, 0 to 799, and 5 to 1456 W at an engine rotational speed of 1400 rpm, and ranged from 0 to 719, 0 to 825, and 18 to 1724 W at an engine rotational speed of 2200 rpm.

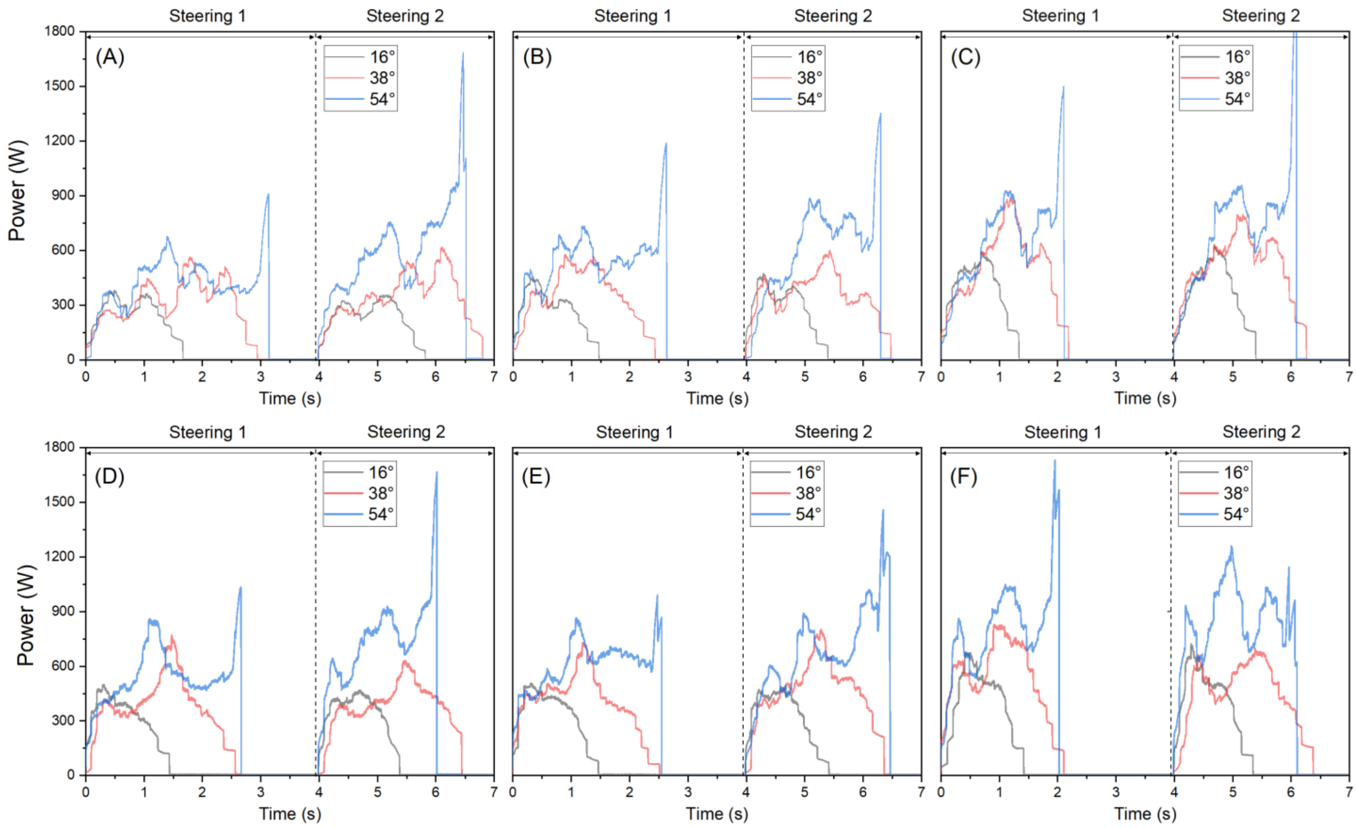

Figure 6. Representative results of required power measurement for the EHPV based on each working condition case (**A**–**F**): Case (**A**) = left steering, engine speed 900 rpm; Case (**B**) = left steering, engine speed 1400 rpm; Case (**C**) = left steering, engine speed 2200 rpm; Case (**D**) = right steering, engine speed 900 rpm; Case (**E**) = right steering, engine speed 1400 rpm; and Case (**F**) = right steering, engine speed 2200 rpm.

