

Damper Control Using a Sliding Mode Algorithm

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ABSTRACT

Sliding mode algorithms are highly responsive and robust, leading to their use in air-fuel ratio and device control systems. Altering the switching line gradient enables their ability to suppress disturbance to be freely set. However, to date no applied research has been conducted to verify these characteristics. In the research presented in this paper, the ability of a sliding mode algorithm to suppress disturbance was lowered to enable the construction of a high-compliance servo control system used for shift control in an automated manual transmission where compliance control is required during shifting. The sliding mode algorithm was employed in position control to ensure contact between the sleeve and the synchronizer ring and force control to enable the synchronization of the main shaft and counter-shaft through sleeve force. The compliance established between the sleeve and the synchronizer ring by this means has enabled the previously required mechanical buffer to be eliminated, and shift time has been reduced to 350msec. In addition, stabilizing sleeve force has suppressed bouncing and stoppage of the sleeve and failure of the synchronizer ring during shifting.

1. Introduction

Sliding mode control⁽¹⁾ (SMC) is highly responsive and robust, and has been used for air-fuel ratio control^{(2), (3)}, device control⁽⁴⁾, and other systems. In addition, SMC has the ability to freely set the disturbance suppression characteristic of the system by altering the gradient, V_{POLE} , of the switching function. However, no applied research had previously been conducted on this ability. This research focused on this characteristic, by way of a controller to dampen impacts (damper control) and to lower the disturbance suppression characteristic by altering V_{POLE} .

Figure 1 shows an outline of the variable-speed gear^{(5), (6)} used as the controlled object in this research. The shift rod is driven by the motor, and shifting is performed by coupling the sleeve to the next gear via the fork. In automated manual

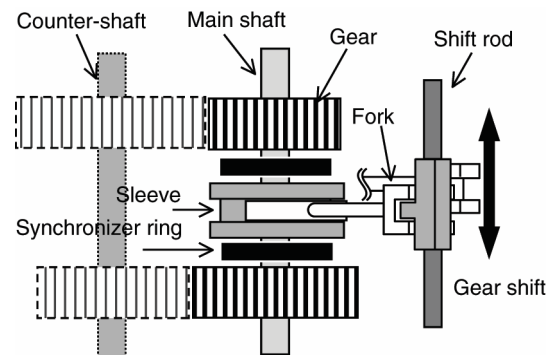


Fig. 1 Outline of AMT mechanism

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transmissions (AMT), the sleeve contacts the synchronizer ring in the shortest time possible during shifting, then a certain pressing force is applied to the synchronizer ring to synchronize the revolution of the main shaft and counter-shaft. Often when the sleeve contacts the synchronizer ring the sleeve bounces off the synchronizer ring, or the sleeve is pressed into the gear by an excessive impact force before synchronizing with the synchronizer ring. Different methods have been used to counter this, such as reducing the variation at the target position to lower the sleeve movement speed just before contact between the synchronizer ring and the sleeve, or recently by adding a damper system to mechanically dampen the impact force. However, the former method increased the shifting time and the latter one resulted in a more complex system of additional weight and size.

This research applied SMC to AMT in order to shorten the shifting time without the use of a mechanical damper system that was formerly considered necessary. In addition, this also suppressed bouncing and stoppage of the sleeve and prevented failure of the synchronizer ring when shifting gears.

2. Features of Sliding Mode Control

In SMC, the deviation $E(k)$ is defined as the difference between actual position $P(k)$ and target value of controlled object $P_{cmd}(k)$ in Eq. (1), and the switching function $\sigma(k)$ by Eq. (2).

$$E(k) = P(k) - P_{cmd}(k) \quad (1)$$

$$\sigma(k) = E(k) + V_{POLE}E(k-1) \quad (2)$$

Figure 2 shows the phase plane that has $E(k)$ and $E(k-1)$ as the respective coordinate axes. The straight line indicates that the switching function σ is zero, which is called the switching line on the phase plane (see Fig. 2).

