Article

PID Control Algorithm Based on Hydraulic Oil Viscosity for the Proportional Valve of the Planting Depth Control System

Md. Abu Ayub Siddique[1], Wan-Soo Kim[1], Yeon-Soo Kim[1,2], Taek-Jin Kim[1], Chang-Hyun Choi[3], Hyo-Jai Lee[4], Sun-Ok Chung[1], Yong-Joo Kim[1,*]

[1] Dept. of Biosystems Machinery Engineering, Chungnam National University, Daejeon, 34134, Republic of Korea; engg.ayub64@gmail.com (M.A.A.S.); ws6602@hanmail.net (W.S.K.); kimtech612@gmail.com (Y.S.K.); taekjin79@nate.com (T.J.K.); sochung@cnu.ac.kr (S.O.C.); babina@cnu.ac.kr (Y.J.K.)

[2] Convergence Agricultural Machinery Group, Korea Institute of Industrial Technology, 119, Jipyeonmgseon 3-gil, Baeksan-myeon, Gimje-si, Jeollabuk-do, 54325, Republic of Korea

[3] Dept. Bio-Mechatronics Engineering, Sungkyunkwan University, Republic of Korea; choiauto@skku.edu(C.H.C)

[4] Dept. of Bio-industry Mechanical Engineering, College of Industrial Science, Kongju National University, 54, Daehakro, Yesan, Chungnam, 32439, Republic of Korea; leehjai@kongju.ac.kr (H.J.L)

* Correspondence: babina@cnu.ac.kr; Tel.: +82-10-9811-5290

Abstract: This study was conducted to develop a PID control algorithm considering viscosity for the planting depth control system of a rice transplanter using various hydraulic oils at different temperatures and to evaluate the performance of the control algorithm, and compare the performance of the PID control algorithm without considering viscosity and considering viscosity. In this study, the simulation model of the planting depth control system and a PID control algorithm were developed based on the power flow of the rice transplanter (ERP60DS). The primary PID coefficients were determined using the Ziegler–Nichols (Z–N) second method. Routh's stability criteria were applied to optimize the coefficients. The pole and double zero points of the PID controller were also applied to minimize the sustained oscillations of the responses. The performance of the PID control algorithm was evaluated for three ISO (The International Organization for Standardization) standard viscosity grade (VG) hydraulic oils (VG 32, 46, and 68). The results show that the control algorithm considering viscosity is able to control the pressure of the proportional valve, which is associated with the actuator displacement for various types of hydraulic oils. It was noticed that the maximum pressure was 15.405 bars at 0, 20, 40, 60, 80, and 100 °C for all of the hydraulic oils. The settling time and steady-state errors were 0.45 s at 100 °C for VG 32, and 0% for all of the conditions. The maximum overshoots were found to be 17.50% at 100 °C for VG 32. On the other hand, the PID control algorithm without considering viscosity could not control the planting depth, because the response was slow and did not satisfy the boundary conditions. The PID control algorithm considering viscosity could sufficiently compensate for the nonlinearity of the hydraulic system and was able to perform for any of temperature-dependent viscosity of the hydraulic oils. In addition, the rice transplanter requires a faster response for accurately controlling and maintaining the planting depth. Planting depth is highly associated with actuator displacement. Finally, this control algorithm considering viscosity could be helpful in minimizing the tilting of the seedlings planted using the rice transplanter. Ultimately, it would improve the transplanter performance.

Keywords: transplanter; hydraulic oil; temperature; viscosity; proportional valve

1. Introduction

Transplanters are mainly used to plant grown seedlings on a seedbed for various agricultural crops such as rice, corn, cabbage, soybean, broccoli, and sesame. The world market of rice transplanter is dramatically increasing day by day due to the shortage of daily labor and the aging of the farmers. Goldstein Research [1] reported that the global rice transplanter market is estimated to reach USD 13.06 billion in 2024 from USD 8.07 billion in 2016. Kim [2] stated that the exports of Korean rice transplanter are decreasing compared with the previous year. On the other hand, approximately 6.7% of the farmers in Korea were over 65 years old in 2010, and this is expected to increase to 11.3% in 2050 [3]. Therefore, rice transplanters are an inevitable technology for rice farming. However, transplanters are completely mechanized in Korea, which accounts for 99.9% [4]. The main drawback of the existing transplanters is that they use an on–off valve that is unable to perform precisely. The planting depth control system is one of the crucial working parts of the rice transplanter, which is related to the planting accuracy and yield of rice. Sanusan [5] reported that the planting depth of the seedlings significantly affected the rice yield. Bozorgi [6] also reported that the optimum spacing of the seedling increased the rice production. Therefore, a precise technology is required for the accurate planting of the seedlings. In addition, the paddy field is not uniformly level, needs a float sensor in the rice transplanter that maintains the planting depth, but the existing rice transplanter using the on–off valve cannot consider the fluctuation of the soil level to plant the seedlings. As a result, the planted seedlings become tilted because of being pressed and pushed in the soil by the float sensor. Therefore, highly precise and modern technologies are required to control the plant depth, which ultimately enhances the performance of the transplanter and meets the farmers' demand.

Recently, hydraulic proportional valves have been extensively used in most of controlling the pressure or flow for automobiles industries [7–9]. Generally, they are used as flow actuators for hydraulic pistons in a higher level of control loops and for controlling the larger hydraulic valves directly, but a solenoid or an on/off valve cannot directly control this [10,11]. Over the last couple of years, many efforts have been initiated to implement proportional valves in the agricultural machinery for performance improvement. Some of the companies, such as Yanmar, Kubota, and Claas have applied proportional valves to their agricultural machines for precise performance [12–14]. Siddique [15] applied proportional valves in a rice transplanter and developed a simulation model for enhancing the performance. Manzone [16] adapted a proportional valve to a hydraulic transmission system for mounting the trailers, in order to protect from damage during operations. The proportional valve was also adapted to the power shuttle system of a tractor in order to control the pressure for clutch actuation [17]. He also reported that the proportional valve actually performed so as to control the engage and disengage of the clutch. Foster [18] developed a velocity control system applying the proportional valve for a self-propelled windrower. The results indicated that the proportional valve displaced the pintel arms equally. A hydraulic actuator and proportional valve were also applied to the precision agriculture like liquid manure applications. Saeys [19] developed a depth control system for a tractor using a proportional valve in order to regulate the actual working depth of the rotary implements. He also mentioned that a hydraulic actuating system was a common approach in agriculture. Saeys [20] also used the proportional valve to splay liquid manure precisely. Therefore, the proportional valve was implemented to control the planting depth of a rice transplanter for enhancing the performance.