The power distribution was found to demonstrate large fluctuations. In particular, the power consumption tended to increase rapidly at the point where the maximum steering angle was reached, which means that the sudden increase in steering torque must be considered when designing EHPVs. Considering that the experiment was conducted on smooth, urethane road surface conditions, this suggests that more fluctuations in power can occur when the tractor is working on soil. In conclusion, for the stability of the tractor auto steering system, it is helpful to reduce the variation of flow rate and pressure in the design of the EHPV.

3.2. Statistical Analysis of the Hydraulic Characteristics for Auto-Steering Tractor EHPVs

3.2.1. Flow Rate

The statistical analysis findings for the flow rate characteristics of the EHPV in line with each working condition are illustrated in Table 4. The average value of the flow rate in the working conditions was in the range of 4.87–9.42 Lpm, and the maximum value was in the range of 6.69–12.95 Lpm. CV ranged from 0.160 to 0.361. The LSD outcomes in line with the steering angle (indicated by subscripts a, b, and c in each row) were observed to be statistically significantly different under all engine rotational speed conditions. The LSD results based on the engine rotational speed (indicated by subscripts A, B, and C in each column) also displayed statistically significant differences in all steering angle conditions. The results of the LSD post-validation show that both the steering angle and engine rotational speed are major factors affecting the flow rate characteristics of EHPVs. The flow rate supplied to the steering unit through the gear pump is entirely proportional to the engine rotational speed, but most EHPVs have a structure in which a reduced flow rate within the designed range is supplied through a flow control valve. Nevertheless, the engine rotational speed has a clear influence on the flow rate characteristics of the EHPV, and it can be expected that the higher the engine rotational speed of the tractor, the more flow rate is supplied to the EHPV and the faster the steering is performed.

Table 4. Statistical analysis results of the flow rate for the tractor steering system according to the working conditions (unit: Lpm).

Engine Speed (rpm)	Descriptive Statistics	Left Steering			Right Steering		
		SA 16 *	**SA 38**	**SA 54**	**SA 16**	**SA 38**	**SA 54**
900	Max.	6.69	7.72	9.47	7.81	9.22	10.21
	Min.	0.02	0.01	0.01	0.01	0.01	0.60
	Avg. ± std.	4.87 ± 1.28^{Cc}	5.52 ± 1.42^{Cb}	6.84 ± 1.71^{Ca}	6.04 ± 1.42^{Cc}	6.22 ± 1.74^{Cb}	7.84 ± 1.48^{Ca}
	CV	0.263	0.256	0.250	0.235	0.280	0.189
1400	Max.	8.81	8.62	10.48	8.77	9.78	10.63
	Min.	0.01	0.01	0.10	0.01	0.01	0.30
	Avg. ± std.	5.57 ± 1.81^{Bc}	6.04 ± 1.73^{Bb}	7.46 ± 1.73^{Ba}	6.39 ± 1.49^{Bc}	6.65 ± 2.09^{Bb}	8.10 ± 1.30^{Ba}
	CV	0.324	0.286	0.232	0.264	0.314	0.160
2200	Max.	8.58	9.93	10.95	10.40	10.14	12.95
	Min.	0.01	0.01	0.13	0.01	0.01	0.64
	Avg. ± std.	6.41 ± 1.85^{Ac}	7.03 ± 1.93^{Ab}	8.39 ± 1.57^{Aa}	6.54 ± 2.36^{Ac}	7.10 ± 2.27^{Ab}	9.42 ± 2.02^{Aa}
	CV	0.289	0.275	0.187	0.361	0.319	0.214

* SA 16, 38, and 54 indicate steering angles at 16°, 38°, and 54°, respectively. Note: Means with different superscripts (a, b, c) in each row and different superscripts (A, B, C) in each column are significantly different at $p < 0.05$ according to LSD multiple range tests.

