

Hydraulic Control Technologies with Robust Stability and Performance for CVT Start Clutch

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ABSTRACT

Honda Multi Matic S is a lightweight compact CVT with a hydraulically controlled wet multiple plate clutch (start clutch) used for starting. The start clutch is controlled with the torque converter as a reference, but the actual pressure is not sensed. This results in an issue in which the start characteristics are affected by temperature changes, age deterioration of the hydraulic circuit, and changes in hydraulic pressure characteristics due to process dispersion of components. Accordingly, in this research, a hydraulic servo system was configured in order to realize robust start clutch control with respect to temperature changes in particular. The controllers were composed of a two degree of freedom control system. In the design of the feedback controller, μ -synthesis was used, and variations in characteristics were actively taken into consideration.

As a result, the performance was enhanced, particularly at low temperatures, and a roughly equivalent rise time and overshoot rate were achieved at both ambient and low temperatures.

1. Introduction

The Honda Multimatic S⁽¹⁾ is a compact and lightweight continuously variable transmission (CVT) that has been developed independently by Honda. The components have been modified to produce a highly efficient and low cost system. Torque converters and electromagnetic clutches can be used as the CVT start equipment, but the Honda Multimatic S uses hydraulically controlled, wet multiple plate clutches (start clutches). In addition, a start clutch is positioned downstream from the pulley (Fig. 1), which achieves flexible start characteristics by controlling torque near the axle.

The start clutch system comprises the electronic control unit (ECU), linear solenoid (LSOL), hydraulic circuit, and wet multiple plate clutches. First, the ECU determines the target pressure from the start torque with reference to the torque converter, and outputs current based on a current versus pressure characteristic map. In accordance with this current, the pistons of the wet multiple plate clutches are operated with hydraulic pressure that was adjusted by the LSOL and hydraulic circuit, and start torque is generated [Fig. 2(a).]

However, since the actual hydraulic pressure is not sensed, the start characteristics are affected by changes in the temperature-dependent response characteristics of the clutch hydraulic pressure. In addition, the start

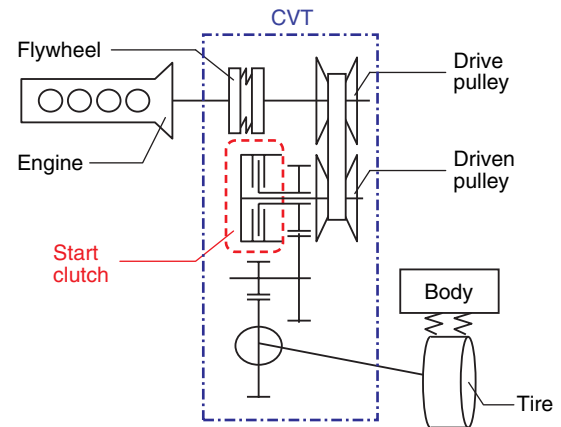


Fig. 1 Layout of start clutch

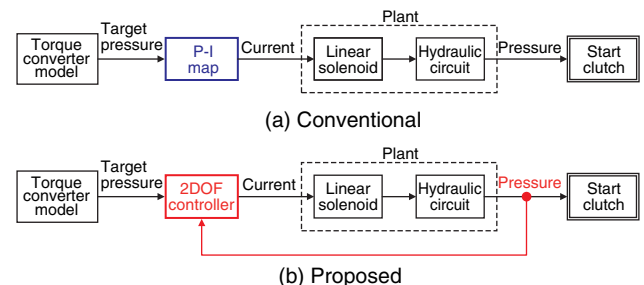


Fig. 2 Block diagram of pressure control

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characteristics may also be changed by variations in the adjustment pressure point, which may be caused by dispersion of the LSOL current, thrust, or the spring constant in the pressure control valve, and age deterioration of the clutch.

In response, this paper sets reducing the effects of temperature changes on the start characteristics as a special objective, and constructs a hydraulic servo system based on electronic control, which uses two degree of freedom (2DOF) control that enables the target tracking and disturbance rejection characteristics to be set independently [Fig. 2 (b)]. Many construction methods have been proposed for 2DOF control and their respective effectiveness reported^{(2), (3)}. Here, the method of positioning feedforward (F/F) control and feedback (F/B) control in parallel⁽⁴⁾ was used.

