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Paper

Speed Control Method for Tilling Claw of Electric Tiller Considering Actual Periodic Reaction Torque

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In a push-type electric tiller, the vehicle vibrates when the ground shoves the tilling claw during tilling motion. A torque is generated from the ground during tilling, and it is called reaction torque. Vehicle vibration degrades the operability of the vehicle and creates irregularity in the soil. Therefore, a tilling claw should maintain a constant speed, and should compensate for the reaction torque from tilling. The reaction torque from tilling has a periodicity. Therefore, repetitive control is suitable for the speed control of the tilling claw. In practical situations, the periodicity of the reaction torque from tilling changes when the speed of the tilling claw changes. Furthermore, there are variations in the condition of the soil surface. Repetitive control does not compensate for the variation in the periodicity and condition of the soil. This study proposes a method that combines two other methods. The first method compensates for the variation in the periodicity of the reaction torque from tilling. The second method estimates and compensates for the variation in the soil surface. The effectiveness of the proposed method is confirmed based on the experimental results.

Keywords: electric tiller, speed control, repetitive control, reaction torque from tilling

1. Introduction

In Japan, agriculture is conducted in both small and medium scales; thus, a push-type electric tiller is suitable for Japanese agriculture [1][2]. Furthermore, agriculture technologies with high labor productivity are needed in developing countries [3]. A push-type electric tiller is one of the agriculture technologies with high labor productivity. Figure 1 shows a push-type electric tiller. An engine-driven tiller has high power and low maintainability and operability, while an electric tiller has low power and high maintainability and operability [4][5].

Farmers are aging, and elder farmers already have a weak musculature. Additionally, the low operability of a tiller is an obstacle for novice farmers. In previous research [6][7], disturbances are compensated for using driven wheels to improve operability. This compensation method targets disturbances from the ground to the driven wheels. Thus, the reaction torque from tilling is not assumed. The reaction torque from tilling is not accurately compensated for solely by driven wheels because the reaction torque from tilling is propagated to a vehicle body through the tilling claw mechanism. The relationship between the tilling claw and the reaction torque from tilling is more intimate than that between the driven wheels and the reaction torque from tilling. Therefore, this study focuses on compensating for the reaction torque from tilling using a tilling claw.

The reaction torque from tilling has periodicity [8][9]. A zero-order disturbance observer does not suppress periodic disturbances. Repetitive control suppresses such periodic disturbances [10]–[12]. Moreover, compensation through repetitive

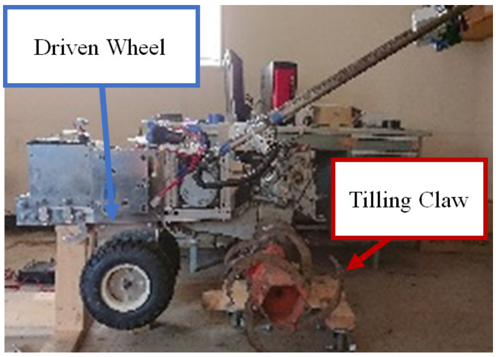

Fig. 1. Electric tiller

control is faster than a disturbance observer because repetitive control is a type of feedforward (FF) control [13]. In the industrial field, repetitive control is used when a system has periodic disturbance [14][15]. Thus, repetitive control is suitable for compensating for the reaction torque from tilling. In actual farm work, the command speed of the tilling claw changes. In an actual case, the variations in the soil surface are intense. The variations in the amplitude and the time shift of the reaction torque from tilling emerge because of the variations in the soil surface. This study proposes a compensation method combining two other proposed methods. The first proposed method is repetitive control considering the angle of the tilling claw. The reaction torque from tilling depends on this angle [16][17]. Therefore, the suppression performance of the reaction torque is maintained in the first proposed method even if the command speed of the tilling claw changes. The second proposed method focuses on the memory disturbance observer. This observer compensates for the variations in the soil surface. Such variations are obtained through errors in the internal and actual models. The memory

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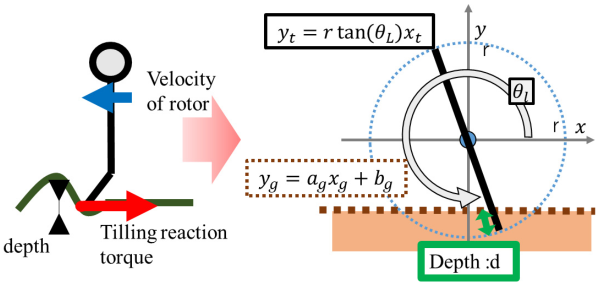

Fig. 2. Reaction torque from tilling

disturbance observer is based on the communication disturbance observer.

2. Reaction Torque from Tilling

A tilling claw repetitively stirs the soil. A reaction torque then occurs in the soil because of the tilling claw. The reaction torque depends on the angle of the tilling claw [9].

The reaction torque from tilling is modeled using drag [17], which is expressed in Eq. (1). τ_{till} is the reaction torque from tilling. In this model, the flow of particles in the soil is assumed to be fluid. In the equation, ρ, C_d, V, w, and d denote the fluid density, drag constant, speed of the tilling claw, width of the tilling claw, and depth of tilling, respectively. The linear velocity V is proportional to the loader-side velocity ω_L. This relation is expressed as Eq. (2). r is the length of the tilling claw. The loader-side angle θ_L is time-integrated loader-side velocity ω_L expressed as Eq. (2).

$$\tau_{till} = \frac{1}{2}\rho C_d V^2 wd \cdots\cdots (1)$$

$$V = r\omega_L,\ \theta_L = \int \omega_L dt \cdots\cdots (2)$$

The depth of tilling is determined herein based on the angle of the tilling claw. This model defines the rectangular coordinate, whose origin is the rotation center point of the tilling claw. Figure 2 shows this rectangular coordinate. The tip point of the tilling claw is defined as x_t; y_t and expressed as Eq. (4). The boundary of the ground (x_g; y_g) is assumed as the linear function and expressed as Eq. (5). a_g; b_g denote the ground surface parameters. The depth of tilling d is the norm of the tip point (x_t; y_t) of the tilling claw and the cross point of Eqs. (4) and (5), which are shown in Fig. 2 and expressed as Eq. (3).