However, proportional valves are highly nonlinear, which impacts the accuracy, stability, and performance of the hydraulic system [21–23]. Temperature is the main reason for the nonlinearity of a hydraulic system, and oil temperature is the most important parameter for increasing the performance of the hydraulic system. This is because the oil temperature is closely related to the variation of oil viscosity and the leakage of the hydraulic system, which greatly influences the damping ratio of the proportional valve and makes the system unstable [24,25]. Chen and Wang [26] reported that the temperature of the hydraulic oil may change the viscosity, vapor pressure, and bulk modulus of the system. Javalagi and Singireddy [27] reported that the performance of the hydraulic system depends on the viscosity of the hydraulic oil. Therefore, a control algorithm was applied in the model to control the hydraulic system, as it was highly nonlinear as a result of the temperature of the hydraulic oils. This study is focused on controlling the pressure of the proportional valve,

because the supplied pressure of the valve is associated with the actuator movement. The planting depth depends on the actuator movement. To control the pressure of the proportional valve, a control algorithm is important for controlling the planting depth of the rice transplanter uniformly and precisely.

Nowadays, a model–based control algorithm such as the proportional–integral–derivative (PID) is widely used to control the nonlinearity of the hydraulic system [28–32]. In addition, the PID control algorithm is comparatively easier to design as a model–based control algorithm [33], and to determine the PID coefficients, one can use Ziengel–Nichols (Z–N) methods [34]. Anthonis [35] developed a PID control algorithm for an automatic depth control system so as to maintain the cutting depth as constant as possible. Condon [36] developed a PID control algorithm for a depth control system for a peat milling machine. An on–off control algorithm was designed for controlling the depth of the rotary implements [37]. Søgaard [38] developed an automatic control algorithm for a finger weeder in order to keep the constant working depth and to minimize vibrations from the soil. Weatherly and Bowers [39] also developed a proportional control algorithm for controlling the seeding depth of a seed planter. As every machine has its own dynamics properties, a new machine needs a new control algorithm. Therefore, Siddique [40] developed a PID control algorithm for controlling the planting depth of a rice transplanter based on the actuator displacement, without considering the viscosity. Because the actuator displacement of the rice transplanter is directly associated with planting performance, the uniformity and actuator displacement depends on the flow rate of hydraulic oils [41]. As the viscosity change of the hydraulic oils has a great influence on the flow rate, the effects of the viscosity and temperature of the hydraulic system are the main concerns for controlling the hydraulic actuator displacement of a rice transplanter.

The purpose of this study to develop a new control algorithm considering various hydraulic oil viscosities at a reference temperature. The viscosity of various hydraulic oils varies at different grades of hydraulic oils. There is very little researches that has been conducted considering the viscosity of various hydraulic oils, especially for agricultural machinery. In this study, various ISO (The International Organization for Standardization) standard hydraulic oils, available in the local market in Korea, were used to perform the PID control algorithm. Park [42] reported that the response of the hydraulic system delays at initial operation because of the high viscosity of the hydraulic oils at low temperatures. This is why the proportional valve should supply the accurate pressure to the automatic depth control system of a rice transplanter. Therefore, the specific objectives of this study are as follow: i) to develop a PID control algorithm of the planting depth control system of a rice transplanter; ii) to determine the PID coefficients considering the hydraulic oil viscosity at different temperatures; iii) to evaluate the response characteristics of PID control algorithms.

2. Materials and Methods

2.1. Rice Transplanter

The rice transplanter (ERP60DS) is a six-row diesel rice planting machine, manufactured commercially by Daedong Industrial Company, Korea. ERP 60DS is a highly efficient planting machine designed for almost 1.7 m/s, which reduces the working time. The fuel consumption of this rice transplanter has an excellent efficiency, accounting for around 2754 g/kWh, which is economically friendly for farmers. The hydraulic pump and proportional valve were designed for a high accuracy, and the constant movement of the hydraulic actuator ensures the precise planting depth of the rice seedlings and the efficiency of the rice transplanter. It also helps to minimize the tilting problem of rice seedlings.

The main components of the rice transplanter's hydraulic system are the hydraulic pump, proportional valve, and hydraulic actuator. The hydraulic pump, which has a 4.5 cc/rev displacement, generates hydraulic pressure by operating the engine and supplies to the proportional valve. The proportional valve controls the pressure according to the command of the float sensor. The operating pressure and flow of the proportional valve are 20 MPa and 15 LPM, respectively. The hydraulic actuator adjusts the movement based on the control pressure of the proportional valve. The