2. Plant

The start clutch operates when the piston is actuated by hydraulic pressure that has been adjusted by the LSOL (Fig. 3). When current is supplied to the LSOL, thrust is generated to operate the spool valve and open the oil feed port. Oil is supplied from the oil pump to generate clutch pressure. Conversely, the clutch pressure is reduced by lowering the LSOL thrust to open the drain. The pulsation of the line pressure also affects the clutch pressure, so an accumulator is provided to reduce these effects.

2.1. Modeling

In the LSOL, the characteristics of the input current I_{SC} and thrust F_{SC} generated by the LSOL are approximated by a first-order system.

$$F_{SC} = \frac{k_{IF}}{T_{IF} + 1} I_{SC} \quad (1)$$

The flow Q_{SC} at the LSOL opening depends on the LSOL spool displacement x_{SC} and clutch pressure P_{SC} . In

addition, the flow Q_f to the F/B area of the spool is proportionate to the square root of the pressure difference between P_{SC} and the spool pressure P_f .

$$Q_{SC}(x_{SC}, P_{SC}) = \begin{cases} -CA_{SC}(x_{SC})\sqrt{\frac{2P_{SC}}{\rho}} & (0 \leq x_{SC} \leq x_d) \\ CA_{SC}(x_{SC})\sqrt{\frac{2|P_{CR}-P_{SC}|}{\rho}} \text{sgn}(P_{CR}-P_{SC}) & (x_d < x_{SC} \leq x_{SCmax}) \end{cases} \quad (2)$$

$$Q_f(P_{SC}, P_f) = C \frac{\pi d_o^2}{4} \sqrt{\frac{2(P_{SC} - P_f)}{\rho}} \quad (3)$$

ρ : Oil density

x_d : Drain fully closed position

P_{CR} : Line pressure

x_{SCmax} : Stroke length

d_o : Orifice diameter

Here, C is the flow coefficient, which changes according to the oil temperature. The opening area A_{SC} depends on displacement x_{SC} and is expressed by the following equation.

$$A_{SC}(x_{SC}) = \begin{cases} \pi d_m(x_d - x_{SC}) & (0 \leq x_{SC} \leq x_d) \\ 0 & (x_d < x_{SC} < x_o) \\ 2L_N(x_{SC} - x_o) & (x_o \leq x_{SC} < x_N) \\ 2L_N(x_N - x_o) & \\ + \pi d_m(x_{SC} - x_N) & (x_N \leq x_{SC} \leq x_{SCmax}) \end{cases} \quad (4)$$

d_m : Spool diameter of the main area

x_o : Start position of the notch opening

L_N : Notch width

x_N : Fully open notch position

The following equations pertain to P_{SC} and P_f .

$$\begin{aligned} \frac{V_{CL}}{K} \frac{dP_{SC}}{dt} &= Q_{SC}(x_{SC}, P_{SC}) - Q_f(P_{SC}, P_f) - A_{AC} \frac{dx_{AC}}{dt} \\ \frac{V_f}{K} \frac{dP_f}{dt} &= Q_f(P_{SC}, P_f) + A_f \frac{dx_{SC}}{dt} \end{aligned} \quad (5)$$

V_{CL0} : Initial capacity of the accumulator area

V_{f0} : Initial capacity of the F/B area

A_{AC} : Pressure receiving area of the accumulator area

A_f : Pressure receiving area of the LSOL area

However, note that: $V_{CL} = V_{CL0} + A_{AC} x_{AC}$ and $V_f = V_{f0} - A_f x_{SC}$. K is the bulk modulus, which changes according to the oil temperature and air mix rate inside the oil.