3.2.2. Pressure

The pressure characteristics of EHPVs based on each working condition are shown in Table 5. The average value of the pressure according to the working conditions was in the range of 31.4–59.7 bar, and the maximum value was in the range of 40.9 to 161.1 bar. CV ranged from 0.173 to 0.435. Owing to the rapid increase in pressure under the steering angle condition of 54°, the CV of the pressure was high at 0.357 to 0.435. The pressure characteristics demonstrated a statistically significant difference according to steering angle for all steering direction conditions of LS and RS. Conversely, it was verified that the pressure based on the engine rotational speed did not demonstrate a statistically significant difference in specific conditions (LS 38°; RS 16°; RS 16°). Hence, it was verified that the steering angle possessed a greater effect on the pressure characteristics of the EHPV than the engine rotation speed.

Table 5. Statistical analysis results of the pressure for the tractor steering system according to the working conditions (unit: bar).

Engine Speed (rpm)	Descriptive Statistics	Left Steering			Right Steering		
		SA 16 *	**SA 38**	**SA 54**	**SA 16**	**SA 38**	**SA 54**
900	Max.	41.7	54.5	143.1	43.2	56.2	145.2
	Min.	10.0	9.4	2.1	14.1	0.1	15.2
	Avg. ± std.	31.4 ± 6.5^{Cc}	37.8 ± 9.2^{Bb}	48.3 ± 20.2^{Ca}	34.7 ± 6.5^{Bc}	38.4 ± 9.7^{Cb}	53.3 ± 19.1^{Ba}
	CV	0.208	0.244	0.418	0.188	0.252	0.357
1400	Max.	40.9	50.3	147.2	43.1	56.3	150.6
	Min.	17.6	7.7	0.9	16.4	6.4	10.4
	Avg. ± std.	32.3 ± 5.6^{Bc}	37.7 ± 9.2^{Bb}	50.9 ± 22.1^{Ba}	35.0 ± 6.5^{Bc}	41.2 ± 8.3^{Bb}	53.9 ± 22.6^{Ba}
	CV	0.173	0.201	0.435	0.185	0.200	0.419
2200	Max.	49.4	62.3	156.1	50.5	56.6	161.1
	Min.	13.6	15.9	12.3	15.2	2.7	15.5
	Avg. ± std.	37.2 ± 7.7^{Ac}	46.9 ± 10.5^{Ab}	53.6 ± 23.3^{Aa}	38.1 ± 8.0^{Ac}	43.4 ± 9.2^{Ab}	59.7 ± 23.0^{Aa}
	CV	0.208	0.225	0.435	0.211	0.212	0.385

* SA 16, 38, and 54 indicate steering angles of 16°, 38°, and 54°, respectively. Note: Means with different superscripts (a, b, c) in each row and different superscripts (A, B, C) in each column are significantly different at $p < 0.05$ according to LSD multiple range tests.

3.2.3. Required Power

The power characteristics of EHPVs based on each working condition are demonstrated in Table 6. The average value of power according to the working conditions was in the range of 238–819 W, and the maximum value was in the range of 378–1980 W. CV was 0.294–0.473. Owing to LSD post-analysis, power characteristics following the steering angle conditions portrayed statistically significant differences in all engine rotation speed conditions. Alternatively, no statistically significant differences existed in power under some of the engine rotational speed conditions (900 rpm and 1400 rpm) and under RS and 38° steering angle conditions. The steering angle exhibited a greater effect on the power characteristics of the EHPV than the engine rotation speed. When steering at a steering angle of 54°, a high output of up to 1980 W is required, but this is primarily applicable when the tractor wheels are almost fully turned. In actual tractor operation, it can be predicted that the average power demand of the EHPV is below 1000 W.

Table 6. Statistical analysis results of the required power for the tractor steering system according to the working conditions (unit: W).