piston and rod diameter of the actuator are 55 and 15 mm, respectively and this actuator movement is the planting depth. Ultimately, the proportional valve helps to control the uniform planting depth of a rice transplanter. The rice transplanter and its main hydraulic components are shown in Figure 1.
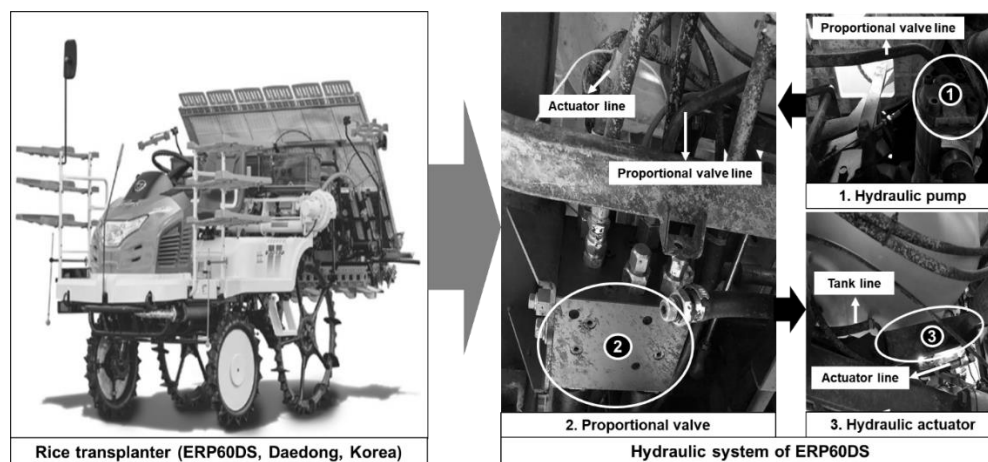

Figure 1. Rice planting machine and its hydraulic system.

2.2. Simulation Model of the Planting Depth Control System

The planting depth control system of the rice transplanter is developed and simulated by LMS AMESim (version 16, Imagine S.A. Company, France). The simulation model was developed based on the power flow of the planting depth control system using the hydraulic proportional valve for enhancing the comprehensive performance of the rice transplanter. The power flow of the simulation model was considered on the basis of a real rice transplanter (ERP 60DS, Korea). The simulation model of the automatic planting depth control system was to control the pressure for both without considering and considering viscosity of the hydraulic oil. The control algorithm was applied using MATLAB Simulink (The MathWorks, Inc., Natick, MA, USA), which is shown in Figure 2.

The flow was generated by the hydraulic pump and was supplied to the proportional valve. The supplied pressure from the proportional valve controlled the movement of the hydraulic actuator. In this model, there was an accumulator to reserve the flow for an emergency flow supply to the hydraulic actuator. Also, the pilot check valve was used in this model, which helped to hold the hydraulic actuator at any position. Using the pilot check valve, the transplanter could stop the planting device at any depth or height.

The simulation model of the planting depth control system of the rice transplanter was composed of a 4.5 cc/rev and a 2650-rated rotational speed hydraulic pump for generating the flow and supplying it to the proportional valve. The proportional valve, which had a 20 MPa operating pressure was used to regulate the hydraulic actuator movement. The piston and rod diameters of the hydraulic actuator were 55 and 15 mm. The planting depth of the rice seedling directly depended on the actuator movement that was controlled by the proportional valve. Also, the hydraulic actuator was used for balancing the load of the proportional valve.
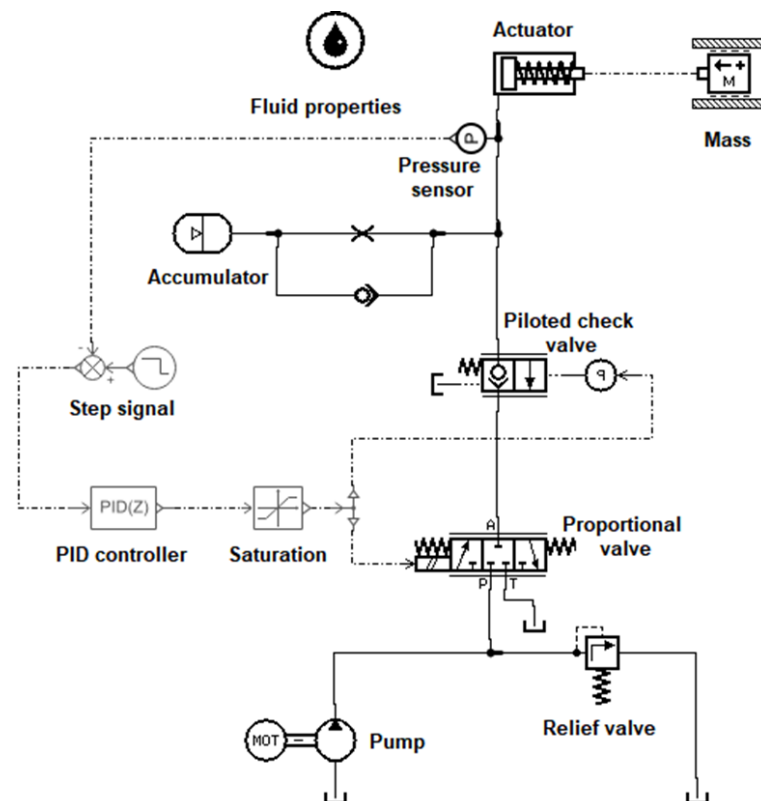
Figure 2. Simulation model and PID (proportional–integral–derivative) control algorithm of the planting depth control system of a rice transplanter.

2.3. Design of the PID Control Algorithm

In this section, the PID algorithm considering viscosity was developed and another PID algorithm without considering viscosity [40] was summarized shortly to compare the performance of both PID algorithms. Actually, the PID control algorithm without considering viscosity was designed to control the displacement of the hydraulic actuator and the hydraulic oil viscosity was not considered to determine the PID coefficients.

2.3.1. PID control algorithm without considering viscosity

In general, the single-acting actuator control algorithm was developed considering the flow rate, supply pressure, damping ratio and natural frequency of the proportional valve. Recently, single-acting actuators have been getting priority over the double-acting actuators for being simple and cost effective. Also, they can minimize size and optimize space [43]. Figure 3 shows the proportional–integral–derivative (PID) control algorithm for position control without considering viscosity [40]. The control plant was designed by the second order transfer function.
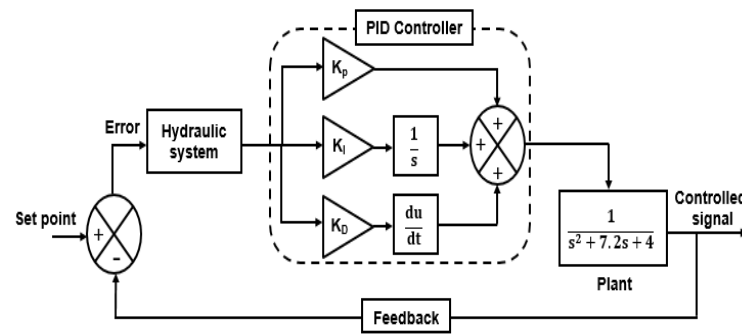
Figure 3. PID control algorithm for pressure control without considering viscosity [40].

