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An Improvement of Simple Adaptive Control Method by Use of Derivative Action and Its Application to DD Servo System

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Abstract: The simple adaptive control (SAC) method has attracted attention for interest of the simple structure of its adaptive controller. We establish that the introduction of output derivative action to the original SAC system definitely improves the response characteristic of the control system. The effect of such an introduction is confirmed through experimental results by applying the method to a servo control system using a direct drive (DD) motor.

1. Introduction

A key component of electric mechanical system is a servo motor using as actuators of servo systems.[1] So far DC servo system has been mostly used for this purpose. However, DC servo motor is used with a sort of reduction devices. An example is Harmonic Drive which has the factor of non-linear friction and backlash and which sometimes decreases the mechanical rigidity. The influence of these factors makes difficult to satisfy the requirement of high accuracy and high speed control that are increasingly required in today's mechanical control systems. On the other hand, direct drive (DD) system can be used without reduction devices. Hence we have the possibility to get high accuracy and high speed control more than DC servo systems. However we have to take into consideration that DD servo system is more sensitive to outer disturbances and more difficult to control. In this paper we examine to control DD servo system by means of simple adaptive control (SAC). The model reference adaptive control method [2][3] is implemented under the condition that the reference model order is not lower than the order of the unknown plant. On the other hand, in the design of SAC, we can select low order model irrespective to the order of the plant. However the plant must satisfy the almost strict positive realness (ASPR) condition. The plant is said to be ASPR, if there exists a static output feedback such that the resulting closed-loop transfer function is strictly positive real (SPR). Actually, DD servo system is not ASPR. Thus we can not apply directly SAC method. But by implementing small gain parallel feedforward compensator (PFC) to the plant, we can get the augmented ASPR plant.[5]-[9] Recently, a concrete and simple design procedure of such PFC was proposed by Iwai et al.[9] However such an implementation of the small gain PFC sometimes causes undesired oscillation, especially in the transient state of control process.[4] In this paper we propose a method to avoid such a phenomenon by adding an output derivative term to the feedback control input. The effectiveness of introducing derivative term is examined by simulation and experiment of the position control of a DD servo system.

2. Construction of SAC with Derivative Action Term

We consider an nth-order single input and single output plant:

$$\dot{x}(t)=Ax(t)+bu(t)+d(t,\bar{y}) \qquad (2.1a)$$
$$y(t)=c^Tx(t) \qquad (2.1b)$$

Here, $\bar{y}(t)$ is detectable state variable vector. The model that the controlled plant is required to follow is given by

$$\dot{x}_m(t)=A_mx(t)+b_mu_m(t) \qquad (2.2a)$$
$$y_m(t)=c_m{}^Tx_m(t) \qquad (2.2b)$$

We assume that equations (2.1) and (2.2) satisfy the following assumptions.

[Assumption]

(1) Equation (2.1) is ASPR. That is, there exists a constant k_e^* such that $G_c(s)=c^T(sI-A_c)^{-1}b$ becomes SPR. Here $A_c=A+bk_e{}^*c^T$.

(2)

$$\det\begin{bmatrix} A & b \\ c^T & 0 \end{bmatrix} \neq 0 \qquad (2.3)$$

(3) There exist $d(t,\bar{y})$ and unknown constants $\rho_0, \rho_1>0$ such that

$d(t,\bar{y})=b\tilde{d}(t,\bar{y})$

and $|\tilde{d}(t,\bar{y})|\leq \rho_0+\rho_1\|\bar{y}\|$

(4) Reference model input $u_m(t)$ is like that states of stable linear dynamic system with input $u_m(t)$ are bounded.

Assumptions (2) and (4) are sufficient conditions which are enable us to realize output model matching.[10] Assumption (3) means that the disturbance depends on the states of the plant in restrictive form. Note that if the disturbance is bounded, it may assume $\rho_1=0$.

