CONCEPT, STRUCTURE AND DESIGN OF "COLLABORATER" IN HUMAN-MACHINE SYSTEM

Koki Shibasato * **Hirofumi Ohtsuka** * **Shigeyasu Kawaji** **

* *Kumamoto National College of Technology, JAPAN*
** *Kumamoto University, JAPAN*

Abstract: A human intervention is essential for human-machine system and human operator's skill affects deeply achievement of the control purpose. By keeping the human operation easy, an operator can concentrate on more advanced decision so that the operation performance is improved. In this paper, a new concept of human-oriented compensator is proposed for improving the human-machine system, which is named "collaborater". The design approach exists in human dynamics, and 2DOF structure is introduced. The simulation results confirm that the time and frequency responses are improved. Moreover an adaptive function against changes of human dynamics is constructed using neural networks. *Copyright ©2005 IFAC*

Keywords: Human-machine interface, Human-centered design, Compensators, PID control, Adaptation, Neural networks

1. INTRODUCTION

Human-machine system is defined as the equipment system in which at least one of the components is a human operator who intervenes in the operation of the machine components, and a master-slave system is well known as the human-machine system. In such a system with bilateral communication, an information transfer delay possibly causes a degradation of control performance. For this problem, Anderson et al. gave some attractive research results which are considered as the genesis of the subsequent master-slave system researches (Anderson and M.W. Spong, 1989). Depending on the sufficient and substantial infrastructure based on the recent developments of computer network, the problem of information transfer delay becomes to be mild problem at present.

Now, the researches on human-machine system are at the turning point of the paradigm. Let's consider the work of the master-slave system that draws a circle correctly with a pen attached at the slave side. Even by the master-slave system that can control manipulators with high precision a slave manipulator cannot realize the desired remote control completely, since a human operation is imperfect. That is to say, a shift of the control design from the theoretical issue to the practical issue is expected.

Interest in modeling the behavior of a human as an active feedback control device began during World War II (Hess, 2000). To design satisfactory manually controlled systems researchers began analyzing the neuro-muscular characteristics of the human operator. The input to the human is a visual signal indicating the error between desired and actual system output. Kleinman et al. applied optimal control theory to develop a model of human response behavior in manual tracking tasks (Kleinman *et al.*, 1970; Baron *et al.*, 1970). The model contains time delay, a representation of neuromotor dynamics, and controller remnant as limitations. Recently, Furuta considers that the analysis of human control action is one of fundamental problems in the study of human adaptive mechatronics, and from view of which he has analyzed a saturating actuator in human-machine system (Furuta *et al.*, 2004).

In this paper, a new compensation mechanism in human-machine system is proposed with consideration of a human dynamics model. On the occasion of operating a human-machine system, the insufficiency of capability to generate a suitable target command in the brain makes a human operator fail in operation. So, the control performance of human-machine system is improvable by some equipment that compensates the shortage of operation. Mere not the conventional automatic control machine but such a compensator can be regarded as the new control element aiming at realization of cooperation with people and a machine. The compensator is named "collaborater" in the meaning of what works in cooperation with people. However, a human has an excellent adaptability to the environment. When a collaborater is applied to a human-machine system, it is anticipated that a human operator adapts oneself to the system including the collaborater and that the human dynamics will change little by little from the human model as a result of repetition. This may decrease the effects of collaborater. In order to recover the compensation performance, an adaptive collaborater that estimates the human dynamics by neural networks is proposed.

2. CONCEPT OF COLLABORATER

Let's consider the scene where a person is driving a vehicle, as an example. Although a skillful person can drive a vehicle satisfactorily, an unskilled person cannot do so. The difference between the two persons is based on whether they have the knowledge about vehicle dynamics. An unskilled person does not have proper knowledge such as relation between an angle of steering and action of tires, a change of turning radius depending on the speed and so on, and cannot drive a vehicle just as they want to. In a driving school, a learner handles a vehicle according to instructor's advice. When driving is not suitable, the instructor in the driver's assistant seat compensates the driver's action: the instructor turns the steering wheel and gives good advice (see Fig. 1). Compared with self-education, the ability of handling a vehicle can be effectively improved by receiving suitable feedback from an expert.