2.3.2. PID control algorithm considering viscosity

To develop the PID control algorithm considering viscosity, the mathematical model for a single-acting actuator and proportional valve was designed considering the third order transfer function. The hydraulic actuator and proportional valve model are shown in Equation (1), as follows:

$$G(s) = \frac{K_{input}}{A} \frac{\omega_n^2}{s(s^2 + 2\,\zeta\omega_n s + \omega_n^2)}, \tag{1}$$

where ζ is the valve damping ratio; ω_n is the valve natural frequency of proportional valve which is denoted by Hz; and $\frac{K_{input}}{A}$ is calculated as 0.02. In this study, the natural frequency (ω_n) was considered to be 5 Hz to calculate the actuator transfer function, and the damping ratio was the variable used to find the primary PID coefficients, because the viscosity of the hydraulic oils affected the damping ratio. According to Amirante [44], the range of natural frequency of a commercial proportional valve is 20 to 85 Hz for the stabilization of the system. This is because the lower natural frequency of the proportional valve has no resonance peak, and the resonance phenomena are important to realize a precise and accurate control system. The PID controller has also its own transfer function, shown in Equations (2)–(4).

$$G_c(s) = K_p(1 + \frac{1}{T_i s} + T_d s), \tag{2}$$

$$G_c(s) = 0.6K_{cr}(1 + \frac{1}{0.5P_{cr}s} + 0.125P_{cr}s), \tag{3}$$

$$G_c(s) = 0.075K_{cr}P_{cr} \frac{(s + \frac{4}{P_{cr}})^2}{s}, \tag{4}$$

where $G_c(s)$ is the transfer function of the PID control algorithm; K_p, T_i, and T_d are the coefficients of the proportional, integral, and derivative, respectively; K_{cr} is the critical proportional gain, which is determined by the Routh array; and P_{cr} is the corresponding critical period, shown in Equation (5).

$$P_{cr} = \frac{2\pi}{\omega_{cr}}, \tag{5}$$

where ω_{cr} is the frequency of the sustained oscillations. To find the frequency of the sustained oscillation, $s = j\omega$ was substituted into the characteristic equation of the plant. From Equation (5), the PID control algorithm had a pole at the origin and double zeros at $s = -4/P_{cr}$. The closed-loop transfer function can be obtained by considering $T_i = \infty$ and $T_d = 0$. The closed-loop transfer function is shown in Equation (6).

$$\frac{C(s)}{R(s)} = \frac{K_p}{s^3 + 8s^2 + 25s + K_p}, \tag{6}$$

Thus, the characteristic equation of the closed-loop was found from Equation (6), as shown in Equation (7).

$$s^3 + 8s^2 + 25s + K_p, \tag{7}$$

The selection of PID coefficients is important to design the PID controller [45]. Therefore, the Ziegler–Nichols (Z–N) second method was applied to select the PID coefficients at various damping ratios of the unit step response of the control algorithm. This is because the Z–N second method does not require the processed model. K_p, T_i and T_d were determined using Equation (8)–(10).

$$K_p = 0.6\, K_{cr}, \tag{8}$$

$$T_i = 0.5\, P_{cr}, \tag{9}$$

$$T_d = 0.125\, P_{cr}, \tag{10}$$

To control the pressure of the proportional valve, a PID (Proportional-Integral-Derivative) controller was designed by MATLAB Simulink. The PID control algorithm considering viscosity is shown in Figure 4.
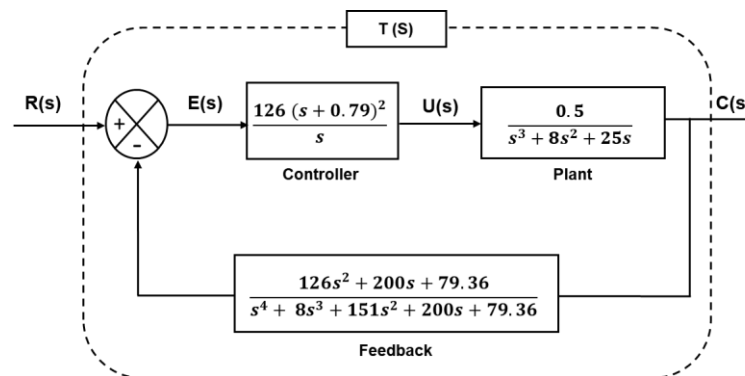

Figure 4. PID control algorithm for position control.

2.4. Initial Coefficients of PID Control Algorithm Considering Viscosity

Figure 5 shows the unit step response at various damping ratios. It was observed that unit step response at damping ratio of 0.8 had the lowest overshoot (57%) and settling time (2.8 s), which were excessive for a rice transplanter. The primary PID coefficients were selected by analyzing the response characteristics of the responses. Routh's stability criteria were applied to minimize the sustained oscillation of the response.
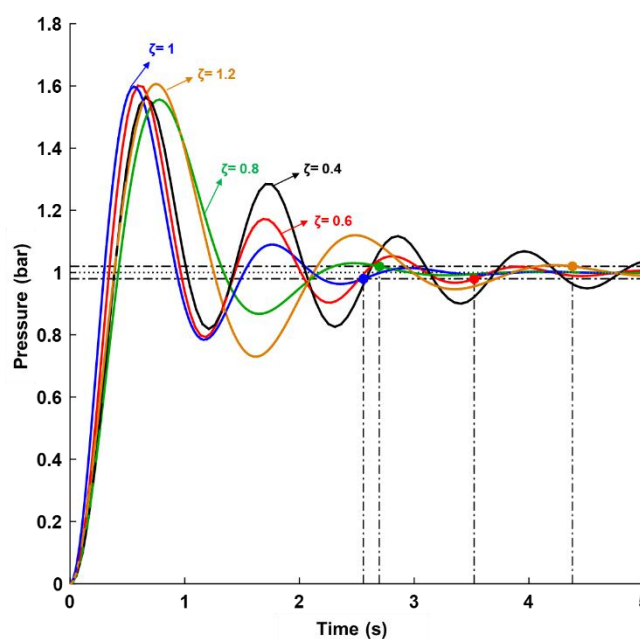

Figure 5. Unit step response at various damping ratios for the PID control algorithm.