SMC restrains the combination of $E(k)$ and $E(k-1)$ (the deviation state) to the switching line, and then the deviation state converges toward the origin of the phase plane along the switching line. In other words, the deviation $E(k)$ converges to zero. The switching line is expressed by Eq. (3) as the relationship between $E(k)$ and $E(k-1)$, and V_{POLE} is set within the range in Eq. (4).

$$E(k) = -V_{POLE}E(k-1) \quad (3)$$

$$-1 < V_{POLE} < 0 \quad (4)$$

Therefore, when the deviation state reaches the switching line after the reaching mode (see Fig. 2), it then converges towards the origin of the phase plane over time. This behavior on the switching line is called sliding mode (see Fig. 2), and the convergence speed of the deviation state toward the origin can be set by V_{POLE} .

As an example of this, Fig. 3 shows the change in the disturbance suppression characteristic according to V_{POLE} when step disturbance is applied. The convergence speed of

the deviation increases as V_{POLE} approaches 0, and decreases as V_{POLE} approaches -1 . This indicates that the compliance can be set by the gradient of the switching line, V_{POLE} .

In this research, the disturbance suppression characteristic is lowered to allow the construction of a high-compliance servo system, and SMC is applied to the shift control of AMT which requires damper control during shifting. This attempt aimed to perform the damping operation in a short period of time without the use of a mechanical damper system. Consequently, V_{POLE} is set to a small value in order to lower the disturbance suppression characteristic when the sleeve contacts with the synchronizer ring. This makes it possible to electrically provide compliance between the sleeve and the synchronizer ring. These details are described below.

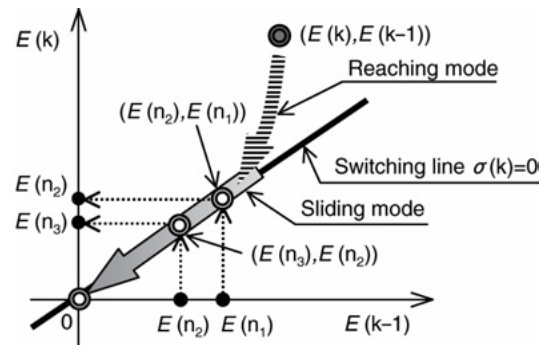


Fig. 2 Sliding mode

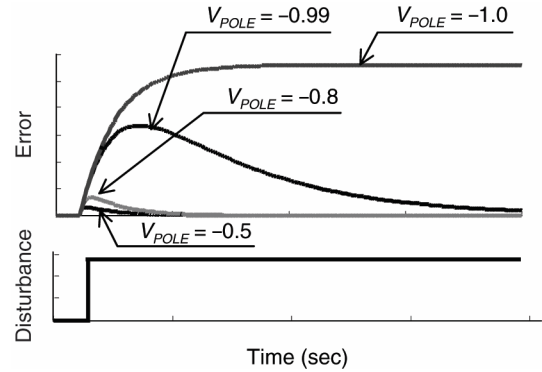


Fig. 3 Effect of changed V_{POLE}

3. Modeling the Shift Mechanism

Figure 4 shows the contact behavior between the sleeve and the synchronizer ring modeled as a collision between an inertial system and a spring-mass system. Here the synchronizer ring is viewed as a spring-mass system having a high stiffness K_{sc} , the motor, fork and other elements are viewed as the inertial system J_m .