2.1 Collaborater

Now, let's introduce a mechanism which is similar to the instructor in driving school.

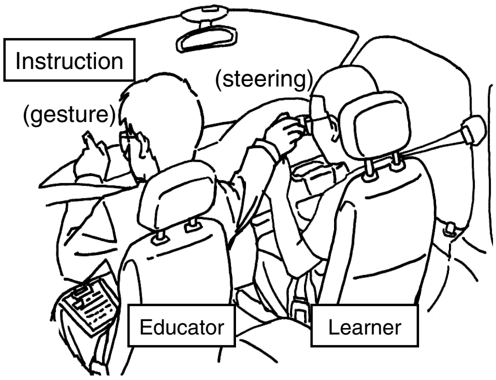

Fig. 1. A scene in driving school

Definition (Collaborater)

Collaborater is the compensator that supports the human decision and action in order to achieve a meaningful work.

Note that the collaborater is one of compensators that realize cooperation work with human operator, so it neither works independently nor disturbs human operation.

2.2 Functions

The above example and the definition of the collaborater indicate that the required functions in the collaborater are summarized as follows.

1. *Sharing the control objects*
   The collaborater understands what human operator wants to do.
2. *Detection of the behavior*
   Human behavior and the motion of machine are detected for evaluating the achievement.
3. *Compensation for the human operation*
   The human operation is properly assisted in order to achieve the control objects.
4. *A grasp of control objects*
   When the vague control objectives are given, it is required that the collaborater converts the objectives into the concrete ones in order to recognize it.
5. *Prediction and Estimation*
   The human operation is supported smoothly by predicting the future state and estimating several parameters.
6. *Instruction to a human operator*
   For improving the human skill, the guidance information is given to the operator by combining vision, hearing, and haptic information.

The functions 1, 2, and 3 are the basic functions of collaborater to achieve necessary effects (Ohtsuka *et al.*, 2003). Moreover, functions 4, 5, and 6 are the extended functions of collaborater. By adding these extended functions appropriately, a finer bilateral cooperative work becomes possible.

3. MAIN RESULTS

3.1 Problem statement

Let's consider a control problem in Fig. 2 in which a human operator controls the machine to follow the target. In this problem the following assumption is set.

Assumption

> *Human dynamics and the machine dynamics do not change during operation.*

Then our problem is stated as *"Design a collaborater that improves the performance of human-machine system."*

3.2 Design of collaborater

A design scheme is summarized in the following three steps.

Step1: Analysis of the structure of the human-machine system

At first, a human dynamics model including psycho-physical responses is derived. As the human dynamics model, the DFF (Delayed-Feed-Forward) model was proposed which describes the sensory functions for the human operation (Ishida and Sawada, 2003). The basic components of the model are the brain, arm and hand, nervous system and eyes. But the impedance factor G_i showing correspondence of position-power has to be taken into consideration in the model. Letting the transfer function of the machine be G_m, the human-machine system is expressed as block diagram in Fig. 3. Human controls his hand $Z(t)$ so as to follow the target $T(t)$.

Table 1. Parameters and variables

Notation	Parameters and Variables
$T(t)$	position of the target
$Z(t)$	position of the hand
$Y(t)$	command signal from the brain
δ	dead time in the nervous system from the retina to the brain
ξ	dead time in the nervous system from the brain to the muscle
τ_1	time constant of the brain
τ_2	time constant of the muscle dynamics
γ	feed-forward gain in the brain

A close look at Fig. 3 reveals that the process in the brain behaves such as a 2DOF controller. The feed-forward block works as the linear prediction, and the feedback block works to reduce the error between the target and the hand. So, this model suggests that the 2DOF structure is advantageous to a collaborater from the viewpoint of an affinity for human operator.