Engine Speed (rpm)	Descriptive Statistics	Left Steering			Right Steering		
		SA 16 *	**SA 38**	**SA 54**	**SA 16**	**SA 38**	**SA 54**
900	Max.	378	615	1684	496	767	1665
	Min.	1	0	0	0	0	14
	Avg. ± std.	238 ± 89 ^{Cc}	321 ± 130 ^{Cb}	498 ± 220 ^{Ca}	324 ± 112 ^{Cc}	373 ± 146 ^{Bb}	621 ± 217 ^{Ca}
	CV	0.375	0.403	0.441	0.346	0.390	0.349
1400	Max.	470	598	1351	502	799	1456
	Min.	0	0	0	0	0	5
	Avg. ± std.	280 ± 115 ^{Bc}	349 ± 132 ^{Bb}	570 ± 219 ^{Ba}	349 ± 125 ^{Bc}	423 ± 168 ^{Bb}	639 ± 202 ^{Ba}
	CV	0.409	0.380	0.384	0.358	0.396	0.316
2200	Max.	629	914	1980	719	825	1724
	Min.	0	0	3	0	0	18
	Avg. ± std.	373 ± 158 ^{Ac}	520 ± 180 ^{Ab}	683 ± 293 ^{Aa}	396 ± 187 ^{Ac}	477 ± 186 ^{Ab}	819 ± 241 ^{Aa}
	CV	0.423	0.346	0.429	0.473	0.410	0.294

* SA 16, 38, and 54 indicate steering angles of 16°, 38°, and 54°, respectively. Note: Means with different superscripts (a, b, c) in each row and different superscripts (A, B, C) in each column are significantly different at $p < 0.05$ according to LSD multiple range tests.

3.3. Evaluation of Hydraulic Characteristics of EHPVs According to Engine Rotational Speed and Steering Angle

3.3.1. Evaluation of Hydraulic Characteristics following Engine Rotational Speed

Figure 7 depicts the effect of engine rotational speed on the hydraulic characteristics (flow rate, pressure, and hydraulic power) of the EHPV. Figure 7A–C display the results of steering left, and Figure 7D–F illustrate the outcomes of steering right. A high R^2 value means a high linear relationship between engine speed and hydraulic characteristics. The R^2 of the flow rate, pressure, and power of the tractor when steering left ranged from 0.993 to 0.999, 0.852 to 0.986, and 0.939 to 0.999, respectively, according to the steering angle. The flow rate depicted a high range of R^2 compared to pressure and power. The R^2 of the flow rate, pressure, and power of the tractor when steering right ranged from 0.875 to 0.987, 0.907 to 0.955, and 0.909 to 0.997, respectively, based on the steering angle.

The results of the simple linear regression analysis for evaluating the hydraulic characteristics of the EHPV using engine rotational speed are presented in Table 7. The overall performance is high across most conditions, indicating that the hydraulic characteristics of the EHPV, including flow rate, pressure, and power, can be effectively described solely by the engine rotational speed. Moreover, it suggests that once the engine rotational speed condition is identified, the hydraulic characteristics of the EHPV can be estimated.