The following relationship exists between x_{SC} , from the balance of forces on the spool, and spool displacement of the accumulator area, x_{AC} .

$$\begin{aligned} m_{SC} \frac{d^2 x_{SC}}{dt^2} + D_{SC} \frac{dx_{SC}}{dt} + k_{SC} x_{SC} &= F_{SC} - P_f A_f - F_{fld} - f_{SC0} \\ m_{AC} \frac{d^2 x_{AC}}{dt^2} + D_{AC} \frac{dx_{AC}}{dt} + k_{AC} x_{AC} &= P_{SC} A_{AC} - f_{AC0} \end{aligned} \quad (6)$$

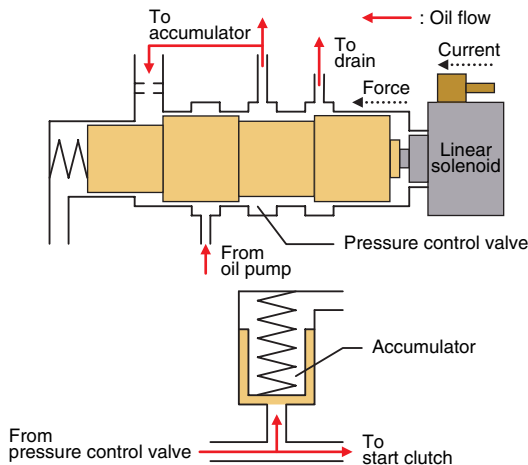


Fig. 3 Hydraulic circuit

m_{SC} : Spool mass of the LSOL area
 m_{AC} : Spool mass of the accumulator area
 k_{SC} : Spring constant of the LSOL area
 k_{AC} : Spring constant of the accumulator area
 f_{SC0} : Spring initial load of the LSOL area
 f_{AC0} : Spring initial load of the accumulator area
 F_{fld} : Fluid force

Here, the ranges of motion for the spools are $0 \leq x_{SC} \leq x_{SC \max}$ and $0 \leq x_{AC} \leq x_{AC \max}$ respectively. D_{SC} and D_{AC} are the coefficients of viscosity, which change according to the oil temperature.

2.2. Linear Model Derivation

The following state space is obtained by expressing the input as current δI_{SC} , the output as clutch pressure δP_{SC} , and linearizing the basic relationship equation obtained in the previous section.

$$\begin{cases} \delta \dot{x} = A\delta x + B\delta u \\ \delta y = C\delta x + D\delta u \end{cases}$$

$$\delta x = (\delta x_{SC}, \delta x_{AC}, \delta \dot{x}_{SC}, \delta \dot{x}_{AC}, \delta P_{SC}, \delta P_f, \delta F_{SC})^T$$

$$\delta u = \delta I_{SC}, \delta y = \delta P_{SC}$$

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ a_{31} & 0 & a_{33} & 0 & a_{35} & a_{36} & a_{37} \\ 0 & a_{42} & 0 & a_{44} & a_{45} & 0 & 0 \\ a_{51} & 0 & 0 & a_{54} & a_{55} & a_{56} & 0 \\ 0 & 0 & a_{63} & 0 & a_{65} & a_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{77} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ b_7 \end{bmatrix}$$

$$C = [0 \ 0 \ 0 \ 0 \ c_5 \ 0 \ 0], D = 0$$

$$a_{31} = -\frac{k_{SC} + K_{fldx}}{m_{SC}}, a_{33} = -\frac{D_{SC}}{m_{SC}}, a_{35} = -\frac{K_{fldP}}{m_{SC}}, a_{36} = -\frac{A_f}{m_{SC}} \quad (7)$$

$$a_{37} = \frac{1}{m_{SC}}, a_{42} = -\frac{k_{AC}}{m_{AC}}, a_{44} = -\frac{D_{AC}}{m_{AC}}, a_{45} = \frac{A_{AC}}{m_{AC}}$$

$$a_{51} = \frac{K_{KSC}}{V_{CL}}, a_{54} = -\frac{K_{AAC}}{V_{CL}}, a_{55} = \frac{K(K_{SCP} - K_f)}{V_{CL}}, a_{56} = \frac{KK_f}{V_{CL}}$$

$$a_{63} = \frac{KA_f}{V_f}, a_{65} = \frac{KK_f}{V_f}, a_{66} = -\frac{KK_f}{V_f}, a_{77} = -\frac{1}{T_{IF}}$$

$$b_7 = \frac{k_{IF}}{T_{IF}}, c_5 = \frac{1}{10^4 g}$$

Figures 4 and 5 show the step response when the oil temperature is 80 °C and -10 °C, and compare the actual response with a simulation using the obtained linear model. There is a good match in both cases. Figure 6 shows a large variation in performance, with a break frequency of approximately 100 (rad/s) when the temperature is 80 °C and approximately 40 (rad/s) when the temperature is -10 °C.