Now, let $e_y(t)=y(t)-y_m(t)$. The control purpose is to construct the control system that achieves $\lim_{t\to\infty} e_y(t)=0$ in the ideal situation. We construct the control input u(t) as follows.

$$u(t)=\theta(t)^T z(t)+k_v\dot{e}_y(t)+u_R(t),\ k_v<0 \quad (2.4)$$

$$\theta(t)=[k_e(t),k_x^T(t),k_v(t)]^T$$
$$z(t)=[e_y(t),x_m^T(t),u_m(t)]^T \quad (2.5)$$

$u_R(t)$: Robust adaptive control term

The main difference of the original SAC and proposed one is that the latter includes the derivative term $k_v\dot{e}_v(t)$. $\theta(t)$, $u_R(t)$ in (2.5) are constructed by following adaptive algorithms.[8]

$$\theta(t)=\theta_P(t)+\theta_I(t) \quad (2.6a)$$
$$\theta_P(t)=-\Gamma_P z(t)e_y(t) \quad (2.6b)$$
$$\dot{\theta}_I(t)=-\sigma(t)\theta_I(t)-\Gamma_I z(t)e_y(t) \quad (2.6c)$$
$$\sigma(t)=\sigma_1 e_y^2(t)/(1+e_y^2(t))+\sigma_2 \quad :\sigma_1,\sigma_2>0 \quad (2.6d)$$
$$\Gamma_P=\Gamma_P^T>0,\ \Gamma_I=\Gamma_I^T>0$$

$$u_R(t)=\begin{cases}-\beta^T(t)\ z_\beta(t)\ \mathrm{sign}\ e_v(t) & :|\beta^T(t)\ z_\beta(t)\ e_v(t)|>\varepsilon\\ -\{\beta^T(t)\ z_\beta(t)\}^2 e_v(t)\ /\ \varepsilon & :|\beta^T(t)\ z_\beta(t)\ e_v(t)|\leq\varepsilon\end{cases} \quad (2.7a)$$

$$\beta(t)=[\beta_0(t),\beta_1(t)]^T,\ z_\beta(t)=[1,\ |\bar{y}|]^T \quad (2.7b)$$

where, ε (>0) is a small setting constant that moderates the chattering induced by changing of $u_R(t)$. $\beta(t)$ is adjusted by the following adaptive algorithm.

$$\beta(t)=\beta_P(t)+\beta_I(t) \quad (2.8a)$$
$$\beta_P(t)=\Gamma_{\beta P}\ z_\beta(t)\ |e_v(t)| \quad (2.8b)$$
$$\dot{\beta}_I(t)=-\sigma_\beta(t)\beta_I(t)+\Gamma_{\beta I}\ z_\beta(t)\ |e_v(t)| \quad (2.8c)$$
$$\sigma_\beta(t)=\sigma_{\beta 1}\ e_v^2(t)/(1+e_v^2(t))+\sigma_{\beta 2}\ :\sigma_{\beta 1},\sigma_{\beta 2}>0 \quad (2.8d)$$
$$\Gamma_{\beta P}=\Gamma_{\beta P}^T>0,\ \Gamma_{\beta I}=\Gamma_{\beta I}^T>0$$

where, equation (2.8) has a function to estimate an upper bound of disturbance $|d(t,\bar{y}(t))|$.

Now, we must show the stability of the control system (2.1),(2.2),(2.4)~(2.8). First, for simplicity, we consider the case that the disturbance $d(t,\bar{y})$ can be neglected. In this case, we can put $u_R(t)\equiv 0$ in equation (2.4). Then, by assumption and the Kalman-Yakubovich lemma, there exists symmetric positive definite matrices P and Q that satisfy the following equation

$$A_c^TP+PA_c=-Q,\ b^TP=c^T \quad (2.9)$$

Now, matrix $D=I-k_vbc^T$ has property that $\det D=1-k_vb^TPb>0$ by $k_v<0$ and equation (2.9). Let us consider the case of perfect output model following: $e_v(t)\equiv 0, t\geq 0$ and define its ideal states by $x^*, u^*, y^*=y_m$. Then there exist S_1 and S_2 satisfying

$$u^*=S_1x_m(t)+S_2u_m(t).$$

from the low proposed by Broussard[10] under assumption (2) and (4). As a result, the following error equation is obtained.