$$d = r\sqrt{\left(\cos\theta_L - \frac{b_g}{\tan\theta_L - a_g}\right)^2 + \left(\sin\theta_L - \frac{b_g \tan\theta_L}{\tan\theta_L - a_g}\right)^2} \cdots\cdots (3)$$

$$y_t = r\tan(\theta_L)x_t \cdots\cdots (4)$$

$$y_g = a_g x_g + b_g \cdots\cdots (5)$$

3. Conventional Method

Repetitive control is suitable because a reaction torque from tilling periodically occurs. The tilling claw of an electric tiller is modeled as a single inertia system. Figure 3 presents a feedback (FB) speed control system for a tilling claw. $\omega_L^{ref}(k)$, $\omega_L^{res}(k)$, ω_M^{res}, $i_m(k)$, T_s, and R_g denote the command speed of the tilling claw, responsive speed of the tilling claw, responsive speed of the motor, motor current, sampling period of the control system, and gear ratio, respectively. The FB speed control system only uses a rotary encoder without a torque sensor. The plant system, which is discretized using a zero-order hold (ZOH), is expressed as Eq. (6). K_T, J, and D are the torque, inertia, and friction constants, respectively. The FB controller is similarly expressed in Eq. (7). The relation of the loader-side velocity ω_L and the motor-side velocity ω_M is expressed as Eq. (8) by R_g.

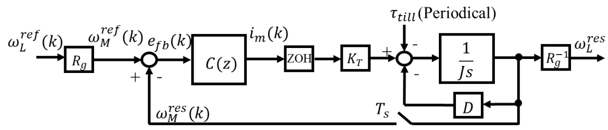

Fig. 3. Feedback speed control system

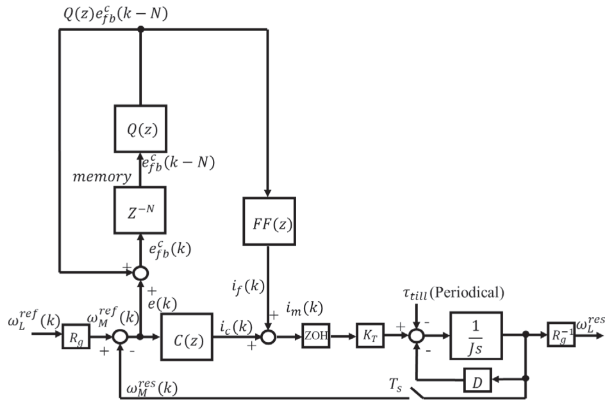

Fig. 4. Conventional method

$$P(s) = \frac{K_T}{Js + D},\ P(z) = \mathcal{Z}\{P(s)\} \cdots\cdots (6)$$

$$C(s) = K_P + K_I\frac{1}{s},\ C(z) = \mathcal{Z}\{C(s)\} \cdots\cdots (7)$$

$$\omega_L = R_g^{-1}\omega_M \cdots\cdots (8)$$

A periodic error occurs when the speed of the tilling claw is controlled using only the FB controller. Such periodic error is defined as only-FB error $e_{fb}(k)$. $e_{fb}(k)$ depends on the reaction torque $\tau_{till}(k)$, and is expressed as Eq. (9). $\tau_{till}(k)$ is the periodic function with period N and expressed as Eq. (10). The current $e_{fb}(k)$ is equal to the error before a single period. This relationship is expressed through Eq. (11).

$$e_{fb}(k) = \frac{P(z)}{1 + C(z)P(z)}K_T^{-1}\tau_{till}(k) \cdots\cdots (9)$$

$$\tau_{till}(k-N) = \tau_{till}(k) = \tau_{till}(k+N) \cdots\cdots (10)$$

$$e_{fb}(k-N) = e_{fb}(k) = e_{fb}(k+N) \cdots\cdots (11)$$

A conventional method [18] periodically memorizes $e_{fb}(k)$ and compensates for the reaction torque based on this memory.

Figure 4 shows block diagrams of the conventional method [19], where $Q(z)$ and $FF(z)$ are the low-pass filter (LPF) and the FF controller, respectively, and $Q(z)$ limits the bandwidth of the FF controller.

The FF controller, which is expressed as Eq. (12), is designed using the FB control loop. The transfer function from $e_{fb}(k)$ to the motor current $i_m(k)$ is obtained. The FF controller has a two-sample delay for stabilization.

$$FF(z) = \frac{1 + C(z)P(z)}{P(z)} z^{-2} \quad \cdots\cdots (12)$$

$e^c_{fb}(k)$ is estimated through Eq. (13) based on memory. $e^c_{fb}(k)$ is estimated as $e_{fb}(k)$ in a conventional system. The error and the FF current are expressed through Eqs. (14) and (15), respectively.

$$e^c_{fb}(k) = Q(z)e^c_{fb}(k - N) + e(k) \quad \cdots\cdots (13)$$

$$e(k) = \frac{P(z)}{1 + C(z)P(z)} K_T^{-1} \tau_{till}(k) - \frac{P(z)}{1 + C(z)P(z)} i_f(k) \quad \cdots\cdots (14)$$

$$i_f(k) = Q(z)FF(z)e^c_{fb}(k - N) \quad \cdots\cdots (15)$$

$$Q(s) = \frac{\omega_q}{s + \omega_q}, \quad Q(z) = \mathcal{Z}\{Q(s)\} \quad \cdots\cdots (16)$$

Here, N is the number of samples, which is determined from the disturbance period divided by the sampling period. $Q(z)$ is the low-pass filter expressed as Eq.(16). ω_q is gain to decide bandwidth. Eq. (17) is obtained through Eqs. (12)–(15). In addition, $Q(z)$ is considered to be 1 because the bandwidth of $Q(z)$ is sufficiently higher. From Eq. (17), the reaction torque from tilling, $\tau_{till}(k)$, is accurately memorized as $e^c_{fb}(k)$. The FF current is calculated using $e^c_{fb}(k)$ of the previous period. The reaction torque from tilling is accurately suppressed if Eq. (11) is established.