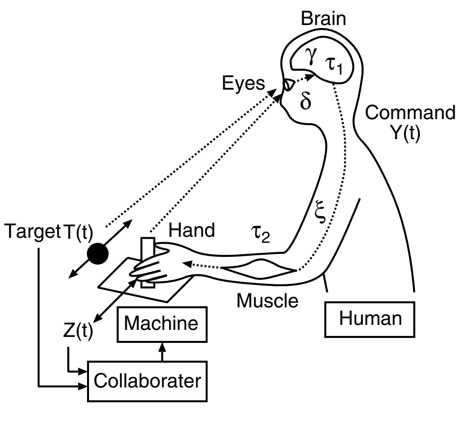

Fig. 2. Human operator model

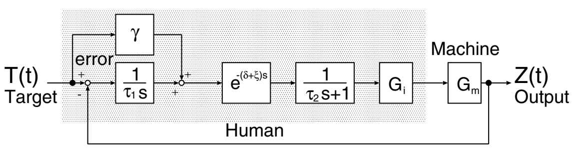

Fig. 3. Block diagram of a human-machine system

Step2: Parameter tuning of 2DOF compensator

The human-machine system in Fig. 3 seems to be composed of the virtual plant and a virtual 2DOF controller as shown in Fig. 4. If the transfer function from the input to the output yields good response, the 2DOF controller may act appropriately on the virtual plant. The virtual controller of an inexperienced operator has not probably tuned well to the whole system, so the collaborater needs to compensate the insufficiency of the operator. Since signal processing in the brain is a 2DOF structure and includes dead time, a PID compensator with the same structure is applied to the controller. Thus the control elements C_1, C_2 are described as follows

$$C_1 = K_D s + K_P + \frac{K_I}{s}, \tag{1}$$

$$C_2 = \beta s + \alpha, \tag{2}$$

where K_P, K_I, and K_D are proportional gain, integral gain and differential gain of C_1, respectively. α and β are proportional gain and differential gain of C_2.

And the difference between the C_1, C_2 and the human model are given by

$$C_1' = C_1 - \frac{1}{\tau_1 s}, \tag{3}$$

$$C_2' = C_2 - \gamma. \tag{4}$$

Step3: Construction of the collaborater

C_1' and C_2' are designed in step2. Accordingly, the block diagram is rearranged so that the signal is connected outside of the human function. Consequently, using 2DOF PID compensator which is designed for the virtual plant, a collaborater is constructed as C_1'' and C_2''.

$$C_1'' = \frac{K_D s + K_P + (K_I - \frac{1}{\tau_1})\frac{1}{s}}{\tau_2 s + 1} G_i e^{-(\delta+\xi)s} \tag{5}$$

$$C_2'' = \frac{\beta s + (\alpha - \gamma)}{\tau_2 s + 1} G_i e^{-(\delta+\xi)s} \tag{6}$$

Based on the design scheme, a basic collaborater has been designed. The collaborater includes the functions (1–3). Since the collaborater is designed under the condition that dynamics of the human and machine is known well, it is very important to construct a numerical model of human appropriately and identify the parameter correctly.

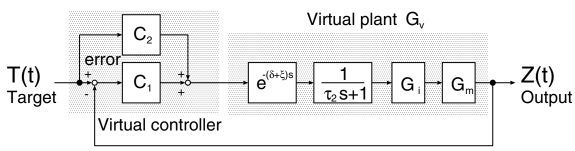

Fig. 4. Virtual plant and controller

3.3 Simulations

Simulation examples are demonstrated for examining the effectiveness of the proposed method. The object of the control is to reduce the distance between the machine position and the target position to zero.

Consider that the mechanical system G_m is a damped mass-spring system as follows.

$$G_m = \frac{1}{Ms^2 + Ds + K} \tag{7}$$

where $M = 2$ [kg], $D = 40$ [Ns/m] and $K = 400$ [N/m]. The parameters of the model are set as follows: $\delta = 0.05$, $\xi = 0.05$, $\tau_1 = 0.1$, $\tau_2 = 0.1$, $\gamma = 1.5$, $G_i = 100$.