3. Controller Design

3.1. Controller Structure

The controller comprises a 2DOF control system to

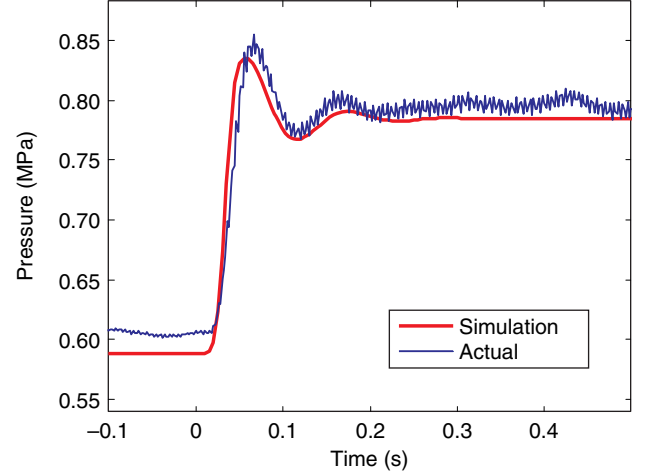


Fig. 4 Step response (80 °C)

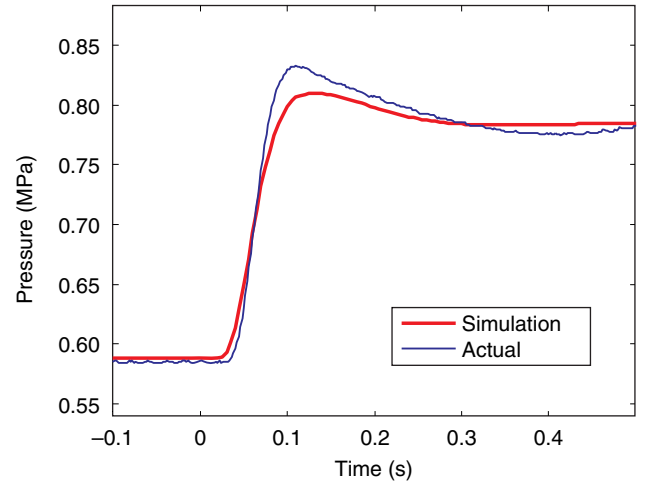


Fig. 5 Step response (-10 °C)

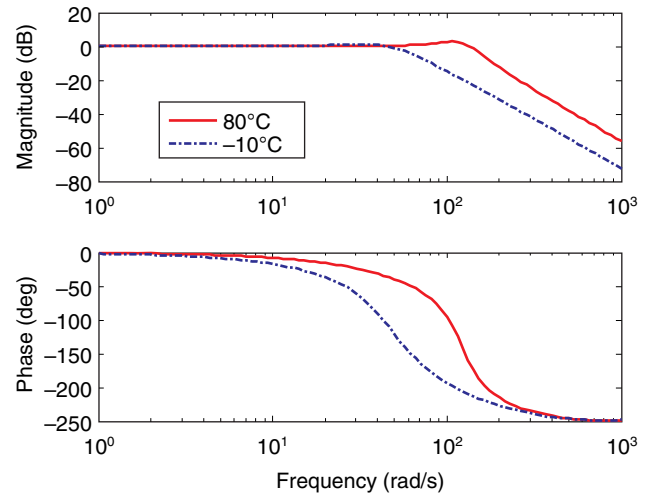


Fig. 6 Bode diagram

help achieve both a quick response and robustness. Although many construction methods have been proposed for 2DOF control, as shown in Fig. 7, the method of positioning an F/F controller and F/B controller in parallel was used.