Equation (5) is an equation of motion for inertial system J_m which takes into account the reaction force F_{sc} from the synchronizer ring and the back electromotive force.

$$J_m \dot{\omega} = \frac{K_m(V_{in} - K_m' \omega)}{R_m} - R_{sc} F_{sc} \quad (5)$$

J_m : Mass of motor, sleeve, fork and shift rod
 V_{in} : Input voltage
 ω : Revolution speed of motor
 K_m : Torque constant
 K_m' : Back electromotive force constant
 R_m : Transformation coefficient of torque
 R_{sc} : Gear ratio of revolution angle of motor and inertial system

On the other hand, the relationship between the revolution speed ω and revolution angle θ of the motor and the sleeve position P_{sc} is obtained by Eq. (6).

$$\begin{cases} P_{sc} = R_{sc} \theta \\ \dot{P}_{sc} = R_{sc} \dot{\theta} = R_{sc} \omega & \therefore \omega = \frac{\dot{P}_{sc}}{R_{sc}} \\ \ddot{P}_{sc} = R_{sc} \dot{\omega} & \therefore \dot{\omega} = \frac{\ddot{P}_{sc}}{R_{sc}} \end{cases} \quad (6)$$

By substituting Eq. (6) into Eq. (5) and rearranging, a continuous-time model is expressed by Eq. (7).

$$\ddot{P}_{sc} = \frac{-K_m K_m'}{J_m R_m} \dot{P}_{sc} + \frac{K_m R_{sc}}{J_m R_m} V_{in} - \frac{R_{sc}^2 R_m}{J_m R_m} F_{sc} \quad (7)$$

In order to express Eq. (7) as a discrete-time model, the state variable P_{sc} is expressed as shown in Eq. (8).

$$x_1 = P_{sc}, \quad x_2 = \frac{dx_1}{dt} \dot{P}_{sc}, \quad \frac{dx_2}{dt} = \ddot{P}_{sc} \quad (8)$$

Equation (8) was then substituted into Eq. (7). Here, with the sampling period defined as T , the continuous-time model in Eq. (7) is transformed by Euler approximation as shown in Eq. (9).

$$\begin{aligned} x_1(k+1) = & \left(2 - \frac{K_m K_m'}{J_m R_m} T\right) x_1(k) - \left(1 - \frac{K_m K_m'}{J_m R_m} T\right) x_1(k-1) \\ & + \frac{K_m R_{sc}}{J_m R_m} T^2 V_{in}(k) - \frac{R_{sc}^2}{J_m} T^2 F_{sc} \end{aligned} \quad (9)$$

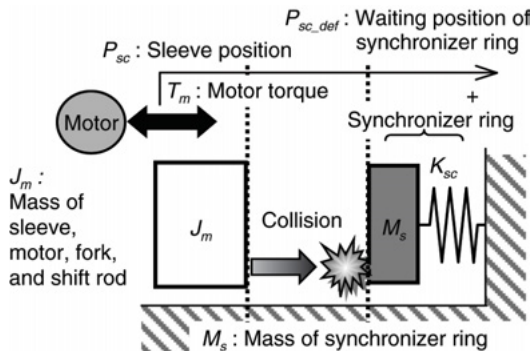


Fig. 4 Modeling of shift mechanism

Therefore, the discrete-time model is expressed as the Auto-Regressive with eXogeneous (ARX) model⁽⁷⁾ shown in Eq. (10).

$$P_{sc}(k+1) = a_1 P_{sc}(k) + a_2 P_{sc}(k-1) + b_1 V_{in}(k) + d \quad (10)$$

$$\begin{cases} a_1 = 2 - \frac{K_m K_m'}{J_m R_m} T, \quad a_2 = -1 + \frac{K_m K_m'}{J_m R_m} T, \\ b_1 = \frac{K_m R_{sc}}{J_m R_m} T^2, \quad d = \frac{R_{sc}^2}{J_m} T^2 F_{sc} \end{cases} \quad (11)$$

The model parameters a_1 , a_2 , and b_1 in Eq. (11) are identified by the least squares method based on the input voltage V_{in} (V) and the sleeve position P_{sc} (mm) data.

4. Control Design

4.1. Control Requirements

The control requirements for the motorized AMT shift actuator are as follows:

- (1) Tracking performance to the target value
- (2) Prevention of sleeve bounce, stoppage, and collision
- (3) Synchronization of main shaft and counter-shaft revolutions

4.2. Control System Configuration

The synchronizer ring control system is comprised of a V_{POLE} scheduler block, a target value calculation block and a compliance controller as shown in Fig. 5.