From the design scheme mentioned in section 3.2, C_1 and C_2 are obtained by applying the ultimate sensitivity method referred to as Ziegler-Nichols method. The PID gain and the key parameters in equations (1), (2) are as follows: $K_P = 4.143$, $K_I = 23.05$, $K_D = 0.238$, $\alpha = -2.088$, $\beta = -0.033$. Then, the collaborater with transfer function is given by

$$C_1'' = \frac{0.238s + 4.143 + \dfrac{13.05}{s}}{0.1s + 1}\, 100\, e^{-0.1s}, \tag{8}$$

$$C_2'' = \frac{-0.033s - 3.588}{0.1s + 1}\, 100\, e^{-0.1s}. \tag{9}$$

The Bode plots of the human-machine system are shown in Fig. 5. The bandwidth frequency without applying the collaborater is about 6.0 [rad/s], and the phase angle reaches -180 [deg] at 7.6 [rad/s]. On the other hand, the bandwidth of the system with the collaborater is 11.1 [rad/s], and the phase angle reaches -180 [deg] at 11.6 [rad/s]. The Bode plots illustrate that addition of the collaborater to the human-machine system widens the bandwidth and prevents the phase lag.

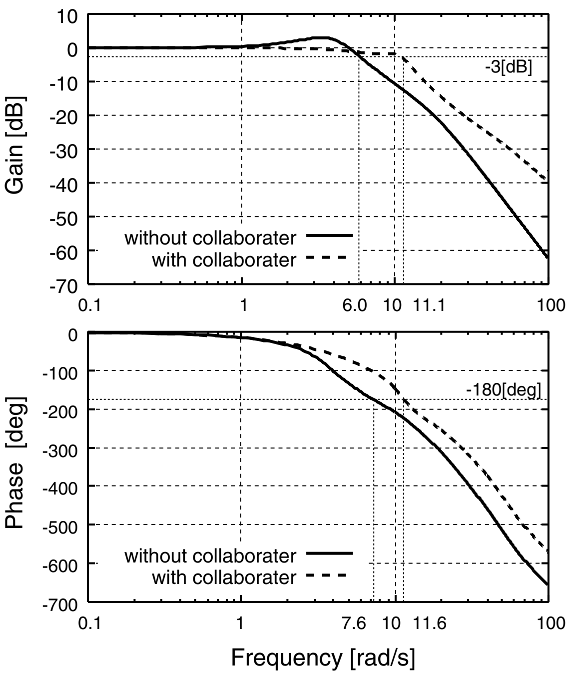

Fig. 5. Bode plots of the human-machine system

Note that it is possible to design a collaborater which widens the frequency bandwidth further than the previous example. If the bandwidth is widened further, however, an operator would recognize the difficulty in keeping the operational feeling. Remember that a collaborater is not an automatic controller, but the compensator that works together with people. Therefore, it is appropriate that the bandwidth of human-machine system with collaborater is almost twice as long as that of human-machine system without collaborater.

Figure 6 shows the step response with the magnitude 0.1. The reference signal is supplied into the system at the time 1 [s]. The specifications are shown in Table 2. By applying the collaborater to the human-machine system, the overshoot decreases to 1/10 and the settling time decreases to 1/5. Also the delay time and the rise time are reduced. Although a little vibration is observed in the transient response, the step response is improved on the whole.

Table 2. Specifications of the step response

Specifications	N/A	Collaborater
Overshoot [%]	26.9	2.40
Delay time [s]	0.37	0.25
Rise time [s]	0.31	0.22
Settling time [s]	1.94	0.41

Simulation results show that the collaborater improves the response to the step input. Now, let's focus our attention on the human force. Figure 7 shows the human force in the step response. When the collaborater is not applied, human force vibrates in order to cancel the influence of a spring in the mechanical system. On the other hand, by applying the collaborater, the overshoot is almost eliminated and the human force shows smooth curve without oscillation. From this viewpoint it is expected that the operator can control the machine easily.