2.5. Performance Evaluation of the Control Algorithms

The planting depth control system of the rice transplanter is highly precise technology. The planting depth control system requires a faster rise for precisely and uniformly planting the seedlings. Therefore, the settling time of the response was considered to be less than 1 s, and the maximum overshoot was less than 25% [34]. The satisfactory boundary conditions for the planting depth control system are shown in Figure 6. The target value of the maximum overshoot (25%) means that if the overshoot is increased over 25%, the control algorithm will not have satisfied the response. On the other hand, the hydraulic actuator of the transplanter cannot move linearly. Also, this control algorithm cannot control the planting depth of the transplanter. In the case of the settling time, the target value was considered to be 0.9 s in order to determine the primary PID coefficient. The boundary condition of the control algorithm indicates that this control algorithm is able to perform for the designed model within the restricted ranges. Also, the lower settling refers to the better performance of the model. However, the settling time (0.9 s) is enough to determine PID coefficients for the automatic depth control system of a rice transplanter. The higher settling time also affects the planting performance of the transplanter [46]. The steady-state error, which is another important character to control the planting depth control system, was considered to be less than 1% [47]. Therefore, the responses characteristics of both control algorithms should satisfy the boundary conditions or target values, in order to minimize the tilting problem of the automatic planting depth control system and improve the performance of transplanter.
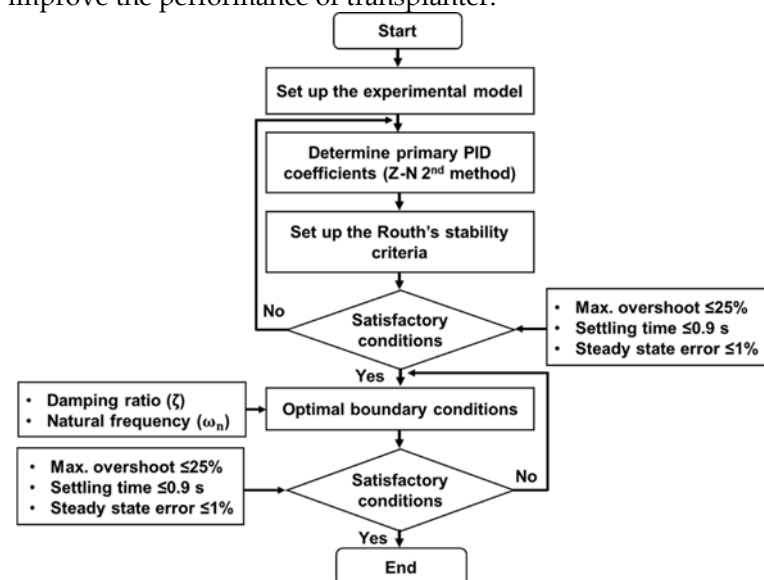

Figure 6. The boundary conditions of the control algorithms considering and without considering viscosity.

Hydraulic oil is a medium of power transmission in the system or machinery. Most of the hydraulic oils are classified with ISO standards. In this study, three ISO (The International Organization for Standardization) standard hydraulic oils available in the Korean local market for agricultural machinery namely Kixx RD HD (VG 32, 46, 68) were selected to determine the PID coefficient. The VG stands for the viscosity grade of the hydraulic oils. Generally, the highest temperature of the hydraulic oil of agricultural machinery is 100 ℃ for all-weather conditions [48]. This temperature range was divided into five levels of equal intervals (0, 20, 40, 60, 80, and 100 ℃) in order to determine the viscosity of the selected hydraulic oils from a standard viscosity index. The viscosity of the selected hydraulic oils is shown in Figure 7.
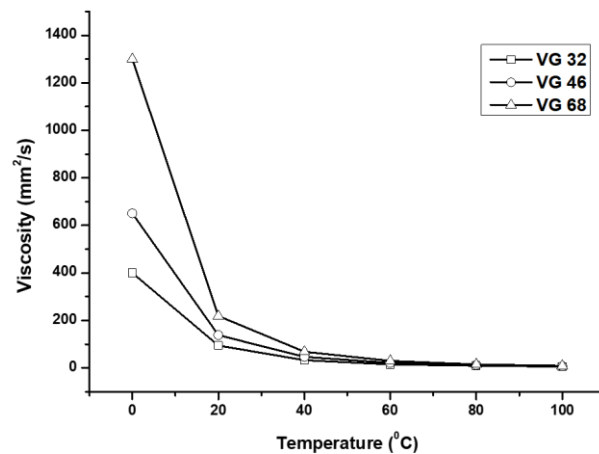
Figure 7. The viscosity of the hydraulic oils at various temperatures.

It is shown that viscosity decreased with the increase of temperature. This means that viscosity is inversely proportional to the temperature. Viscosity may cause the interaction forces of molecules that offer resistance to flow for a fluid. Park [42] reported that the pressure of hydraulic oils cannot occur at a low temperature because of the high viscosity. As a result, the delay times of the controlled pressure will increase. When the temperature of the hydraulic oil is increased, the molecules of the hydraulic oil slide over each other easily making the oils less viscous [49,50]. This means the flow rate increased and transmitted the power. The specifications of the selected hydraulic oils are listed in Table 1.