4.3. Mode Judgment

The sleeve behavior during shifting is classified into the following modes:

- MODE1: Shift command - Synchronizer ring waiting position
 MODE2: Contact with synchronizer ring - Synchronization of main shaft and counter-shaft revolutions
 MODE3: Engagement after synchronization - End of shifting operation

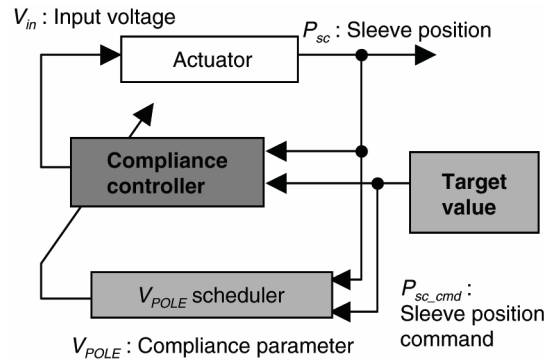


Fig. 5 Block diagram of compliance controller

The mode judgment conditions are given by the sleeve position. However, when shifting from MODE1 to MODE2, P_{sc} variation DP_{sc} is used for the mode judgment shown in Eq. (12).

$$DP_{sc}(k) = P_{sc}(k) - P_{sc}(k-1) \quad (12)$$

When the value DP_{sc-wv} obtained by wavelet transformation of Eq. (12) exceeds the MODE2 judgment threshold value W_{mode2} , the system judges that revolution synchronization has started and shifts to MODE2. The mode judgment conditions for each mode are as follows.

MODE1: $P_{sc} < P_{sc-def}$

MODE2: $P_{sc} > P_{sc-def}$ and $DP_{sc-wv} < W_{mode2}$

MODE3: $P_{sc} > P_{sc-mode3}$

DP_{sc-wv} : Wavelet transformed value of DP_{sc}
 W_{mode2} : MODE2 judgment threshold value
 $P_{sc-mode3}$: MODE3 judgment threshold value (sleeve position)

Wavelet transformation is used to block frequency components of the Nyquist frequency or higher, and to amplify and output the low-frequency component gain. This is an effective filtering method for extracting the low-frequency range behavior of controlled objects with high levels of backlash and friction, such as transmissions. The wavelet transform algorithm is comprised as shown in Fig. 6, and performs filtering by repeating the process of half band low-pass filter G and the data decimation processing two times.

4.4. Sliding Mode Controller

4.4.1. V_{POLE} setting

As shown in Fig. 7, V_{POLE} is set to a large value (< 0) to enhance the tracking performance of the actual position P_{sc} to the target value P_{sc-cmd} and to raise the disturbance suppression characteristic until the sleeve contacts the synchronizer ring.

In addition, when the sleeve reaches the synchronizer ring waiting position P_{sc-def} , V_{POLE} is set to a value near -1 to lower the disturbance suppression characteristic in preparation for contact with the synchronizer ring and protect the synchronizer ring. Therefore, V_{POLE} is set as follows in each mode.

MODE1: Large V_{POLE} : High convergence speed

MODE2: Small V_{POLE} : High impact damping ability

MODE3: Large V_{POLE} : High convergence speed

4.4.2. Derivation of the control inputs

The control input V_{in} of the sliding mode controller is obtained by Eq. (13). V_{in} is expressed as the sum of the three inputs of the equivalent control input U_{eq} , reaching law input U_{rch} , and adaptive law input U_{adp} .

$$V_{in}(k) = U_{eq}(k) + U_{rch}(k) + U_{adp}(k) \quad (13)$$

The equivalent control input U_{eq} is used to restrict the deviation state to the switching line. Strictly speaking, U_{eq} holds the deviation state at an arbitrary position on the phase plane.