Next, let us observe the behavior of the collaborater carefully (see Fig. 8). C_1'' generates the force toward the same direction as the human operator and has

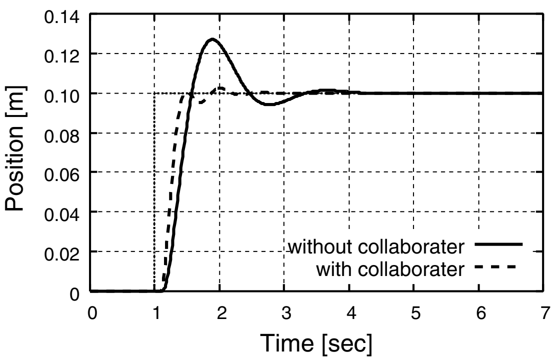

Fig. 6. Step response of the human-machine system

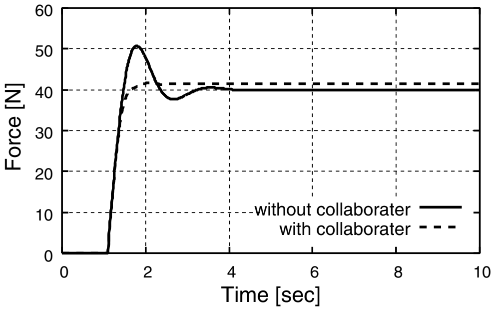

Fig. 7. Human force in the step response

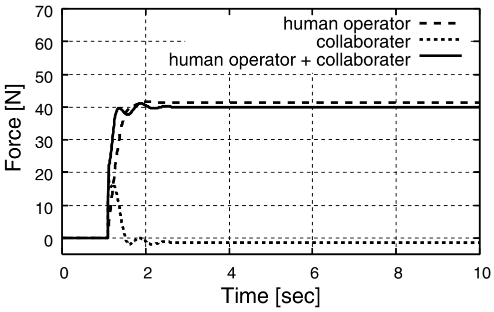

Fig. 8. Human force and output of the collaborater

a large output especially at the rise. It is equivalent to increase the effect of error feedback function in the brain. C_2'' has the negative quantity in order to increase the robustness against disturbance and affects especially at a steady state. The collaborater generates the opposite output at times, so it seems contradictory to the assistance of human operation. However, it reduces the overshoot and the influence of disturbance. From simulation results, it is concluded that the collaborater functions well.

4. ADAPTIVE COLLABORATER USING NEURAL NETWORK

4.1 Adaptive collaborater

In the previous section the fundamental design scheme of collaborater and simulation results were presented. In the simulation it was supposed that human dynamics does not change during operation. Since the operation time is not so longer, it is proper to suppose that the human dynamics does not vary rapidly during the operation. However, a human has an excellent adaptability to the environment. When a collaborater is applied to a human-machine system, it may be expected that a human operator adapts oneself to the system including the collaborater and that the human dynamics will change little by little from the human model as a result of repetition. If a human operator changes own characteristics, whole the input-output dynamics of the human-machine system including collaborater changes inevitably. Because of human learning, it is feared that the application of collaborater may deteriorate the frequency response and the time-domain response conversely.

Thus, an adaptive collaborater that learns the human dynamics and tunes oneself is introduced. Since it is expected that the time constant of synapses τ_1 and the feed-forward gain γ change by repetitious work, the adaptive collaborater estimates the parameters: $\hat{\tau}_1$ and $\hat{\gamma}$ (see Fig. 9). Here, a neural network is adopted in order to estimate human dynamics. Since a correlation between τ_1 and γ is not clear, the estimation functions that learn human dynamics are constructed independently by two neural networks.