Table 1. Specifications of the selected hydraulic oils

Items	Parameters	Items	Parameters
Brand (model)	Kixx (RD HD)	ISO VG	32, 46, and 68
Density kg/L @15°C	0.855,0.860, and 0.866	Viscosity index	114, 112, and 109
Kinematic viscosity (mm²/s) @40°C	32, 46.2, and 67.4	Kinematic viscosity (mm²/s) @100°C	5.60, 7.09, and 9.04
Pour point (°C)	−39, −36, and −27	Flash point (°C)	221, 232, and 235

3. Results and Discussion

3.1. PID Coefficients for PID Control Algorithm Considering Viscosity

The PID coefficients of the control algorithm considering viscosity were determined at a damping ratio of $\zeta = 0.8$ of the proportional valve, using the pole of origin and double zero points of the PID control algorithm. Routh's stability criteria were also applied to minimize sustained oscillations. The selected coefficients were K_p = 15, T_i = 10.75, and T_d = 0.43. The settling time and maximum overshoot were calculated as being approximately 0.90 s and 19.90%, respectively, and the steady-state error was found to be 0% (zero). The response of the PID control algorithm considering the viscosity of the hydraulic oils is shown in Figure 8.
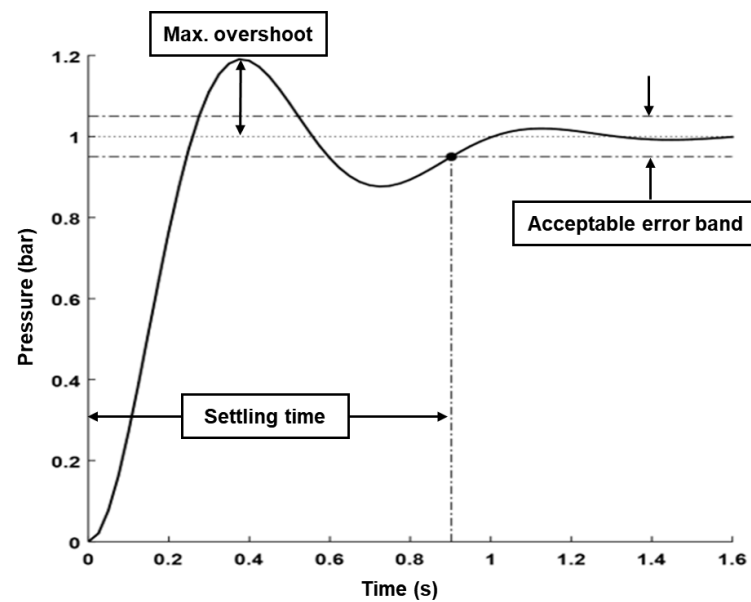
Figure 8. The responses of the PID control algorithm.

The coefficients of the control algorithm satisfied the boundary conditions of the control methodology. The coefficients of the control algorithm with it's response characteristics are listed in Table 2. It is important to analyze the response characters of the control algorithm for various hydraulic oils in order to select the best PID control algorithm for controlling the pressure of the model.
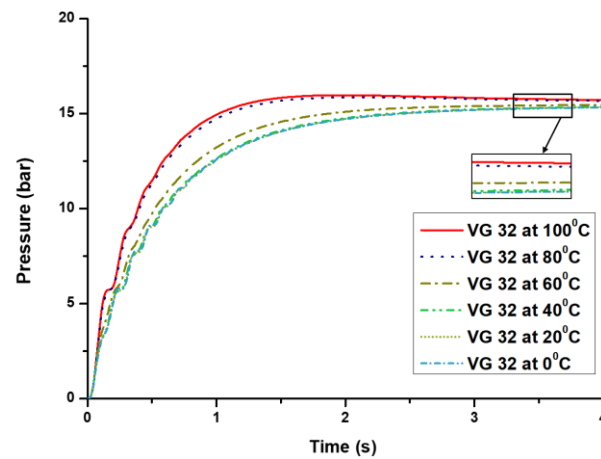
Table 2. The response of the PID coefficients considering viscosity.

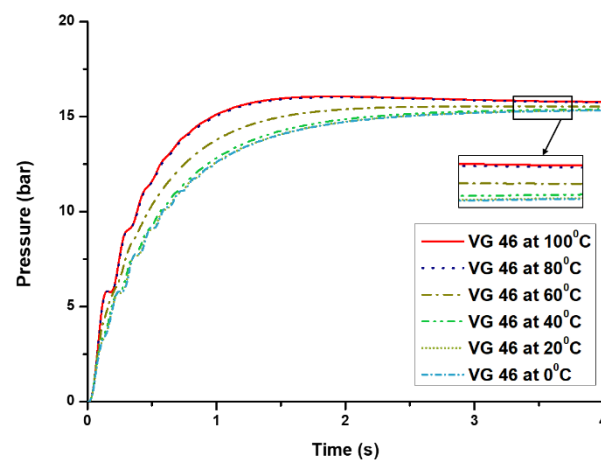| Control algorithm	Max. overshoot (%) ≤ 25%	Settling time [1] (s) ≤ 0.9 s	Steady-state error (%) ≤ 1%
(K_p = 15, T_i = 10.75, and T_d = 0.43)	19.90	0.90	0

[1] The settling time was set within the range of 5% of the final value.
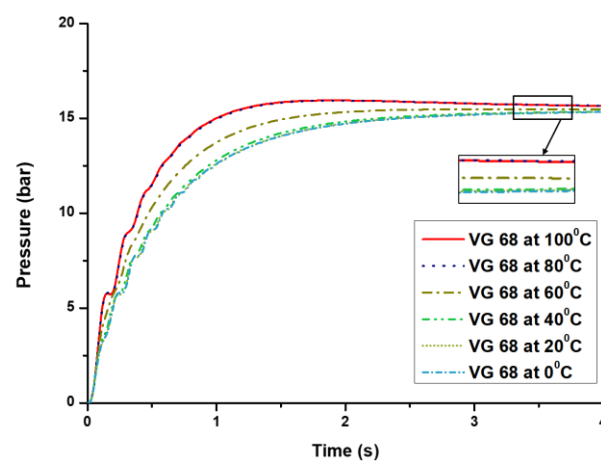
3.2. Performance of PID Control Algorithms