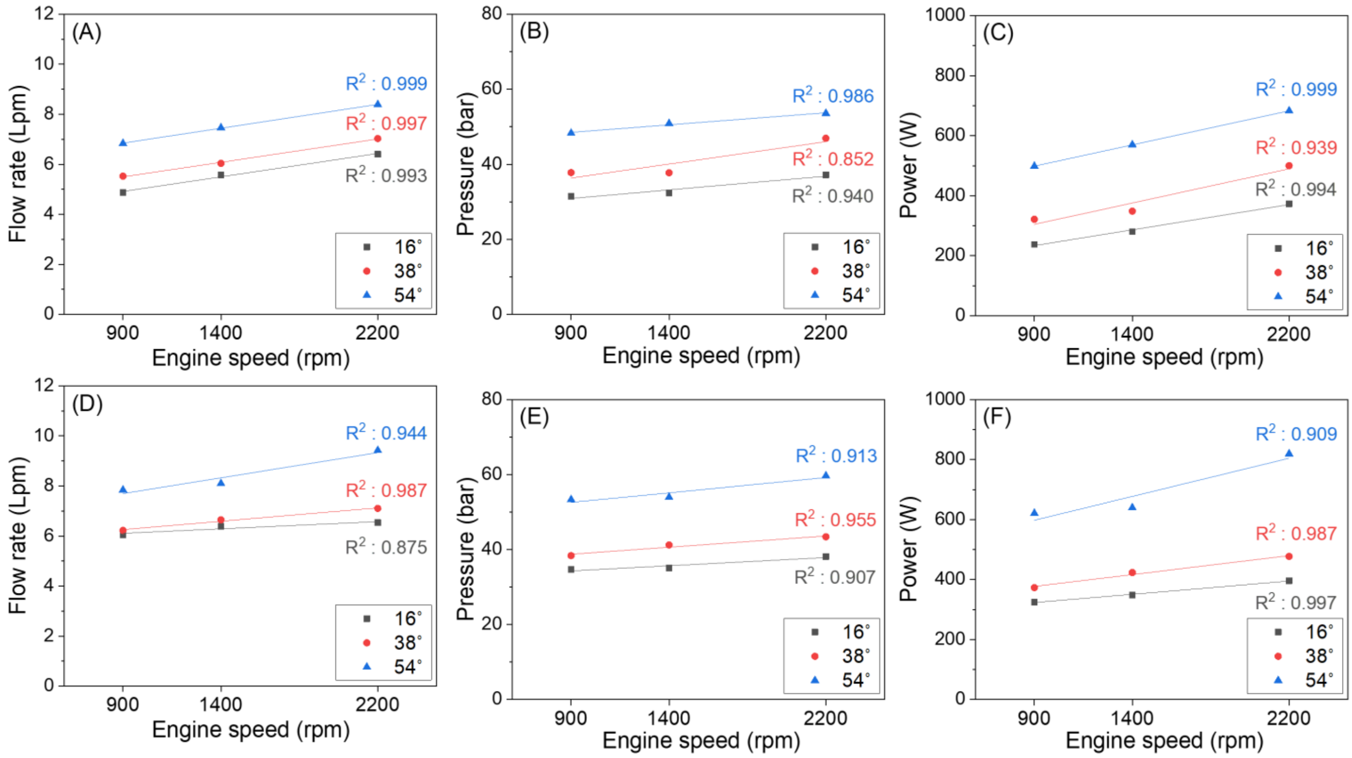

Figure 7. Evaluation results of hydraulic characteristics of the EHPV based on engine rotational speed: Case (**A**–**C**) = left steering; Cases (**D**–**F**) = right steering.

Table 7. Outcomes of regression analysis of the hydraulic characteristics of the tractor EHPV following engine rotational speed.

Items	Steering	Steering Angle	Equation	Pearson's r	R^2	Adj. R^2
Flow rate	LS	16	$y = 0.00117S_e$* + 3.8633	0.996	0.993	0.985
		38	$y = 0.00117S_e + 4.4476$	0.999	0.997	0.995
		54	$y = 0.00119S_e + 5.7754$	0.999	0.999	0.999
	RS	16	$y = 0.00036S_e + 5.7805$	0.935	0.875	0.750
		38	$y = 0.00067S_e + 5.6560$	0.993	0.987	0.973
		54	$y = 0.00126S_e + 6.5640$	0.972	0.944	0.888
Pressure	LS	16	$y = 0.00457S_e + 26.7773$	0.970	0.940	0.880
		38	$y = 0.00746S_e + 29.6195$	0.923	0.852	0.703
		54	$y = 0.00401S_e + 44.8996$	0.993	0.986	0.972
	RS	16	$y = 0.00275S_e + 31.8236$	0.952	0.907	0.814
		38	$y = 0.00375S_e + 35.3689$	0.977	0.955	0.911
		54	$y = 0.00511S_e + 47.9787$	0.955	0.913	0.826
Power	LS	16	$y = 0.10518S_e + 139.2046$	0.997	0.994	0.988
		38	$y = 0.14224S_e + 176.6751$	0.969	0.939	0.878
		54	$y = 0.14189S_e + 370.8443$	0.999	0.999	0.999
	RS	16	$y = 0.05528S_e + 273.3504$	0.999	0.997	0.995
		38	$y = 0.07910S_e + 305.7478$	0.994	0.987	0.975
		54	$y = 0.15918S_e + 454.3579$	0.953	0.909	0.818

* S_e indicates engine rotational speed.

3.3.2. Hydraulic Characteristics Evaluation according to the Steering Angle

Figure 8 outlines the effect of the steering angle on the hydraulic characteristics (flow rate, pressure, and hydraulic power) of the EHPV. Figure 8A–C depict left steering outcomes, and Figure 8D–F display right steering results. The R^2 of the flow rate, pressure, and power of the tractor when steering left ranged from 0.864 to 0.923, 0.897 to 0.999, and 0.858 to 0.963, respectively, based on the steering angle. All hydraulic characteristics depicted a high range of R^2. The R^2 of the flow rate, pressure, and power of the tractor when steering right ranged from 0.749 to 0.827, 0.828 to 0.920, and 0.801 to 0.873, respectively, according to the steering angle. All hydraulic characteristics demonstrated high R^2 values but slightly lower than the outcomes when steering left.