U_{eq} is calculated as a value that satisfies Eq. (14).

$$\sigma(k+1) = \sigma(k) \quad (14)$$

Here, $\sigma(k)$ is the switching function, and is defined by Eq. (16) using the deviation $E_{sc}(k)$ obtained from the actual sleeve position and the sleeve position target value in Eq. (15).

$$E_{sc}(k) = P_{sc}(k) - P_{sc-cmd}(k) \quad (15)$$

$$\sigma(k) = E_{sc}(k) + V_{POLE}E_{sc}(k-1) \quad (16)$$

Substituting Eq. (10), (15) and (16) into Eq. (14) and rearranging, U_{eq} is obtained as shown in Eq. (17).

$$U_{eq}(k) = \frac{1}{b_1} \{ (1 - V_{POLE} - a_1)P_{sc}(k) + (V_{POLE} - a_2)P_{sc}(k-1) + P_{sc-cmd}(k+1) + (V_{POLE} - 1)P_{sc-cmd}(k) - V_{POLE}P_{sc-cmd}(k-1) \} \quad (17)$$

The reaching law input U_{rch} is used to converge the deviation state toward the switching line and is expressed by Eq. (18).

$$U_{rch}(k) = -\frac{K_{rch}}{b_1} \sigma(k) \quad (18)$$

K_{rch} : Reaching law gain

The adaptive law input U_{adp} is used to suppress modeling error and disturbance, and to place the state onto the switching line. U_{adp} is expressed by Eq. (19).

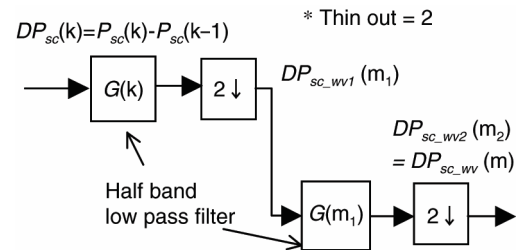


Fig. 6 Wavelet transform algorithm

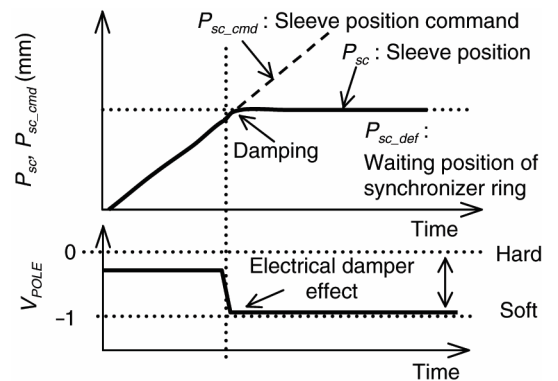


Fig. 7 Compliance effect

$$U_{adp}(k) = -\frac{K_{adp}}{b_1} \sum_{i=0}^k \sigma(i) \quad (19)$$

K_{adp} : Adaptive law gain

4.5. Calculation of the Target Values

The ramped path that is temporarily held at the synchronizer ring balk position shown in Fig. 8 is used as the target value. At this time, the balk position is set to the maximum design tolerance value, but the variation of the actual balk position causes the variance of the sleeve pressing force during revolution synchronization.

Therefore, when the sleeve exceeds P_{sc_def} and stops at the target value hold portion shown in Fig. 9, SMC displaces P_{sc_cmd} to the addition target value U_{fb_cmd} by voltage feedback in order to stabilize the pressing force.