Let NN_1 and NN_2 be the estimation functions for τ_1 and γ, respectively. The neural networks have been trained by using the time series data from 0 [s] to 0.25 [s] in a step response: the reference signal, the human force and the output of the machine. Here, the network is composed of a single hidden layer. As a result of training the network, the mean square error of the output of NN_1 is 2.92×10^{-5} and that of NN_2 is 5.32×10^{-5}. Also τ_1 and γ were changed finely and the estimation error was examined. These results confirmed that the estimation error of time constant is less than 20% and that of γ is less than 2%.

4.2 Simulation results

Consider the case when a collaborater is applied to human-machine system and a human operator adapts oneself to the system including the collaborater as a result of repetitious work. In this problem, suppose that initial parameters of the human model are $\tau_1 = 0.1$ and $\gamma = 1.5$. Next, a time invariant collaborater and an adaptive collaborater are designed and applied to the human-machine system. Assume that parameters change to $\tau_1 = 0.16$ and $\gamma = 1.0$ consequently by the repetitious operation. Now, compare the step response of the time invariant collaborater and that of the adaptive collaborater (see Fig. 10). Here, initial values of $\hat{\tau}_1$ and $\hat{\gamma}$ are given as τ_1 and γ. Due to the dead time, a step response comes out after 0.1 [s] from the change of the target. After that, the adaptive collaborater could estimate the time constant and the feed-forward gain from the input-and-output data for 0.25 [s], and applies $\hat{\tau}_1$ and $\hat{\gamma}$ instead of τ_1 and γ: $\hat{\tau}_1$ and $\hat{\gamma}$ are estimated as 0.1494 and 0.9861 respectively (true value: $\tau_1 = 0.16, \gamma = 1.00$). After estimation of τ_1 and γ, the time response is improved by the adaptive collaborater.

Let's focus on the relation between parameter change and frequency response in order to investigate the validity of the adaptive collaborater. Bandwidth of the system with collaborater is shown in Fig. 11. Bandwidth is increased as the decrease of τ_1 and the increase of γ, and it changes rapidly in the vicinity

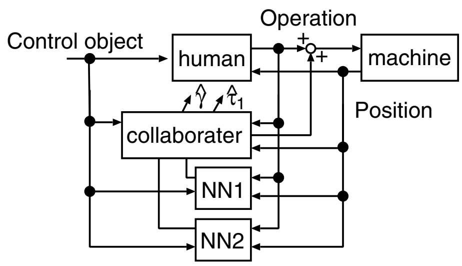

Fig. 9. Structure of the adaptive collaborater

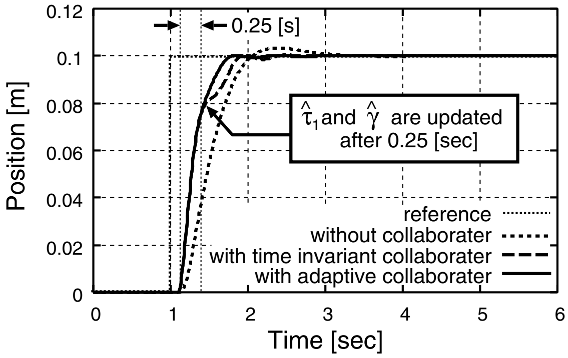

Fig. 10. Step response of the adaptive collaborater

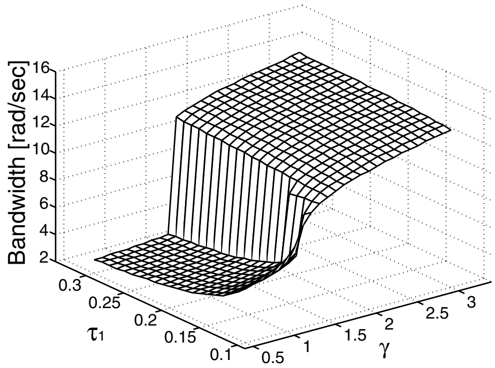

Fig. 11. Bandwidth of the human-machine system with collaborater

of $\gamma = 1.5$ that was used to design a collaborater. Generally, the collaborater has much effect near the dynamics that was used to design. If human prediction accuracy deteriorated from the initial state, the compensation by the collaborater does not have much effect on the tracking performance. When human prediction performance deteriorates, even if a time invariant collaborater is applied to a human-machine system, it is hard to expect the good control. However the simulation result illustrates the possibility that the collaborater assists human operation appropriately by the adaptation of human dynamics and recovers the control performance.