$$e^c_{fb}(k) = \frac{P(z)}{1 + C(z)P(z)} K_T^{-1} \tau_{till}(k) \quad \cdots\cdots (17)$$

Eq. (18) is obtained from Eq. (10). The transfer characteristic from $\tau_{till}(k)$ to $e(k)$ is obtained from Eqs. (10), (12), (14), (15) and (17) and expressed as Eq. (19). A two-sample delay by the FF controller is ignored. In addition, $Q(z)$ is assumed as 1 because the $Q(z)$ bandwidth is sufficiently higher. Eq. (19) becomes 0 from Eq. (18).

$$\tau_{till}(k) - \tau_{till}(k - N) = 0 \quad \cdots\cdots (18)$$

$$e(k) = \frac{P(z)}{1 + C(z)P(z)} K_T^{-1} \{\tau_{till}(k) - \tau_{till}(k - N)\} = 0 \quad \cdots\cdots (19)$$

However, Eq. (11) is the ideal condition. In a push-type electric tiller, the command speed of the tilling claw changes. In the actual case, the command speed of the tilling claw also changes. Hence, the periodicity of the reaction torque from tilling changes as well. Eq. (11) is not established when a variation in the command speed of the tilling claw occurs. In addition, variations in the soil surface occur, and when they do, Eq. (11) is also not established. A conventional method does not have sufficient suppression performance.

4. Proposed Method

This study proposes a repetitive control that compensates for the reaction torque under variations in the command speed of the tilling claw. Furthermore, this study also proposes a compensation method using a memory disturbance observer to suppress variations in the soil surface.

4.1 Repetitive Control considering Angle of Tilling Claw A conventional method does not compensate for the reaction torque when its periodicity changes because the repetitive controller memorizes $e_{fb}(k)$ based on the time period. The reaction torque occurs once in a single rotation by one tilling claw even if the period of the reaction torque changes (e.g., to $8, 10, \ldots, n$ [s]). The proposed repetitive controller memorizes the considered angle of the tilling claw (Fig. 5). Figure 6 presents the flowchart of the memory system of the proposed method. θ_{old} and e_{old} are the angle of the tilling claw before 1 sample and $e^p_{fb}(k - N_r|\theta_{L(k)})$, respectively.

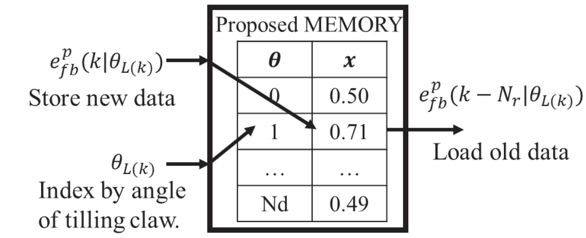

Fig. 5. Memory system with the angle of the tilling claw

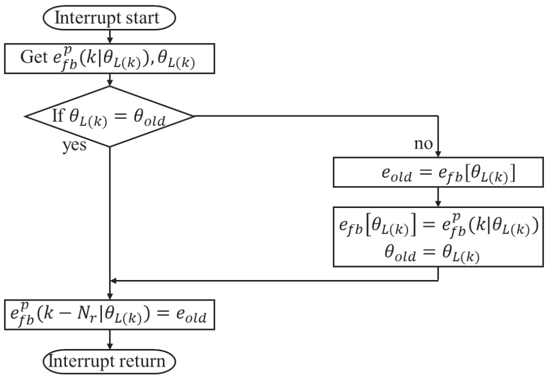

Fig. 6. Flow chart of the proposed memory system

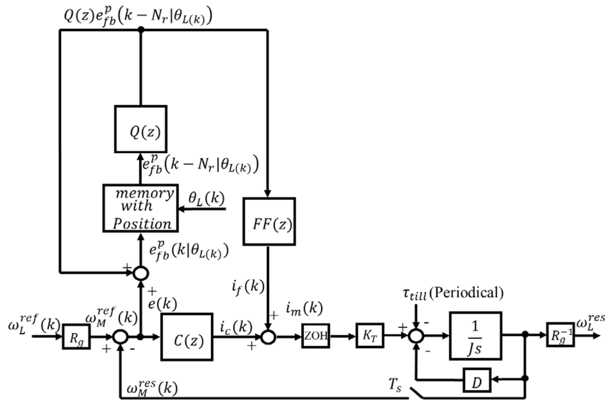

Fig. 7. Proposed repetitive control (the first proposed method)

Figure 7 shows a block diagram of the proposed repetitive control. In the proposed repetitive control, the estimated only-FB error is defined as $e^p_{fb}(k|\theta_{L(k)})$. $e^p_{fb}(k|\theta_{L(k)})$ is the estimated only-FB error when the angle of the tilling claw is $\theta_L(k)$. The relationship of $e^p_{fb}(k|\theta_{L(k)})$ through one rotation is expressed as Eq. (20). This equation is a temporal expression using N_r, where N_r is the number of samples in a single rotation.

$$e^p_{fb}(k - N_r|\theta_{L(k)}) = e^p_{fb}(k|\theta_{L(k)}) = e^p_{fb}(k + N_r|\theta_{L(k)}) \quad \cdots\cdots (20)$$

$$here,\ N_r = N_r(k|\theta_{L(k)})$$

$$e^p_{fb}(k|\theta_{L(k)}) = Q(z)e^p_{fb}(k-N_r|\theta_{L(k)}) + e(k) \cdots\cdots (21)$$

$$e(k) = \frac{P(z)}{1+C(z)P(z)}K_T^{-1}\tau_{till}(k) - \frac{P(z)}{1+C(z)P(z)}i_f(k) \cdots (22)$$

$$i_f(k) = Q(z)FF(z)e^p_{fb}(k-N_r|\theta_{L(k)}) \cdots (23)$$

The characteristic of $\tau_{till}(k)$ to $e^p_{fb}(k|\theta_{L(k)})$ is expressed in Eq. (26). The error from a two-sample delay is ignored when the sampling period is sufficiently short.