Equations (20) to (24) show equations of voltage feedback.

$$U_{fb}(k) = U_{fb_ini}(k) + U_{rch_ufb}(k) + U_{adp_ufb}(k) \quad (20)$$

$$U_{rch_ufb}(k) = -K_{rch_ufb} \sigma_{ufb}(k) \quad (21)$$

$$U_{adp_ufb}(k) = -K_{adp_ufb} \sum_{i=0}^k \sigma_{ufb}(i) \quad (22)$$

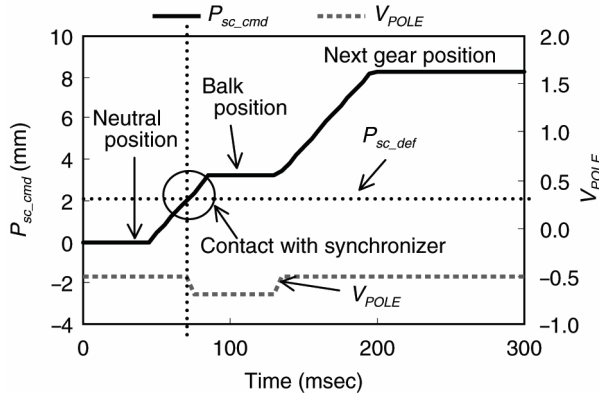


Fig. 8 Time series data for target value

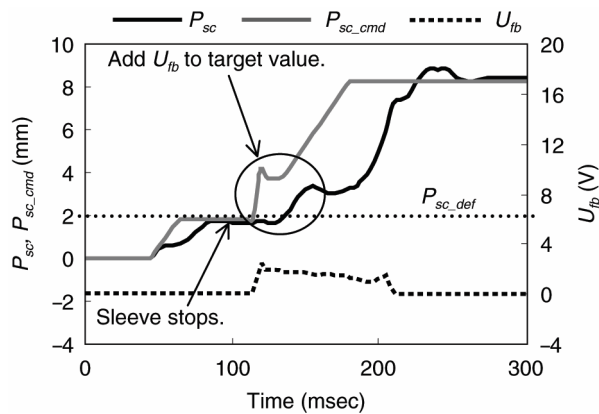


Fig. 9 Alteration of target value by voltage feedback

$$\sigma_{ufb}(k) = E_{ufb}(k) + V_{POLE_ufb} E_{ufb}(k-1) \quad (23)$$

$$E_{ufb}(k) = V_{in_ave}(k) - U_{fb_cmd} \quad (24)$$

$U_{fb_ini}(k)$: Voltage feedback initial value
 $V_{in_ave}(k)$: Input voltage moving average value
 U_{fb_cmd} : Voltage addition target value

5. Vehicle Test Results

5.1. Effects of Varying V_{POLE}

Figure 10 shows the test results when there is no target value hold portion, V_{POLE} is constant at -0.45 , and mode judgment is not performed. Figure 10 shows the behavior when shifting from the previous gear position through the neutral position to the next gear position. The sleeve advances at a constant speed near the synchronizer ring waiting position P_{sc_def} , which causes the synchronizer ring and the sleeve to collide and the elastic deformation of the synchronizer ring. If too great of an impact force is applied, the sleeve may be pushed into the gear without synchronizing or may bounce back to the engagement dog.

Figure 11 shows the results when there is no target value hold portion, but mode judgment is performed and V_{POLE} is varied.