$$\dot{e}_x(t)=A_Pe_x(t)+b_P\Delta u(t),\ e_y(t)=c_P^Te_x(t) \quad (2.10)$$
$$\Delta u(t)=\zeta^T(t)z(t),\ \zeta^T(t)=\theta(t)-\theta^*$$
$$\theta^*=[k_e^*,\ S_1,\ S_2]^T \quad (2.11)$$
$$A_P=D^{-1}A_c,\ b_P=D^{-1}b,\ c_P=c$$

Here, P_1 be $P_1=PD$. From the equation (2.9), P_1 satisfies $PD=(PD)^T>0$. Therefore $P_1=P_1^T>0$. Let

$$V(t)=e_x^T(t)P_1e_x(t)+\zeta_I^T(t)\Gamma_I^{-1}\zeta_I(t)$$
$$\zeta_I(t)=\theta_I(t)-\theta^*$$

be a candidate of the Lyapunov Function. Then from equations (2.4) to (2.6), the boundedness of $e_x(t)$ and $\zeta_I(t)$ can be shown in accordance with reference [8]. By the result mentioned above, boundedness of $\theta_P(t)$, u(t), $\dot{e}_v(t)$ are also shown. Therefore in case without disturbance, all states of control system under control input (2.4) is bounded. Furthermore the boundedness in case with disturbance can be verified by above result and assumption (3) in accordance with reference [8]. However its procedure is very complicated. Therefore we omitted the proof here.

3. Application to DD Servo System

3.1 Plant model and reference model

To examine the effectiveness of proposed method, a computer simulation and experiment are shown by using a DD servo experiment system.

The outline of experimental device is shown in Fig.1. The device is constructed of one arm with changeable end weight, DD servo motor and personal computer. The Motor angle which is equivalent to position of the arm is measured by encoder pulse counter board that sets up in expansion slot of personal computer type PC 9801 RA. Input signal to DD servo driver is calculated by personal computer followed in above mentioned SAC algorithm by measured angle. Calculated input signal is transformed to analog voltage signal by digital to analog converter and sent to DD servo driver. DD motor is controlled by these signals. The inertia of arm can be changed by the exchange of the end weight.

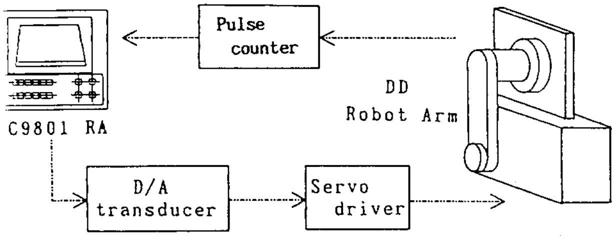


Fig.1 Outline of experimental device

Equation of motion is represented by

$$\dot{x}(t)=\begin{bmatrix}0&1\\0&0\end{bmatrix}x(t)+\begin{bmatrix}0\\1/J\end{bmatrix}u(t)+\begin{bmatrix}0\\1\end{bmatrix}d(t,\bar{y}) \quad (3.1a)$$

$$y(t)=[1\ \ 0]x(t) \quad (3.1b)$$

where

$$x(t)=[\theta,\dot{\theta}]^T,\ u(t)=\tau(t)$$

$$\hat{d}(t,\bar{y})=(mgr/J)\sin\theta$$

J: Inertia moment of arm and rotor.
m: Mass of arm and end weight.
g: Gravity acceleration.
r: Length from the center of the motor to the center of gravity of the arm.
θ: Angle of arm from vertical line.
τ: Output torque of motor.