$$e^p_{fb}(k|\theta_{L(k)}) = \frac{P(z)}{1+C(z)P(z)}K_T^{-1}\tau_{till}(k) + Q(z)e_{fb}(k-N_r|\theta_{L(k)}) - z^{-2}Q(z)e_{fb}(k-N_r|\theta_{L(k)}) \cdots (24)$$

$$if,\ e^p_{fb}(k|\theta_{L(k)}) \approx e^p_{fb}(k-2|\theta_{L(k-2)}) \cdots (25)$$

$$e^p_{fb}(k|\theta_{L(k)}) = \frac{P(z)}{1+C(z)P(z)}K_T^{-1}\tau_{till}(k) \cdots (26)$$

Eq. (20) is established despite the variation in the period of the reaction torque. Therefore, Eq. (26) is also established. The proposed repetitive control suppresses the reaction torque because $e^p_{fb}(k|\theta_{L(k)})$ is equal to $e_{fb}(k|\theta_{L(k)})$. The proposed repetitive control also maintains the suppression performance of the reaction torque under a variation in the command speed of the tilling claw.

4.2 Memory Disturbance Observer

During a soil disturbance, the soil varies with the tilling motion. Soil disturbance occurs through a variation in the soil surface [9].

A variation in the soil surface is time shifted (Fig. 8). N_r is the period of compensation in the proposed control system; N_a is the period of the actual reaction torque influenced by a variation in the soil surface; and N_j is the difference between N_a and N_r, which is expressed as Eq. (27). A variation in the soil surface is assumed herein as a time shift of N_j.

A time shift of N_j occurs in a plant system from Fig. 8. The reaction torque is delayed N_j sample against $e^p_{fb}(k-N_r|\theta_{L(k)})$. In other words, $e^p_{fb}(k-N_r|\theta_{L(k)})$ goes forward to the N_j sample against the actual reaction torque. Therefore, this paper assumes that a disturbance occurs in the memory of a repetitive controller, which is defined as a memory disturbance (MD) in this paper.

This study proposes that the memory of a repetitive controller be corrected using the estimated MD. The MD corresponds to a network disturbance (ND) in a communication disturbance observer (CDOB) [20][21], and is denoted through Eq. (28). The CDOB has been used for the compensation of the time delay [22][23]. The MD assumes a variation in the soil surface as an additive disturbance. The MD also considers a variation in the amplitude of the reaction torque. Therefore, the MD observer is able to compensate for the non-periodic disturbance.

$$N_a = N_r + N_j \cdots (27)$$

$$MD = e^p_{fb}(k-N_r|\theta_{L(k)}) - e_{fb}(k|\theta_{L(k)}) \cdots (28)$$

Then,

$$e^p_{fb}(k|\theta_{L(k)}) = e^p_{fb}(k-N_a|\theta_{L(k)}) \cdots (29)$$

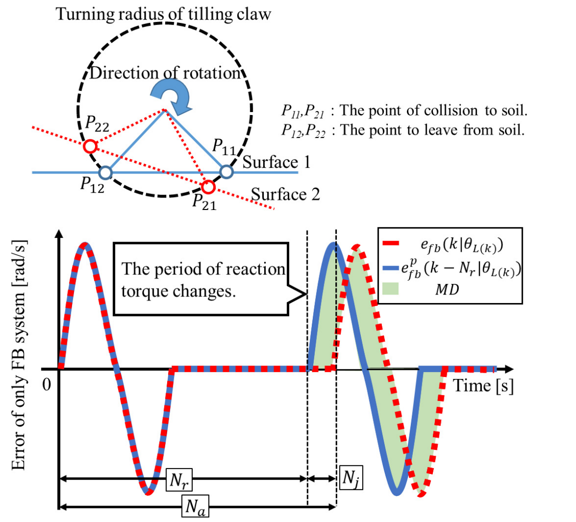

Fig. 8. Memory disturbances

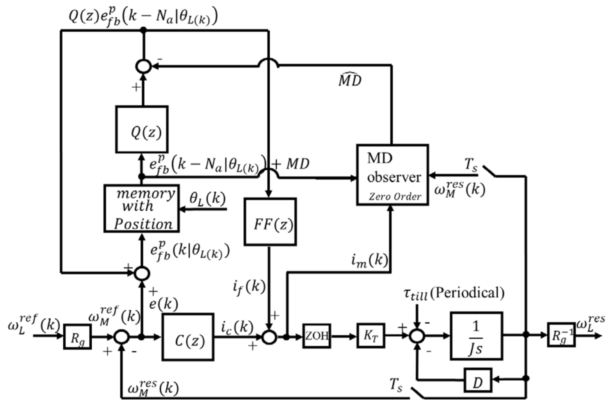

Fig. 9. Proposed method

Here, $e_{fb}(k)$ of Fig. 3 is denoted as Eq. (30).

$$e_{fb}(k) = H(z)\left\{K_T i_m(k) - \left(J\frac{z}{T_s(z-1)} + D\right)\omega_M(k)\right\} \cdots (30)$$

$$here,\quad H(z) = \mathcal{Z}\left\{\frac{s}{Js^2 + (D+K_TK_P)s + K_TK_I}\right\} \cdots (31)$$

Hence,

$$MD = e^p_{fb}(k-N_r|\theta_{L(k)}) - H(z)\left\{K_T i_m(k) - \left(J\frac{z}{T_s(z-1)} + D\right)\omega_M(k)\right\} \cdots (32)$$

$$\hat{MD} = Q_g(z)e^p_{fb}(k-N_r|\theta_{L(k)}) - Q_g(z)H(z)\left\{K_T i_m(k) - \left(J\frac{z}{T_s(z-1)} + D\right)\omega_M(k)\right\} \cdots (33)$$

$$Q_g(s) = \frac{\omega_g}{s+\omega_g},\ Q_g(z) = \mathcal{Z}\{Q_g(s)\} \cdots (34)$$

$Q_g(z)$ is a low-pass filter expressed as Eq. (34). ω_g is gain to decide bandwidth. $Q_g(z)$ limits the bandwidth of the MD observer from Eq. (35).