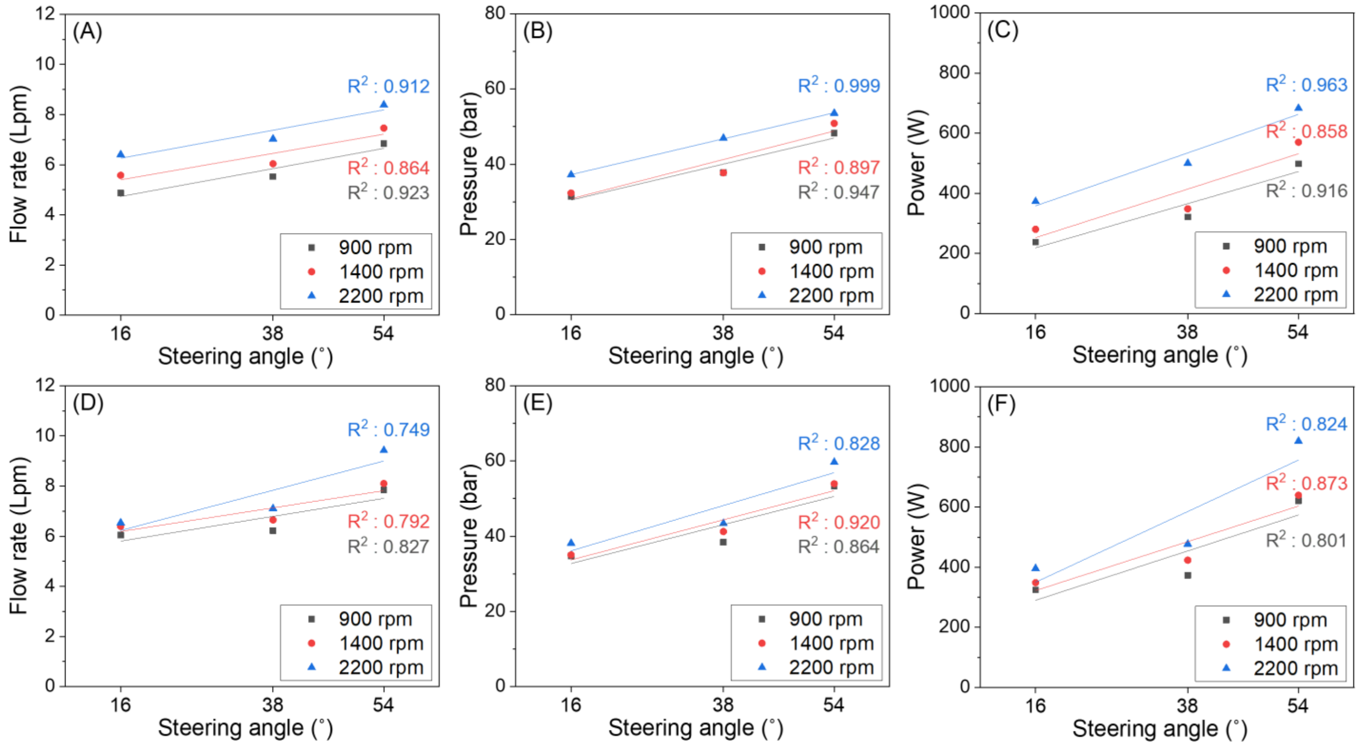

Figure 8. Assessment results of the hydraulic characteristics of EHPVs based on steering angle: Case (**A**–**C**) = left steering; Cases (**D**–**F**) = right steering.

Table 8 indicates the outcomes of a simple linear regression assessment on the hydraulic characteristics of the EHPV using a steering angle. The overall performance is high in all conditions, so the hydraulic characteristics (flow rate, pressure, power) of the EHPV can be described only by the steering angle. Specifically, R^2 values for pressure are higher than those caused by engine rotational speed. When the steering angle condition is identified, it shows that the hydraulic characteristics of the EHPV can be predicted, and the accuracy for pressure is estimated to be high.