Here, disturbance being apparently bounded, we may set $\rho_1=0$. Therefore we can treat as $\beta(t)\equiv\beta_0(t)$ and $z_s(t)=1$ in constructing $u_R(t)$. Next, we consider the following second order stable reference model:

$$\dot{x}_m(t)=\begin{bmatrix}0&1\\-a_{m2}&-a_{m1}\end{bmatrix}x_m(t)+\begin{bmatrix}0\\b_m\end{bmatrix}u_m(t) \quad (3.2a)$$

$$y_m(t)=[1\ \ 0]x_m(t) \quad (3.2b)$$

Here, we select tracking output mode as constant increasing acceleration / constant velocity / constant decreasing acceleration as shown in Fig.2. In this case $u_m(t)$ becomes as follows.

$$u_m(t)=(\ddot{y}_R(t)+a_{m1}\dot{y}_R(t)+a_{m2}y_R(t))/b_m \quad (3.3)$$

Then the error $e_m(t)=y_m(t)-y_R(t)$ satisfies

$$\ddot{e}_m(t)+a_{m1}\dot{e}_m(t)+a_{m2}e_m(t)=0$$

Thus if $e_m(0)=0$, $y_m(t)=y_R(t)$ can be realized. This model construction method is very convenience because it only needs height and width of $\ddot{y}_R(t)$ in apriori.

Since the plant model (3.1) is not ASPR, we are not able to construct SAC servo system. Therefore as derived in [9], we modify the plant by implementing a parallel feedfoward compensator (PFC) $\beta/(s+\alpha)$ as shown in Fig.3. Then the extended plant becomes ASPR as far as α and β are positive constants. Hence we can apply SAC to thus obtained extended plant. Further $y(s)\fallingdotseq y_a(s)$ holds for sufficiently small β so that we can approximately attain the control purpose.

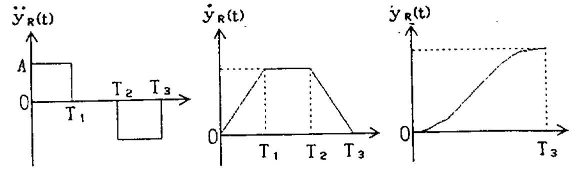


Fig.2 Construction of reference model output

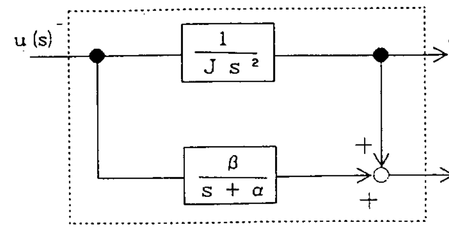


Fig.3 Modified plant by parallel feedfoward compensator

3.2 Simulation result

In the simulation of DD servo system shown in Fig.1, we used following roughly estimated parameter values.

Plant model parameters:

$J=0.1\,(kg\cdot m^2),\ m=2.0\,(kg),\ r=0.12\,(m)$

Reference model parameters:

$a_{m1}=30\,(1/s),\ a_{m2}=200\,(1/s^2)$

$b_m=800\,(1/kg\cdot m^2)$

$y_R(t)$: $A=10\,(rad/s^2)$, $T_1=0.2\,(s)$, $T_2=0.25\,(s)$, $T_3=0.45\,(s)$

Adaptive parameters:

(2.6): $\sigma_1=0.001,\ \sigma_2=0.0001$

$\Gamma_I=\mathrm{diag}[100, 10, 10, 10]$

$\Gamma_P=\mathrm{diag}[50, 5, 5, 5]$

(2.8): $\sigma_{\beta 1}=0.01,\ \sigma_{\beta 2}=0.001$

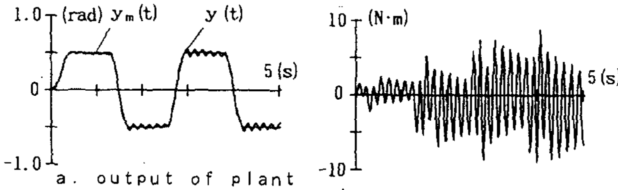
$\Gamma_{\beta I}=5,\ \Gamma_{\beta P}=1,\ \varepsilon=0.1$