Figure 9 shows the proposed method combining an MD observer and repetitive control while considering the angle of the tilling claw.

Eq. (35) is obtained from Eqs. (32) and (33) when the MD observer bandwidth is sufficiently higher.

$$\hat{MD} = Q_g(z)MD$$
$$if, \quad Q_g(z) \approx 1$$
$$\hat{MD} \approx MD \quad \cdots\cdots (35)$$

The memory of the repetitive controller is expressed through Eq. (36).

$$e^p_{fb}(k|\theta_{L(k)}) = e(k) + e^p_{fb}(k - N_a|\theta_{L(k)}) + MD - \hat{MD} \quad \cdots\cdots (36)$$
$$= e(k) + e^p_{fb}(k - N_a|\theta_{L(k)}) \quad \cdots\cdots (37)$$
$$e^p_{fb}(k - N_a|\theta_{L(k)}) = \frac{z^{-N_a}}{1 - z^{-N_a}} e(k) \quad \cdots\cdots (38)$$

Eq. (38) has a periodic function of the actual period N_a. Thus, the proposed method achieves a suppression of the actual reaction torque established using the internal model principle.

Eq. (39) is expressed as the characteristic of $\tau_{till}(k)$ and $i_f(k)$ to $e(k)$.

$$e(k) = \frac{P(z)}{1 + C(z)P(z)} K_T^{-1} \tau_{till}(k) - \frac{P(z)}{1 + C(z)P(z)} i_f(k) \quad \cdots\cdots (39)$$

$i_f(k) = FF(z)e^p_{fb}(k - N_a|\theta_{L(k)})$ is substituted to Eq. (39).

$$e(k) = \frac{P(z)}{1 + C(z)P(z)} K_T^{-1} \tau_{till}(k) - e^p_{fb}(k - N_a|\theta_{L(k)}) \quad \cdots\cdots (40)$$

Eq. (41) is obtained from Eqs. (38) and (40). The current reaction torque is equal to the reaction torque before the N_a sample. This relation is expressed as Eq. (42).

$$e(k) = \frac{P(z)}{1 + C(z)P(z)} K_T^{-1} \{\tau_{till}(k) - \tau_{till}(k - N_a)\} = 0 \quad \cdots\cdots (41)$$
$$here, \quad \tau_{till}(k) - \tau_{till}(k - N_a) = 0 \quad \cdots\cdots (42)$$

The proposed method suppresses the reaction torque even if the periodicity of the reaction torque and the soil surface vary.

5. Experimental Results

5.1 Experimental Setup Figure 10 shows the applied experimental machine. This machine reproduces the tilling motion using a tilling claw, and is made up of a DC servo motor, a gear, a torsion sensor, and a tilling claw. The torque sensor is only used to detect the reaction torque. The bandwidth of the torque sensor is 1 kHz.

An experiment using actual soil does not reproduce the tilling motion because the tilling claw scrapes out most of the soil at one time. Thus, in this study, poly vinyl alcohol gel (PVA-gel) is used instead of actual soil. PVA-gel reverts to its initial state after the tilling claw scrapes it out. PVA-gel is made of 230 g of PVA, 400 g of water, 3 g of boric acid, and 3 g of sodium bicarbonate.

Table 1 lists the experimental conditions. The design conditions of $Q(z)$, $Q_g(z)$, and PI speed controller are denoted below. The relation of $Q(z)$, $Q_g(z)$, and PI controller is the bandwidth of $Q(z)$ > the bandwidth of $Q_g(z)$ > the bandwidth of PI speed control. The filters and the PI controller have a lower bandwidth than the Nyquist frequency. The effectiveness of the proposed method is experimentally confirmed when the command speed of the tilling claw changes. For the initial command speed, the tilling claw turns once during an 8 s period. Repetitive control starts at 108 s. The variation in the command speed of the tilling claw starts at 116 s. The command speed of the tilling claw is constant at 117 s. Thus, the command speed of the tilling claw is 0.66 times slower than the initial command speed.

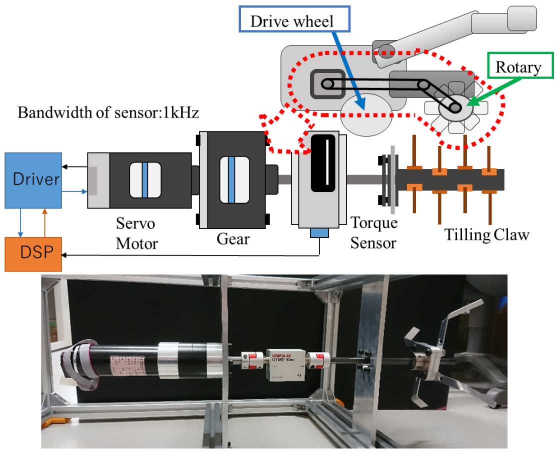

Fig. 10. Experimental machine

Table 1. Experimental conditions

Elements	Value [unit]
Sampling period T_s	1 [ms]
Number of tilling claws	1 [-]
Number of samples N in conventional method	8000 [sample]
Division number of θ_L in proposed method	4000 [-]
Bandwidth of feedback system	25 [rad/s]
Feedback controler P. gain K_P	0.081 [-]
Feedback controler I. gain K_I	1.016 [-]
The filter gain ω_q of $Q(z)$	70 [-]
The filter gain ω_g of $Q_g(z)$	35 [-]
Bandwidth of MD observer	35 [rad/s]
Bandwidth of feedforword system	70 [rad/s]
Initial command speed ω_L^{ref}	0.785 [rad/s]
Deceleration time	1 [s]
Final command speed $\omega_L^{ref}\times0.66$	0.523 [rad/s]
Torque constant K_T	0.039 [Nm/A]
Inatia constant J	6.260 [kgm^2]
Friction constant D	1.4$\times10^{-5}$ [Nms/rad]
Gear ratio R_g	19 [-]

5.2 Experimental Results of Comparison The PI speed control, PI speed control with disturbance observer (DOB), conventional method, and proposed method are compared to confirm the effectiveness of the proposed method. Figure 11 shows the block diagram of the PI speed control with the DOB. The plant system parameters had the same values in Table 1. The conditions of the controller, PVA-gel, and speed command are also the same. Table 2 shows a summary of the bandwidth of each method.