First, to facilitate the setting of a target response, F/F control is expressed by the following equation, with $F(s)$ as the design parameter.

$$u_{ff}(s) = F(s)P(s)^{-1}r(s) \quad (8)$$

At this time, if there are neither disturbances nor modeling errors, then the following is established.

$$y(s) = P(s)u_{ff}(s) = F(s)r(s) \quad (9)$$

Furthermore, to prepare for cases where issues such as modeling errors invalidating the above equation, the following equation expresses the F/B for the difference between the desired output $F(s)r(s)$ and actual output $y(s)$.

$$u_{fb}(s) = K(s)(F(s)r(s) - y(s)) \quad (10)$$

The control input is established by the following.

$$u(s) = u_{ff}(s) + u_{fb}(s) \quad (11)$$

This structure shapes the target response with $F(s)$ and reduces the effects of disturbances and plant characteristic perturbations with $K(s)$, and so has the advantage that these characteristics can be set independently.

As shown in the previous section, there is a large variation in performance between 80 °C and -10 °C oil temperature. For a single F/B controller to maintain robustness under the influence of these kinds of large perturbations, there is no option except to sacrifice control performance and set a conservative F/B. Consequently, two ranges were set: 20 °C or below, and above 20 °C. Separate controllers were designed for these ranges, and the system switches between them. In this way, both control performance and robustness could be achieved.

3.2. F/F Controller Design

First, reference model $F(s)$ was determined to satisfy the specifications of the rise time. Next, the plant $P(s)$ inverse system was used to obtain $H(s)$. In other words: $H(s) = F(s)P(s)^{-1}$.

3.3. F/B Controller Design

H_∞ control is a typical method for robust control

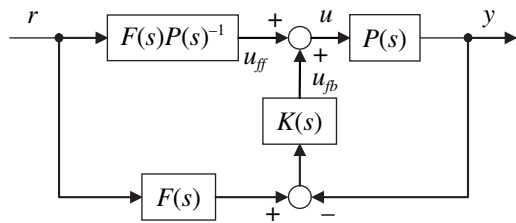


Fig. 7 Two degree of freedom control system

systems. Although design of a controller to stabilize plant set with uncertainties such as time delays and characteristic perturbations in the hydraulic circuit due to temperature changes can be achieved, as a rule, each uncertainty has to be gathered. However, in reality, uncertainties rarely gather in one location only. In general, they are found in multiple locations such as the actuator and sensor (Fig. 8). If these uncertainties are all dealt with together (Fig. 9), areas where uncertainties do not actually exist will also be included. As a result, unnecessary and excessive constraints will be placed on the controller, so that the disturbance rejection characteristics and quick response will not be sufficient.

In contrast, with the μ synthesis⁽⁵⁾, uncertainties can be dealt with as they are. In Fig. 10, the off-diagonal elements are 0 and only the uncertainties that actually exist are dealt with. Using this method, a controller with a better performance can be designed.

Here, a μ controller is designed for structured uncertainties, while considering the generalized plant shown in Fig. 11. The weighting function $W_2(s)$ represents the range of multiplicative perturbations. The broken line in Fig. 12 shows the result of plotting the difference between the nominal model obtained from the average value of anticipated perturbations, such as parameter changes dependent on the temperature and time delays,

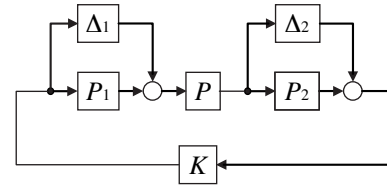


Fig. 8 Original uncertainties

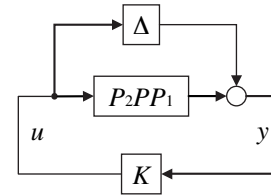


Fig. 9 Unstructured uncertainties

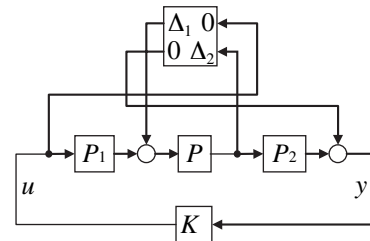


Fig. 10 Structured uncertainties

and the perturbation model that was obtained from the maximum and minimum values. By selecting $W_2(s)$ which covers these plots, robust stabilization was achieved for the anticipated perturbations. $W_1(s)$ is the dynamic characteristic of disturbance, $W_3(s)$ is the weight for the input, and $W_4(s)$ is the fitting parameter. These are selected as shown in Fig. 13 after trial and error.