3.3.3. Evaluation of the Influence of Working Conditions on the Hydraulic Properties of EHPV

Table 9 presents the outcomes of a multiple regression analysis investigating the impact of engine rotational speed and steering angle on EHPV hydraulic characteristics. The use of standardized coefficients allows for a convenient comparison of the effects of independent variables on the dependent variable, as it eliminates the dependence on specific units. The standardized coefficients indicate the magnitude of the regression coefficients. The results of the multiple regression analyses revealed R^2 values of 0.937, 0.942, and 0.928 for flow rate, pressure, and power, respectively, in the LS condition, while the corresponding values for the RS condition were 0.826, 0.876, and 0.835. The standardized coefficients consistently indicated that steering angle exerted a stronger influence on the hydraulic characteristics of the EHPV compared to engine rotational speed across all conditions. Thus, it can be inferred that the steering angle has a more significant effect on the EHPV hydraulic characteristics than the engine rotational speed.

Table 8. Results of regression analysis of the hydraulic characteristics of tractor EHPVs according to the steering angle.

Items	Steering	Engine Speed	Equation	Pearson's r	R^2	Adj. R^2
Flow rate	LS	900	y = 0.05046A_s* + 3.9264	0.961	0.923	0.846
		1400	y = 0.04788A_s + 4.6329	0.930	0.864	0.729
		2200	y = 0.05076A_s + 5.4468	0.955	0.912	0.824
	RS	900	y = 0.07287A_s + 5.0645	0.910	0.827	0.655
		1400	y = 0.04290A_s + 5.5012	0.890	0.792	0.585
		2200	y = 0.04488A_s + 5.0854	0.866	0.749	0.498
Pressure	LS	900	y = 0.43440A_s + 23.5246	0.973	0.947	0.894
		1400	y = 0.47379A_s + 23.2502	0.947	0.897	0.794
		2200	y = 0.43272A_s + 30.3204	0.999	0.999	0.999
	RS	900	y = 0.54714A_s + 27.3615	0.929	0.864	0.728
		1400	y = 0.48524A_s + 25.9252	0.959	0.920	0.840
		2200	y = 0.46994A_s + 25.2074	0.910	0.828	0.657
Power	LS	900	y = 6.67659A_s + 112.0829	0.957	0.916	0.832
		1400	y = 7.34466A_s + 135.2262	0.926	0.858	0.715
		2200	y = 8.01223A_s + 230.1733	0.981	0.963	0.925
	RS	900	y = 7.4635A_s + 170.6954	0.895	0.801	0.603
		1400	y = 7.39471A_s + 204.1820	0.934	0.873	0.745
		2200	y = 10.69033A_s + 179.1830	0.908	0.824	0.649

* A_s indicates steering angle.

Table 9. Results of multiple regression analysis of EHPV hydraulic characteristics according to engine rotation speed and steering angle conditions.

Items	Steering	Equation	R^2	Adj. R^2	SE *	SC **	
						S_e ***	A_s ****
Flow rate	LS	y = 0.0012S_e + 0.0497A_s + 2.906	0.937	0.916	0.3169	0.610	0.751
	RS	y = 0.0009S_e + 0.0575A_s + 3.858	0.790	0.720	0.5861	0.391	0.798
Pressure	LS	y = 0.0053S_e + 0.4470A_s + 17.675	0.942	0.923	2.2896	0.369	0.898
	RS	y = 0.0039S_e + 0.5058A_s + 20.091	0.872	0.830	3.7797	0.240	0.903
Power	LS	y = 0.1300S_e + 7.3440A_s − 35.494	0.928	0.904	45.6628	0.500	0.823
	RS	y = 0.0988S_e + 8.7457A_s + 25.401	0.823	0.764	80.9260	0.333	0.844

* Standardized error, ** Standardized coefficients, *** Engine rotational speed, **** Steering angle.