Figures 12 to 18 show the experimental results. The proposed method compensates for the reaction torque under varying command speeds (Fig. 12).

The suppression performance is evaluated based on the errors from the reaction torque (Fig. 13). With the pro-

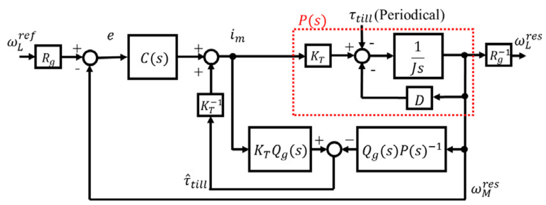

Fig. 11. PI speed control with the DOB

Table 2. Summary of the design conditions of the compared methods

Speed control method	FB Bandwidth(BW)	Observer BW	FF BW
Only-FB system	25 rads	-	-
Conventional method	25 rads	-	70 rads
PI with DOB	25 rads	35 rads	-
Proposed method	25 rads	35 rads	70 rads

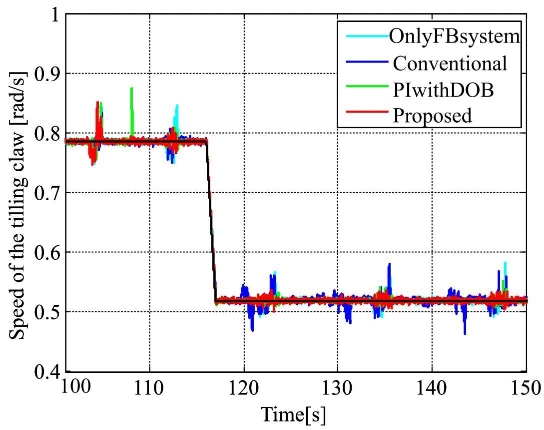

Fig. 12. Speed responses of the tilling claw

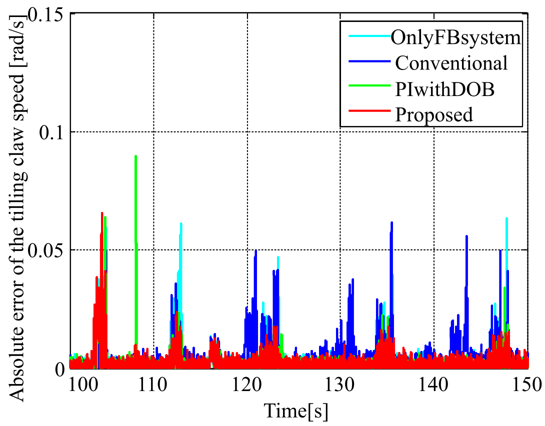

Fig. 13. Absolute errors of the tilling claw speed

posed method, the error in speed reduces from 0.0616 to 0.0174 rad/s (only-FB system), and the suppression performance is improved by 71.2% because the internal model principle is kept by the proposed memory. The effectiveness of proposed method is confirmed by the experimental results. A conventional method does not suppress the reaction torque under varying command speeds. In a conventional method, an error in speed reduces from 0.0589 to 0.0358 rad/s (only-FB system) when the command speed of tilling claw does not change, and the suppression performance is improved by 39.2%. The difference between the proposed method (71.2%) and the conventional method (39.2%) is caused by

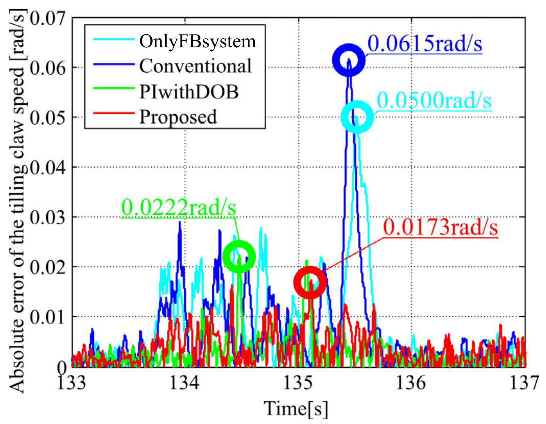

Fig. 14. Absolute errors of the tilling claw speed (zoom)

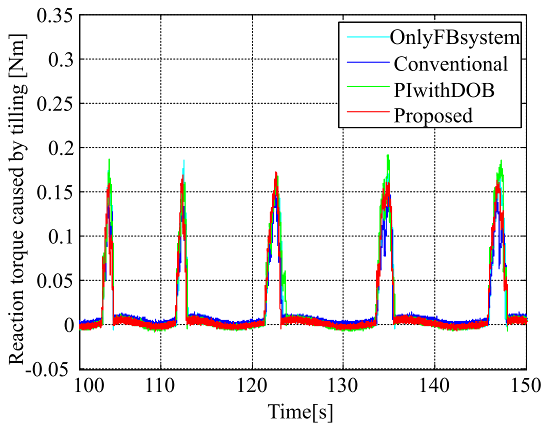

Fig. 15. Reaction torques caused by tilling

the variations in the soil surface.

Figure 14 shows that the proposed method has the most accurate compensation performance between the compared methods when the proposed memory learns enough. The speed error of the proposed method is 0.0173 rad/s, which becomes smaller than that of the PI speed control with DOB (0.0222 rad/s). When the rotary speed changes, the speed error of the conventional method increases by 23% of the speed error of the PI speed control.

The reaction torque periodically occurs (Fig. 15). Figure 16 shows that the motor current increases when the FF control begins. In the conventional method, the motor current fluctuates in a different period against the reaction torque because an internal model is disturbed by itself.