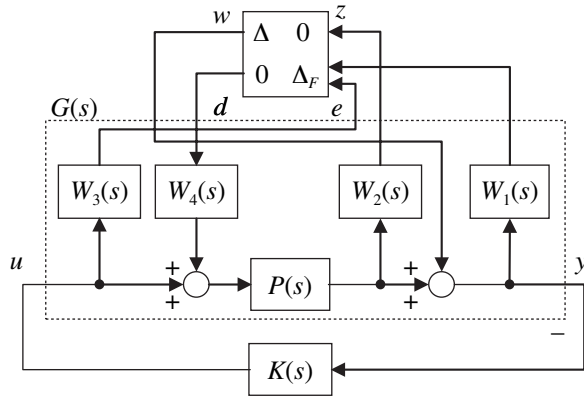


Fig. 11 Generalized plant

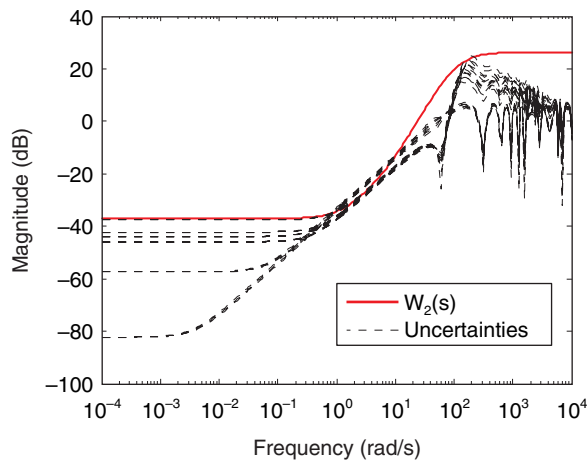


Fig. 12 Bode diagram of uncertainty and weighting function

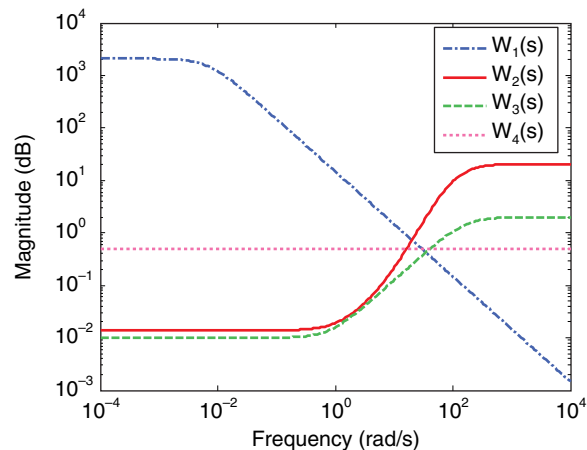


Fig. 13 Bode diagram of weighting function

Table 1 Result of DK iteration

Number of times	1	2	3	3'
Order of K	7	11	13	13
Order of D	0	4	6	6
γ	1.563	0.941	0.922	0.940
μ	1.451	0.941	0.922	0.939

However, DK iteration, the most typical method, was used to obtain the μ controller.

Table 1 shows the trends for μ and γ with DK iteration. 3' for "Number of times" in the table is a recalculation with γ set as the suboptimal. Figure 14 shows the μ plot for a closed-loop system constructed with a μ controller obtained with the first and third DK iteration. Figure 14 shows that for the first iteration, the μ value exceeded 1 in the vicinity of 10-100 (rad/s), but it was below 1 over the entire range for the third iteration. As shown in Fig. 15, this is because the weighting function is adjusted automatically in the DK iteration process, and in particular, the intermediate frequency band is optimized. The Bode diagram of the controller in Fig. 16 shows that the phase proceeds rapidly in the vicinity