5. DISCUSSION

An experimental system that is under development is shown in Fig. 12. An indicator shows the target position and an operator controls a handle to follow the indicator. At this stage, our experiment is in the process of identification of a human model; however, the experimental results similar to the simulations have been obtained with reproducibility (Fig. 13). The effects of the collaborater would depend on how the uncertainty of human dynamics is treated.

6. CONCLUSION

In this paper, a new concept "collaborater" for the support of human operation has been introduced and a design scheme has been illustrated with several simulations. Simulation results have indicated that a collaborater widens the bandwidth of a human-machine system and improves the time response. Although it is feared that human dynamics varies as a result of

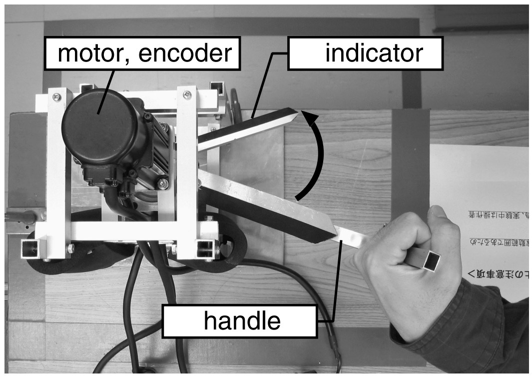

Fig. 12. Experimental system

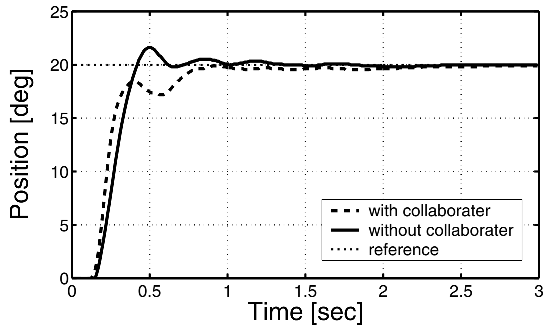

Fig. 13. Experimental results (target : 20[deg])

repetitious operation, it is shown that an adaptive collaborater estimates a human model appropriately and recovers the control performance.

REFERENCES

Anderson, R.J. and M.W. Spong (1989). Bilateral control of teleoperators with time delay. *IEEE Transactions on Automatic Control* **34**(5), 494–501.

Baron, S., D.L. Kleinman and W.H. Levison (1970). An optimal control model of human response part ii: Prediction of human performance in a complex task. *Automatica* **6**, 357–369.

Furuta, K., M. Iwase and S. Hatakeyama (2004). Analysing saturating actuator in human-machine system from view of human adaptive mechatronics. *Proceedings of REDISCOVER 2004* **1**, (3–1)–(3–9).

Hess, R.A. (2000). Human-in-the-loop control. In: *CONTROL SYSTEM APPLICATIONS* (William S.Levine, Ed.). pp. 327–335. CRC press LLC. New York.

Ishida, F. and Y. Sawada (2003). Quantitative studies of phase lead phenomena in human perceptmotor control system. *Transactions of the Society of Instrument and Control Engineering* **39**(1), 59–66.

Kleinman, D.L., S. Baron and W.H. Levison (1970). An optimal control model of human response part i: Theory and validation. *Automatica* **6**, 357–369.

Ohtsuka, H., K. Shibasato, H. Uemura and S. Kawaji (2003). A study on a human-oriented compensator for the human-machine system. *Proceedings of International Conference on Control, Automation and Systems* **1**, 657–662.