The performance of the PID control algorithm without considering viscosity was conducted for various hydraulic oils at six levels of temperatures, which is shown in Figure 9a,b,c. It was noticed that the pressures of the proportional valve for all types of hydraulic oils and all levels of temperatures (0, 20, 40, 60, 80, and 100 ℃) smoothly increased and it took comparatively longer to become stable and stay at a constant pressure. It was observed that the maximum pressure of the proportional valve was around 15.405 bar at 100 ℃ for VG 32 for the lowest viscosity of the hydraulic oil. The pressure of the proportional valve was gradually decreased as the viscosity of the hydraulic oils increased. It was noticed that the overshoot and steady-state error appeared at the higher viscosity means at a lower temperature of the hydraulic oils. It also required a higher settling time.
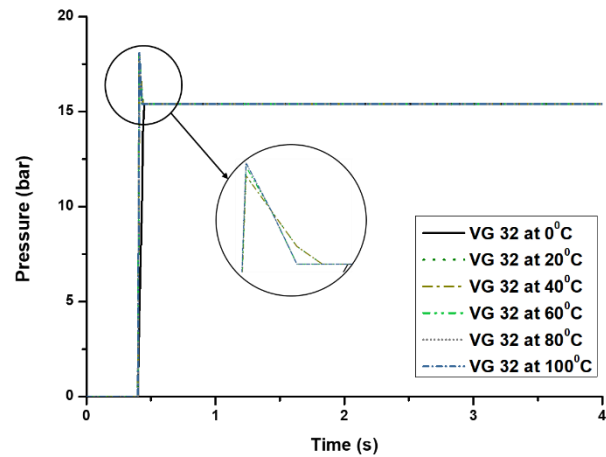
(**a**)

(**b**)

(**c**)

Figure 9. Performance of the control algorithm without considering viscosity at various temperatures, namely: (**a**) hydraulic oils VG 32, (**b**) VG 46, and (**c**) VG 68.
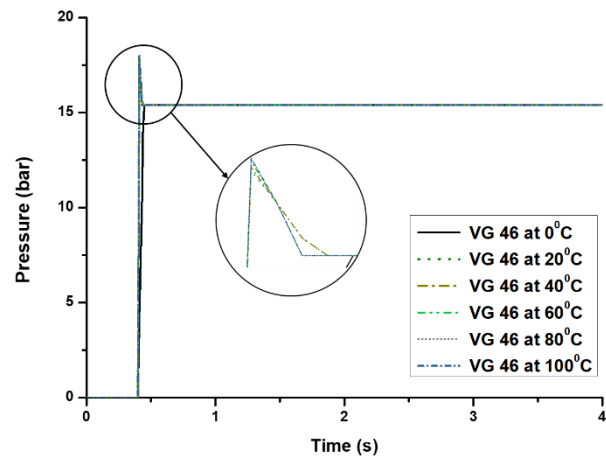
On the other hand, Figure 10 shows the performance of the control algorithm considering the viscosity of the hydraulic oils. The pressure of the proportional valve suddenly rose to a peak after 0.40 s, and had a 5% acceptable error band [47], as shown in Figure 10a,b,c. At 0 °C for the hydraulic

oils (VG 32, 46, and 68), the response was a little slow compared with the other temperature levels of the hydraulic oils. It took a maximum of 0.45 s to be stable. The maximum pressure of the proportional valve was around 15.405 bar at each temperature of the hydraulic oils. Subsequently, the automatic depth control system became stable and was sustained at a constant value.

It was also observed that the PID control algorithm considering viscosity of the hydraulic oils responses quickly for finding the target value. It is clear that the pressure of the proportional valve was constant for changing the viscosity of the hydraulic oils with respect to the temperatures. It indicated the linear movement of the hydraulic actuator. It was also noticed that only the response characteristics were different. Therefore, the response characters of the proportional valve were analyzed.

(a)

(b)

(c)

Figure 10. Performance of the control algorithm considering viscosity at various temperatures, namely: (**a**) Hydraulic oils VG 32, (**b**) VG 46, and (**c**) VG 68.

The response characteristics of the proportional valve were analyzed, and the response of the PID control algorithm without considering viscosity had a lower overshoot at a higher viscosity of the hydraulic oils than that of the PID control algorithm considering viscosity. The overshoot of the PID control algorithm without considering viscosity was calculated to be around 3.85% and 3.48% at 80 and 100 °C of hydraulic oils for VG 32, VG 46, and VG 68, respectively. At 0, 20, 40, and 60 °C for the hydraulic oils, the overshoots were found to be 0%. However, when the higher settling time appeared, accounting for 4 s, is exceeded the boundary condition (0.9 s) of the control algorithm at 0 and 20 °C for all types of oils (VG 32, 46, and 68). In the case of the other temperatures (40, 60, 80, and 100 °C), the responses stayed at an acceptable error band within 2.70 s, which was also larger than the boundary conditions. This means that the float sensor of the transplanter might be delayed when sending a signal to the proportional valve for lifting up and down. It decreased the planting accuracy of a rice transplanter. Also, there was a steady-state error at 0 and 20 °C for VG 32, 46, and 68, accounting for 1% and 0.94%, respectively. The steady-state errors were 0% for the other levels of temperatures (40, 60, 80, and 100 °C), as shown in Table 3. This indicates that the planting depth control system of a rice transplanter had many errors when planting the rice seedling. It could tilt the planted seedlings. As the planting depth control system required a faster response to avoid the tilting problem, this means that the PID control algorithm without considering viscosity is not applicable for the automatic planting control system of a rice transplanter.