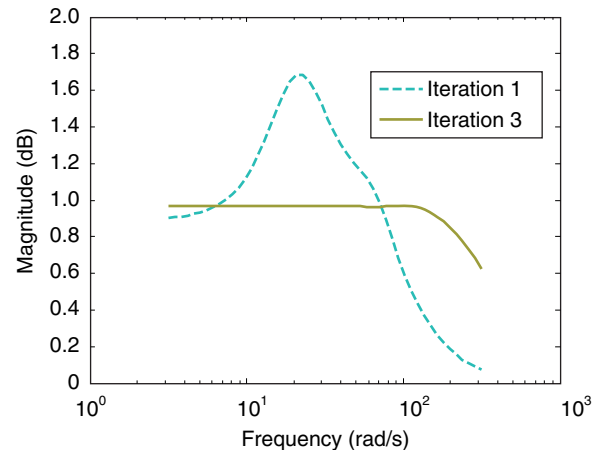


Fig. 14 μ plot

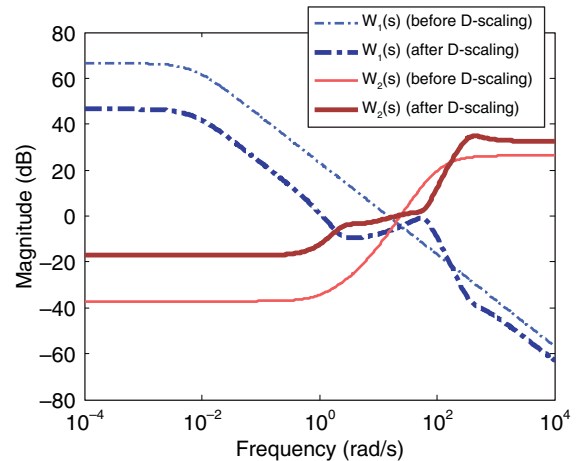
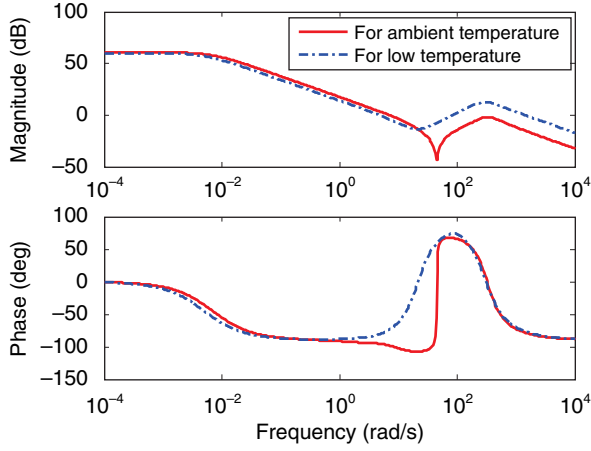


Fig. 15 Result of D-scaling


 Fig. 16 Bode diagram of μ controller

of 10-100 (rad/s), and it can be understood that strong stabilization has been provided to widen the control band.

The ideal frequency characteristics for the controller are typically to increase the gain in order to maintain steady-state characteristics in the low range, while having cut-off characteristics and a gradient of 40-60 (dB/dec) in the high range to reduce the influence of uncertainties and noise. However, other methods can also achieve these objectives with no difference. The intermediate frequency band, however, has a large influence on performance, for which adjustment is difficult. As already described, in μ synthesis, the intermediate frequency band is automatically optimized to a level that is hardly attained manually, so it is a useful tool.

4. Actual System Test Results

4.1. Step Response

Figures 17 and 18 show the step response performed with an actual system, with oil temperatures of 80 °C and -10 °C. At 80 °C, the rise time was approximately the same compared to the open-loop control and the overshoot rate was reduced by approximately 65%. At -10 °C, the

rise time was approximately 20% shorter and the overshoot rate was approximately 0%. These resulted in almost the same rise time and overshoot rate at both 80 °C and -10 °C.