The proposed memory has a more accurate learning to the only-FB error $e_{fb}(k)$ compared to the conventional memory, as shown in Figs. 17 and 18. The enlarged figures are located in the upper right corner of Figs. 17 and 18. Figure 17 depicts that the conventional method does not learn $e_{fb}(k)$ when the period of the reaction torque changes 1.5 times because the conventional method disturbs the internal model principle then. Figure 18 illustrates that the proposed method estimates the only-FB error $e_{fb}(k)$ under a variation in the command speed because of the corresponding internal model. In addition, the maximum estimated error is 0.0126 rad/s. The proposed method estimates well in spite of the actual reaction torque has a variation of the amplitude and the jitter of period.

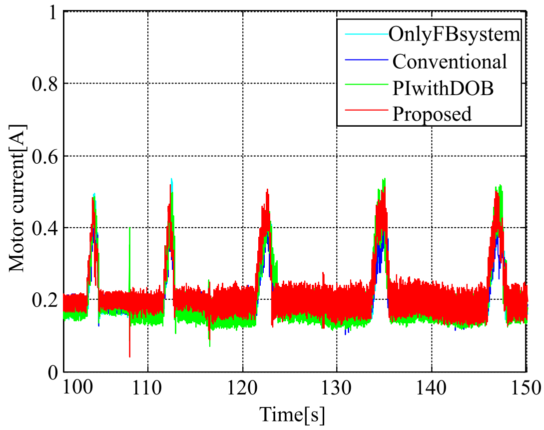

Fig. 16. Motor currents

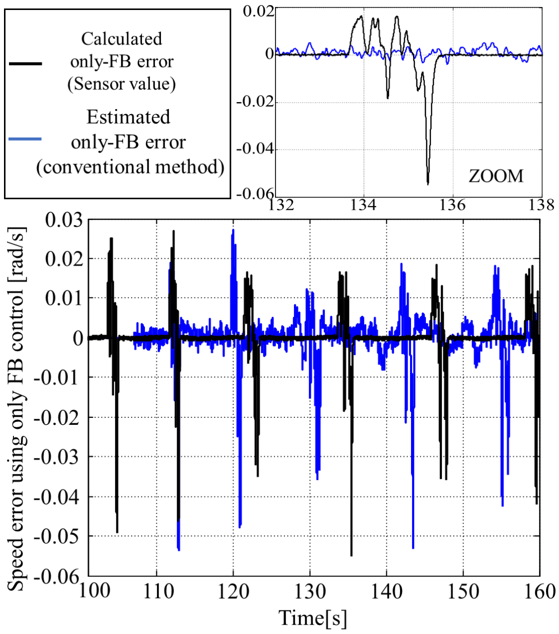

Fig. 17. Estimated only-FB error in the conventional system

In these experiments, the proposed method is robust against jitter and variation of the amplitude of the reaction torque, and has the highest compensation performance for the reaction torque with the specific frequency.

5.3 Experimental Results Using Sinusoidal Speed Command This study conducts experiments to confirm that the reaction torque by the sinusoidal speed command compensates using the MD observer. The period and the amplitude of the reaction torque vary when the speed command is a sinusoidal wave.

This study compares the proposed method with the MD observer and the proposed method without the MD observer. The plant system parameters and the design condition of the controllers have the same values in Table 1. The beginning of the speed control only uses the PI speed controller. Repetitive control starts at 108 s. The speed command changes from ω_{Lini} to ω_{Lfin} in at 116 s. The speed commands are expressed as Eqs. (43) and (44). Table 3 shows the parameters of the sinusoidal wave.

$$\omega_{Lini} = const. \quad \cdots\cdots (43)$$

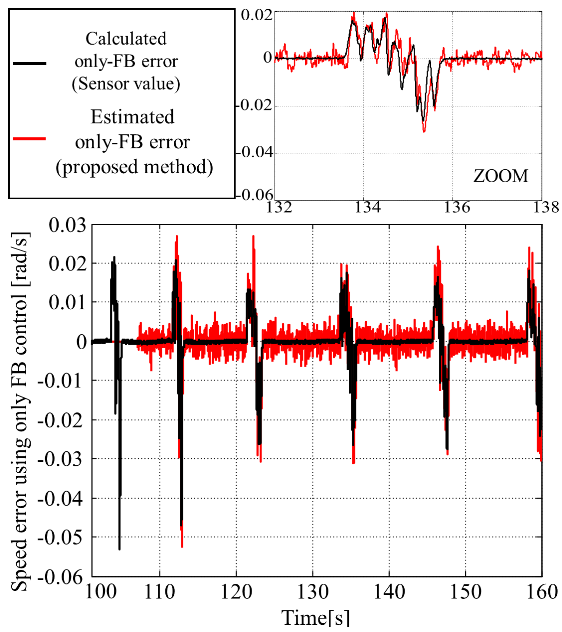

Fig. 18. Estimated only-FB error in the proposed system

Table 3. Speed commands

elements	unit	mean	value
ω_{Lini}	[rad/s]	Initial command speed	0.785
A_c	[-]	Amplitude of sinusoidal command speed	0.393
f_c	[Hz]	Frequency of sinusoidal command speed	0.563

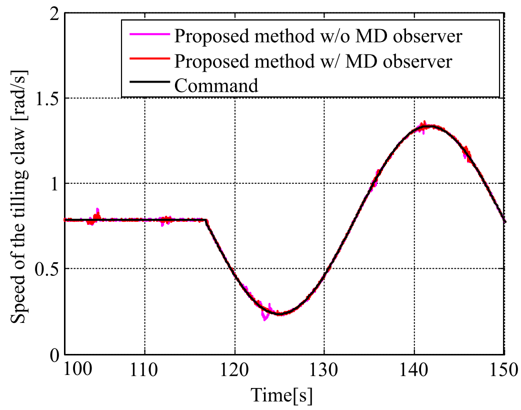

Fig. 19. Speed responses of the tilling claw

$$\omega_{Lfin} = \omega_{Lini} + A_c \sin(2\pi f_c) \quad \cdots\cdots (44)$$

Figure 19 to Fig. 24 show the experimental results. Figure 19 illustrates that the speed response follows the command speed. Figure 20 shows that the maximum velocity vibrations of the proposed method with the MD observer are smaller by 28% compared to the maximum velocity vibrations of the proposed method without the MD observer. The jitter of period and variation of the amplitude of the reaction torque are confirmed from Fig. 21. In Fig. 22, motor currents also have the jitter of period and variation of the amplitude. The MD observer estimates the influence by the variation of the amplitude and the period of the reaction torque from Fig. 23 and Fig. 24. The MD observer estimates the non-periodic disturbance because the MD is defined as an additive disturbance.