Derivative term gain: $k_v=0$ or $-3\,(kg\cdot m^2/s)$

PFC: $F(s)=\beta/(s+\alpha)$: $\alpha=1,\ \beta=0.001$

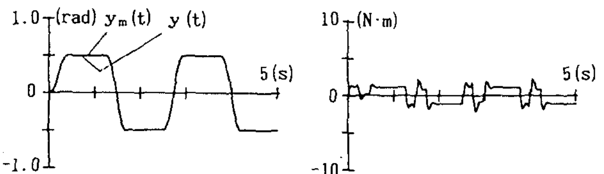
Note that we used the same values as design parameters both in simulation and experiment. Simulation results are shown from Fig.4 to Fig.10. Fig.4 shows a result using usual SAC algorithm. Fig.5 shows the result using SAC plus derivative term and Fig.6 shows the result using SAC plus robust control term $u_R(t)$. In Fig.7, the result considering both derivative term and $u_R(t)$ is shown. Comparing Figs.4 and 5 we can see that the undesirable oscillations of control input are suppressed when we add the derivative action to usual SAC. The best result is obtained in Fig.7. It means that the most effective control is given by SAC with derivative term and $u_R(t)$. Fig.8 and 9 show the effectiveness of the robust adaptive term in case of adding end weight m=3.5kg (r=0.17m).

Tracking error of SAC with robust adaptive term (Fig.9) and of SAC without robust adaptive term (Fig.8) are shown in Fig.10. It is apparent that SAC with robust adaptive term gives better performance concerning the decrease of tracking error.



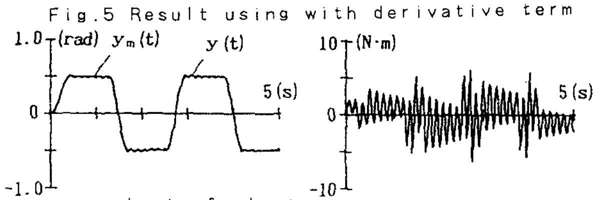
a. output of plant and model
b. control input u(t)

Fig.4 Result using usual SAC



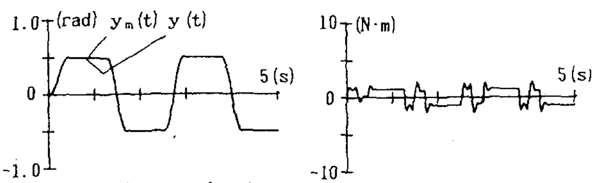
a. output of plant and model
b. control input u(t)

Fig.5 Result using with derivative term



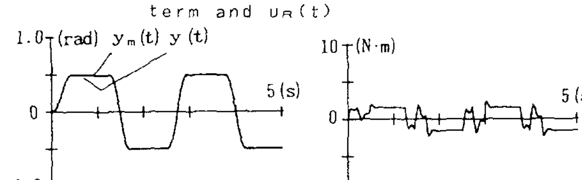
a. output of plant and model
b. control input u(t)

Fig.6 Result using SAC with $u_R(t)$



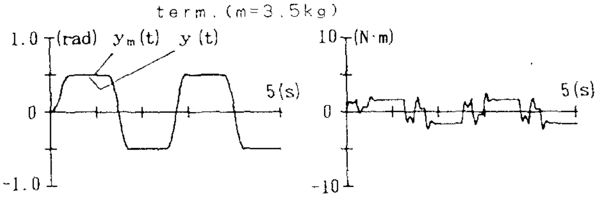
a. output of plant and model
b. control input u(t)

Fig.7 Result using SAC with derivative term and $u_R(t)$



a. output of plant and model
b. control input u(t)

Fig.8 Result using SAC with derivative term.(m=3.5kg)



a. output of plant and model
b. control input u(t)