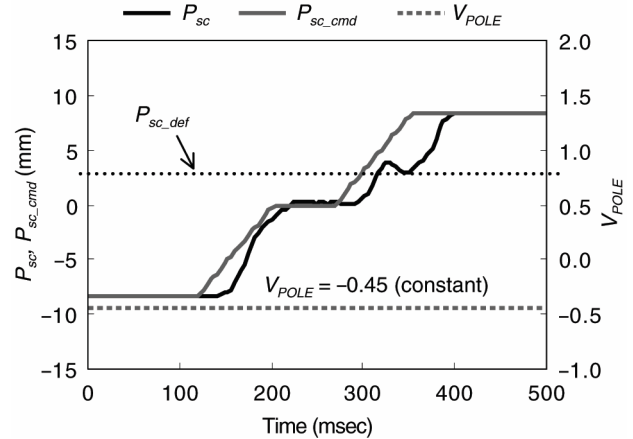


Fig. 10 Test results for constant V_{POLE}

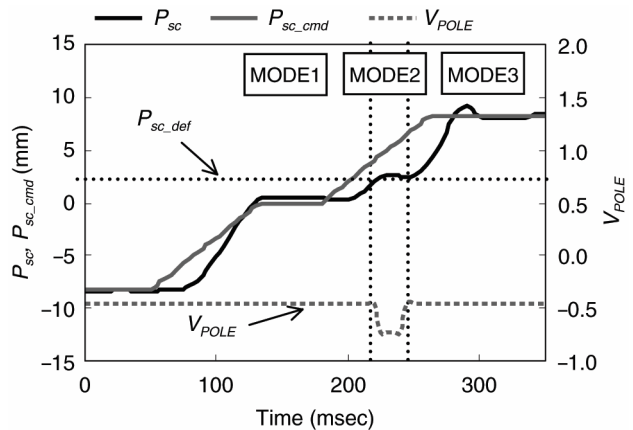


Fig. 11 Test results for variable V_{POLE}

The above-mentioned mode judgment conditions are applied as the V_{POLE} switching conditions. When the sleeve position P_{sc} moves to the synchronizer ring waiting position P_{sc_def} and the sleeve position variation DP_{sc} satisfies the MODE2 conditions, V_{POLE} changes from -0.45 to -0.75 to enhance the compliance. As a result, sleeve bouncing such as that shown in Fig. 10 does not occur.

5.2. Effects of the Target Value Calculation Block

Figure 12 shows the results of adding a target value calculation block to prevent sleeve stoppage due to insufficient pressing force toward the synchronizer ring. When the sleeve exceeds the synchronizer ring resting position P_{sc_def} but stops even though the mode shifts from MODE2 to MODE3, the control input $V_{in}(k)$ is increased by voltage feedback. As a result, the sleeve is pressed slowly to the next gear position by the stabilized pressing force. In addition, gear shifting is performed in the short time of 350 msec.

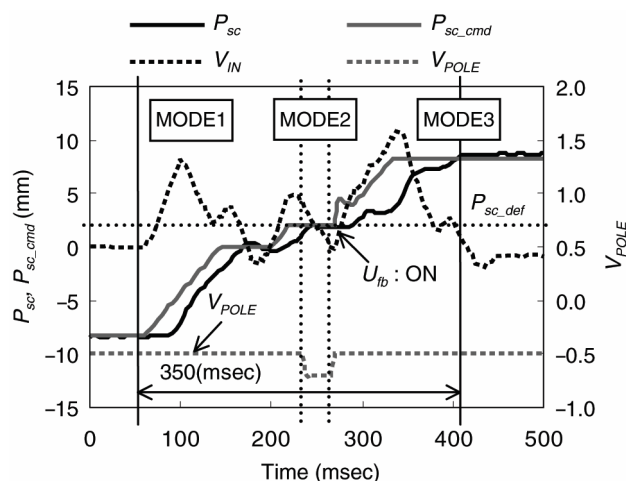


Fig. 12 Test results of for alteration of target value

6. Conclusion

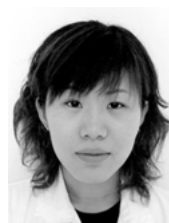
Lowering the disturbance suppression characteristic by altering the SMC switching function gradient V_{POLE} was applied to damper control. This realized the following results for AMT which was the controlled object.

- (1) Gear shifting could be performed in a short time (350 msec) without the use of a mechanical damper system by providing compliance between the sleeve and the synchronizer ring.
- (2) The sleeve pressing force during shifting was stabilized by increasing the input voltage by voltage feedback when the sleeve stopped, which made it possible to suppress bouncing and stoppage of the sleeve and prevent failure of the synchronizer ring when shifting gears.

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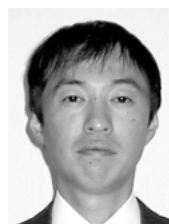
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