In the case of the PID control algorithm considering viscosity, the maximum overshoot was 17.50% for VG 32 at a 100 °C temperature. The notable discrimination is that the overshoot of the PID control algorithm considering viscosity is higher than the PID control algorithm without considering viscosity. However, the maximum overshoot was found to be 26.1% for the four raw corn planters [47]. The minimum overshoot was 0% at 0°C for all types of hydraulic oils. The boundary condition for the maximum overshoot for the automatic planting depth control system of a rice transplanter was 25%. A possible reason was that the control algorithm was tuned to rise very fast, as is required for the automatic depth control system of a rice transplanter. Foster [18] stated that the overdamping system also makes a higher overshoot and a faster response. However, the maximum overshoot satisfied the boundary condition or target value of the PID control algorithm considering viscosity.

Table 2. Comparison of the response characteristics of the PID control algorithms.

Parameter	Temperature (°C)	PID control algorithm	
		Without considering viscosity	Considering viscosity

		VG 32	VG 46	VG 68	VG 32	VG 46	VG 68
Max. overshoot (%) ≤ 25%	0	0	0	0	0	0	0
	20	0	0	0	15.30	15.29	14.70
	40	0	0	0	15.30	15.29	15.29
	60	0	0	0	16.84	16.26	15.87
	80	3.85	3.85	3.85	17.47	16.71	16.40
	100	3.48	3.48	3.48	17.50	16.84	16.72
Settling time (s) ≤ 0.5 s	0	4.0	4.0	4.0	0.45	0.45	0.45
	20	4.0	4.0	4.0	0.42	0.42	0.42
	40	2.70	2.70	2.70	0.43	0.43	0.43
	60	2.70	2.70	2.70	0.42	0.42	0.42
	80	2.70	2.70	2.70	0.42	0.42	0.42
	100	2.70	2.70	2.70	0.42	0.42	0.42
Steady state error (%) ≤ 1%	0	1	1	1	0	0	0
	20	0.94	0.95	0.97	0	0	0
	40	0	0	0	0	0	0
	60	0	0	0	0	0	0
	80	0	0	0	0	0	0
	100	0	0	0	0	0	0

Generally, the maximum overshoot affected the dynamic properties of the proportional valve and hydraulic actuator. It decreased the life cycle of the proportional valve and hydraulic actuator. If the maximum overshoot increased over the boundary condition, the proportional valve could be damaged. However, the maximum settling time was 0.45 s at 0 °C, which was less than the boundary condition (0.9 s) of the control algorithm at all temperatures of the hydraulic oils. This means the proportional valve was able to properly control the planting depth of the rice seedlings. If the settling time was higher than the boundary condition, the rice transplanter could not control the desired depth of seedlings and tilt the planted seedlings. The steady-state error was found to be 0% at any temperature level for any type of hydraulic oil, which was also less than the boundary condition (1%). This means that the PID control algorithm considering viscosity satisfied all of the boundary conditions for the automatic depth control system of a rice transplanter. The response characters are listed in Table 3. These results indicate that the PID control algorithm considering viscosity is feasible for controlling the planting depth of rice seedlings.

Also, He [47] applied a PID control algorithm for four raw corn planter to control the seed plate rotation speed for the seed meter's response and planting quality. He also reported that a faster response is important for improving planting quality and accuracy. In this study, the maximum overshoot was accepted to be 26.10%. Therefore, the PID control algorithm considering viscosity could be adaptable for the automatic depth control system of a rice transplanter for any kind of the hydraulic oils and their reference temperatures, and could result in the quality of the planting seedling and the accuracy.

4. Conclusions

This study developed a PID control algorithm considering the temperature-dependent viscosity of the hydraulic oils for pressure control. First, the simulation model of the planting depth control system and the PID control algorithm were developed based on the power flow of the rice transplanter. Second, the primary PID coefficients were determined by the Ziegler–Nichols (Z–N) second method and optimized by Routh's stability criteria. The pole at the origin and double zero points were also applied to minimize the sustained oscillation of the response. Third, the control algorithms were evaluated for three ISO standard hydraulic oils. In this study, the proportional valve is applied in the planting depth control system of the rice transplanter in order to enhance the

comprehensive performance by controlling the pressure of the proportional valve and the displacement of the actuator, and results are as follows.

1. The PID control algorithm without considering viscosity shows a higher settling time than the boundary condition for various hydraulic oils. Therefore, this control algorithm cannot control the automatic depth control system.

2. In the case of the control algorithm considering viscosity, the PID coefficients were determined to be K_p = 15, T_i =10.75, and T_d = 0.43 at a damping ratio of ζ= 0.8. The maximum overshoot and settling time of the primary response were almost 19.90% and 0.90 s, accordingly, whereas the steady-state error was 0%.

3. It was identified that the maximum pressures of the proportional valve were constant for all conditions, accounting for 15.405 bars.

4. The maximum overshoot was found to be 17.50% at 100 ℃ for VG 32 and the settling time was 0.45 s at 0 ℃ for all of the hydraulic oils, which satisfied the boundary conditions.

In summary, it is expected that this PID control algorithm considering viscosity is able to compensate for the viscous effects of hydraulic oils. It is also expected that this PID control algorithm can perform with accuracy for the temperature-dependent viscosity of any hydraulic oils. The results indicate that the movement of the actuator would be uninformed, as the proportional valve pressures are constant for all of the conditions of the experiment.

In addition, the rice transplanter has required a faster response for accurately controlling and maintaining a uniform planting depth. The planting depth is highly associated with hydraulic actuator displacement. The results indicate that the rice transplanter is capable to plant the seedlings without tilting. The drawback of this study is that the stability test was conducted by only a simulation performance. In the near future, an experimental test bench or field performance will be performed for the validation of the PID control algorithm of the automatic planting depth control system of the rice transplanter. Finally, this control algorithm could be helpful in minimizing the tilting of the planted seedling using a rice transplanter. Ultimately, it would improve the performance and accuracy of the transplanter.

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