Fig.9 Result using SAC with derivative term and $u_R(t)$.(m=3.5kg)

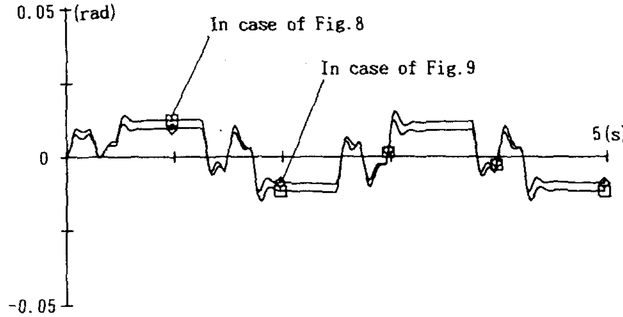


Fig.10 Comparison of tracking error $e_v(t)$

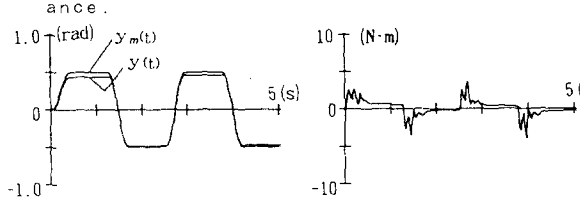
4. Experimental Result

Experimental results of a servo system shown in Fig.1 are given. In this experiment, the control parameter values are fixed as the same values used in the preceding simulations.

4.1 Effectiveness of derivative action

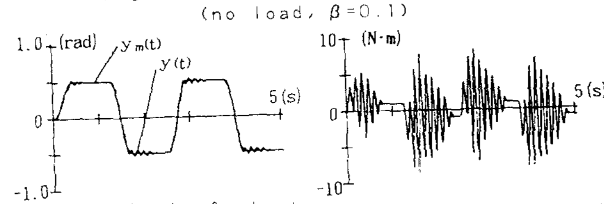
In Figs.11 and 12, effect of the size of parameter β is compared. In Fig.11 we set $\beta=0.1$ and , in Fig.12, $\beta=0.001$. Here we used usual SAC algorithm. The small value β removes the offset. But at the same time it causes undesirable oscillation in the transient process. However, this undesirable phenomenon was very much improved by adding the derivative term into the SAC algorithm as shown in Fig.13, where we used the derivative gain $k_v=-3$. Tracking errors in these 3 cases are given in Fig.14.

Robustness of the proposed algorithm was examined by adding the load on the end of the arm. In this case, the mass of the arm changed from m=2.0 kg (no load) to m=3.5 kg. The responses shown in Figs.15 and 16 express the robust property of the method. However, as shown in Fig.17, addition of the robust compensation term $u_R(t)$ more improves the accuracy of the tracking performance.



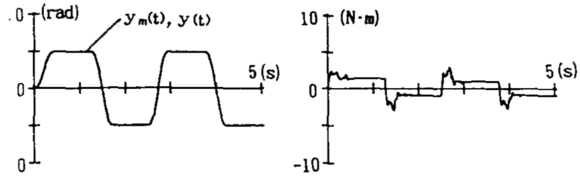
a. output of plant and model
b. control input u(t)

Fig.11 Result using usual SAC (no load, $\beta=0.1$)



a. output of plant and model
b. control input u(t)

Fig.12 Result using usual SAC (no load, $\beta=0.001$)



a. output of plant and model b. control input u(t)

Fig.13 Result using SAC with derivative term.