From the controller outputs in Fig. 17 and 18, it can be understood that sufficient rising characteristics are maintained by the F/F controller output at first, then deviations from the target response, particularly the

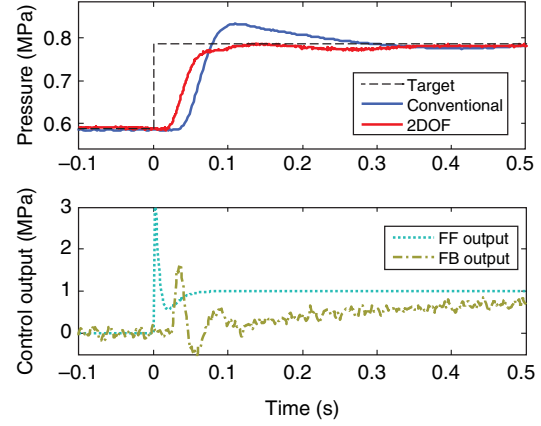


Fig. 18 Step response (-10 °C)

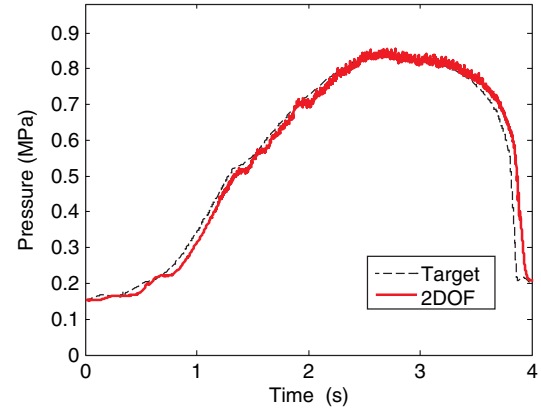


Fig. 19 Operating results (80 °C)

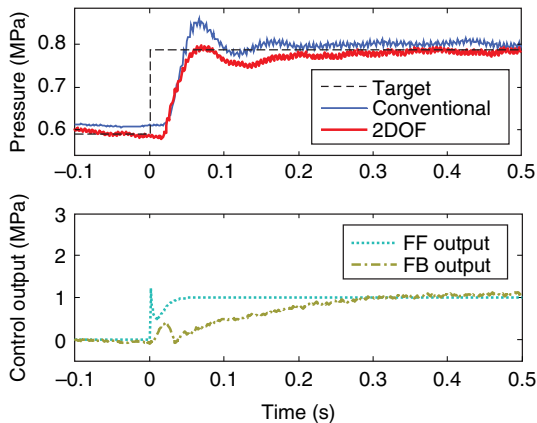


Fig. 17 Step response (80 °C)

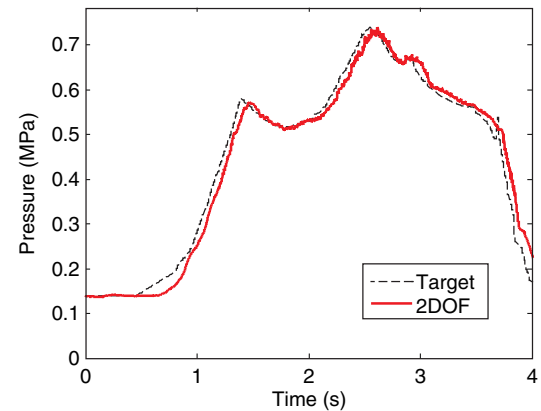


Fig. 20 Operating results (5 °C)

overshoot and steady-state errors, are reduced by the F/B controller, and the 2DOF control system is functioning effectively.

4.2. Operating Results

Figures 19 and 20 show the actual operating results. It can be understood that tracking is good at both 80 °C and 5 °C.

5. Conclusion

A hydraulic servo system was constructed using a 2DOF control system to achieve the robust start clutch control of the CVT start clutch for temperature changes. As a result, the following were achieved.

- (1) The overshoot rate was reduced by approximately 65% at ambient temperature (approximately 80 °C).
- (2) The rise time was shortened by approximately 20% and an overshoot rate of approximately 0% was achieved at low temperature (approximately -10 °C).
- (3) Almost the same values were achieved for the rise time and overshoot rate for both ambient temperature and low temperatures.

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