It is important to note that these results are contingent on the performance of the EHPV's flow control valve. The study employed a control flow rate of 16–24 Lpm for the EHPV. However, if the designer modifies the control flow rate of the flow control valve, the impact of engine speed on the EHPV hydraulic characteristics may either decrease or increase. Therefore, when designing an EHPV for automatic tractor steering, it is advisable to select the control flow rate based on the specific specifications and performance requirements of the tractor.

4. Discussion

A tractor is distinct from a car in that its primary purpose is work rather than transportation. The conventional work of tractors is carried out by fixing the engine rotational speed to the rated speed condition [25]. When employing the automatic steering function in actual work, left and right steering control will be carried out in the process of following the target path, which results in a change in steering angle. High-performance EHPVs are needed for fast and accurate steering control of auto-steering tractors. To develop high-performance EHPVs, it is essential to secure a high level of design reliability. Specifically, since tractors function under various working conditions, it is crucial to obtain actual vehicle data for each EHPV condition. Thus, the data on the hydraulic characteristics of EHPVs under several working conditions collected in this study can be used as basic data for designing highly reliable EHPVs. The hydraulic characteristic data can serve as a useful reference for optimizing design, predicting and enhancing performance during practical usage, as well as developing control algorithms that consider the working conditions of the tractor. Furthermore, since the hydraulic characteristics of EHPVs also impact the lifetime and reliability of EHPVs, the obtained data can be employed for research such as valve life evaluation.

Because of this study, it was verified that the steering angle condition had a higher correlation with the hydraulic characteristics of EHPVs than the engine rotation speed condition. Additionally, the rate of increase in each flow rate, pressure, and power based on the increase in the steering angle was higher than that in the case of engine rotation speed.

Nevertheless, since this study was performed when the tractor was stationary, there is a limitation in not including data when the tractor was running. Xia et al., (2016) demonstrated that the pressure on the steering cylinder increases as the speed of the vehicle decreases [19]. Specifically, the stronger the torque is on the steering wheel, the greater the difference, since the pressure rises more steeply at low speeds. These factors may result in lower pressure in the EHPV during actual driving. However, the load on the tractor that happens when the tractor is driven in soil conditions increases the flow rate, pressure, and power requirements of the EHPV. As such, several conditions, such as speed conditions and road surface conditions, can affect the dynamic characteristics of the tractor EHPV. Thus, to expand the study's outcomes, it is essential to secure data for each condition. If experiments are conducted by subdividing them based on soil conditions and tractor operation types, it is anticipated that the reliability of the hydraulic properties of the EHPV will be enhanced. In addition, the utilization of EHPV's hardware data in conjunction with the development of a mathematical model can greatly benefit the design of control systems. By conducting research on the control response performance of the EHPV, we can anticipate significant advancements in both control system design and the steering performance of automatic steering tractors. These contents mentioned above will be addressed in future studies.

5. Conclusions

This study, as a fundamental investigation for the design of the EHPV in auto-steering tractors, aimed to assess the hydraulic characteristics of the EHPV based on tractor engine rotation speed and steering angle. The hydraulic properties of valves play a crucial role in valve design, performance prediction, lifespan evaluation, and reliability assessment. The key findings of this study are summarized as follows.

(1) ANOVA analysis revealed statistically significant differences in the hydraulic characteristics of the EHPV under different engine rotation speeds and steering angle conditions. These results clearly demonstrate that both working conditions have a significant impact on the hydraulic properties of the EHPV.
(2) The required power exhibited the highest coefficient of variation. By minimizing flow rate fluctuations, it is possible to reduce power fluctuations and enhance the stability of the EHPV.
(3) Through the results of the regression analysis, it was revealed that the engine rotation speed and steering angle had a linear relationship with the hydraulic characteristics of the EHPV and that the steering angle had a greater effect on the hydraulic characteristics.
(4) The design specifications of the flow control valve in the EHPV have a substantial influence on its hydraulic characteristics. Excessive control flow rate may lead to increased power fluctuations, while insufficient control flow rate could compromise steering performance.

In conclusion, this study provides valuable insights into the hydraulic characteristics of the EHPV in auto-steering tractors. The results emphasize the significance of engine rotation speed and steering angle in influencing the hydraulic properties. These findings can contribute to the design, performance optimization, and reliability enhancement of EHPV systems. Future research should focus on analyzing the EHPV hydraulic performance when the tractor is operating in actual soil conditions.

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