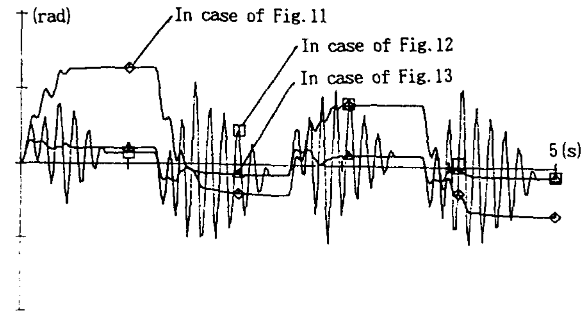
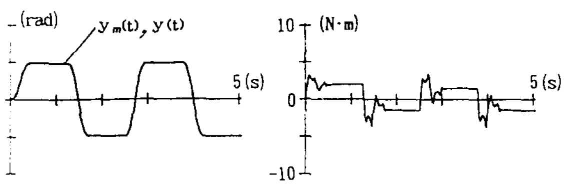
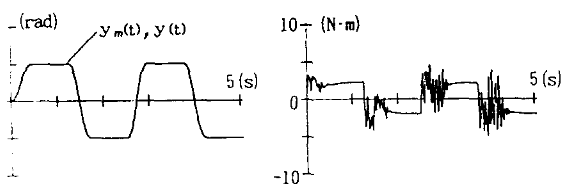


Fig.14 Comparison of tracking error $e_y(t)$



a. output of plant and model b. control input u(t)

Fig.15 Result using with derivative term



a. output of plant and model b. control input u(t)

Fig.16 Result using SAC with derivative term and $u_R(t)$

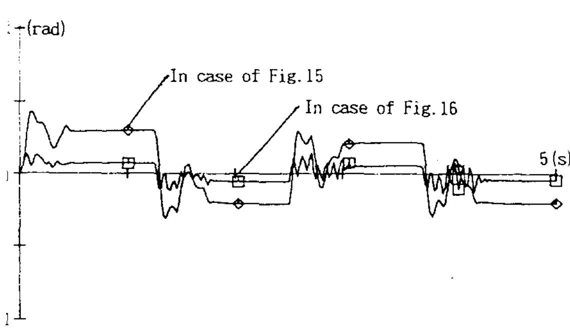


FIG.17 Comparison of tracking error $e_y(t)$

4.2 Comparison of PID control and SAC

Here, the robustness and the high speed tracking property of the proposed SAC algorithm were examined by comparing the conventional PID control algorithm. For this purpose, we used $y_m(t)=0.5\sin(2\pi t)$ as the reference model output. First, we adjusted control parameters in both algorithms such that the resulting tracking error becomes as far as small. Then we added the load at the end of the arm while keeping the same control parameters. The amplitude of the error in the optimal case with no payload was about $3*10^{-3}$(rad). After adding the payload, the amplitude increased to the level of $20*10^{-3}$(rad) in case of PID. But the increase of the amplitude is about 1/2 in case of proposed SAC algorithm as shown in Fig.18. That is, it is shown that SAC algorithm with derivative action has the possibility to attain higher accuracy and robustness under the quick tracking movement.

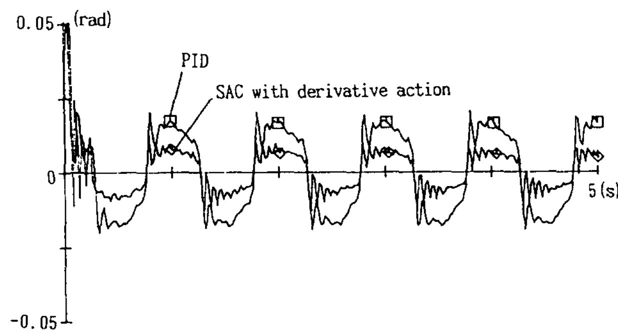


Fig.18 Comparison of tracking error $e_y(t)$

5. Conclusion

In this paper we proposed the introduction of output derivative action to the original SAC algorithm and demonstrated its effectiveness by simulation and experiment of a single-arm servo system. SAC is very simple and easy to realize on line control. However the plant must satisfy the condition of ASPR. If the ASPR condition is not satisfied, then we can make the plant to be ASPR by implementing a parallel feedforward compensator. Unfortunately, it decreases the tracking performance at the same time. However, as mentioned in the preceding sections, the introduction of output derivative action significantly improves the response characteristics of the control system.

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