Therefore, the proposed method with the MD observer is

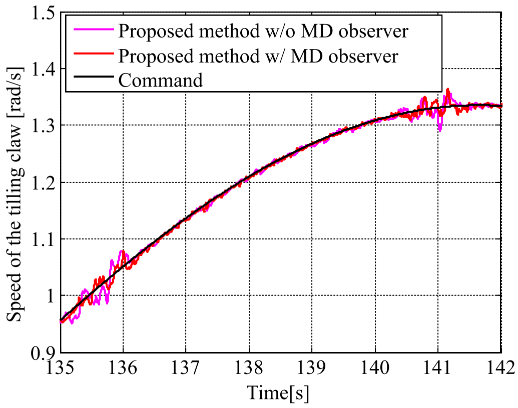

Fig. 20. Speed responses of the tilling claw (zoom)

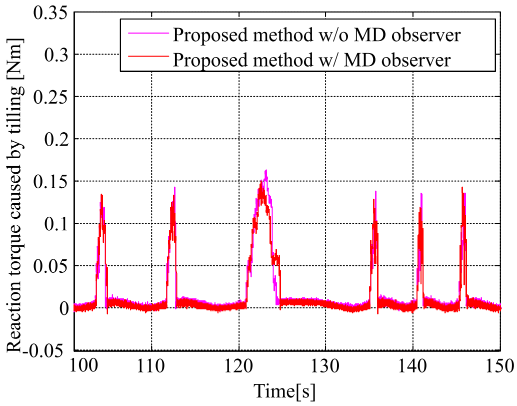

Fig. 21. Reaction torques caused by tilling

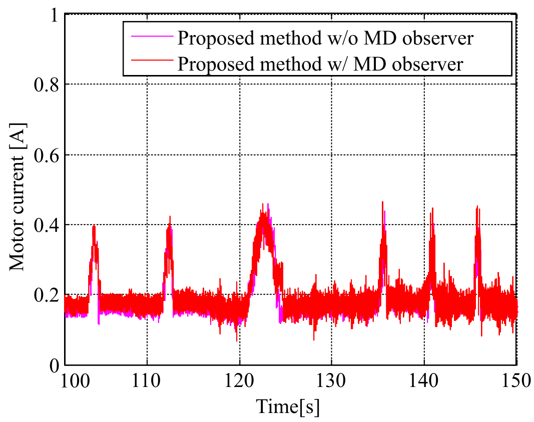

Fig. 22. Motor currents

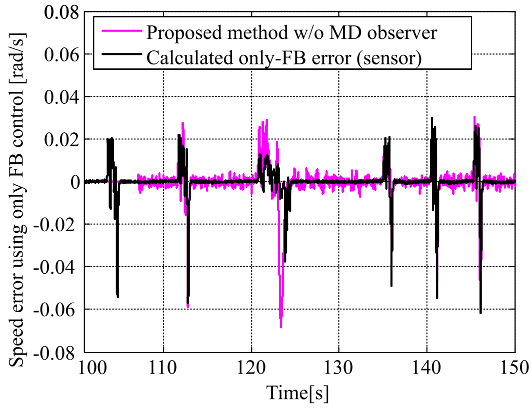

Fig. 23. Estimated only-FB error in the proposed system w/o the MD observer

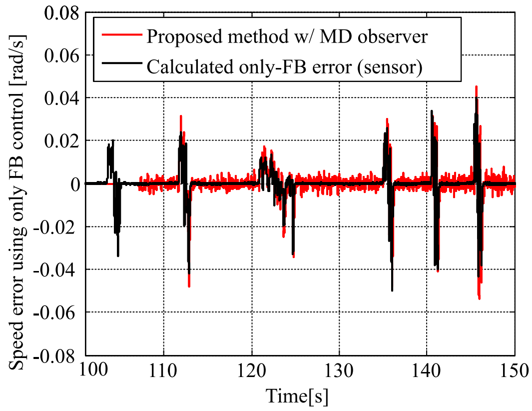

Fig. 24. Estimated only-FB error in the proposed system w/ the MD observer

effective for the jitter of period and the variation of the amplitude of the reaction torque when the speed command is a sinusoidal wave.

6. Conclusion

This study proposed a method combined using two other methods. The first proposed method was the repetitive control considering the angle of the tilling claw. The conventional method memorized the influence of the reaction torque for each period. The suppression performance of the reaction torque for a conventional method degraded when the command speed of the tilling claw changed because the internal model was disturbed by itself. Therefore, the first proposed method memorized the influence of the reaction torque for each rotation of the tilling claw because the reaction torque was dependent on the angle of the tilling claw.

The effectiveness of the proposed method was confirmed based on the experimental results. The time shift of the variation in the soil surface was assumed as the additive disturbance in the memory of the repetitive controller. This disturbance was defined as the MD and included the variation of the amplitude of the reaction torque. The MD observer estimated the MD and compensated for the memory. The MD was equivalent to the ND in the CDOB.

Experiments were conducted herein. The results showed that when the command speed varied, a conventional method incurred non-periodic vibrations. Moreover, the reaction torque was not suppressed. The proposed method accurately suppressed the reaction torque, and did not incur non-periodic vibrations even if the command speed varied. The effectiveness of the repetitive control considering the angle of tilling claw was confirmed.

The variations in the soil surface were a dominant factor in errors in the speed control when the command speed did not vary. The conventional and proposed methods improved the suppression performance of the reaction torque by 39.2% and 71.2%, respectively, against only-FB control. The suppression performance of the proposed method was 32% higher than that of the conventional method despite the same bandwidth of the FF controller. In addition, the effectiveness of the compensation method using an MD observer was confirmed.

Finally, the effectiveness of the proposed method was confirmed based on the experimental results, and the proposed method was suitable for the speed control of a tilling claw.

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