A Study on a Human-Oriented Compensator for the Human-Machine System

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Abstract: A mechanical system controlled by human operator, such as master-slave system, includes human dynamics in the whole system and such a system is called a human-machine system. In the system, operator's skill is required considerably in order to realize a meaningful operation. In this paper, a new concept and design strategy of compensator that improves the operativity of human-machine system are proposed. The compensator is called "collaborater" that is named after "collaborator" who works together with people. We mean not to design the automatic controller but the compensator that works together with a machine so that human feels the fulfillment in the operation. Our aim is to realize cooperation of people and a machine on a higher level.

Keywords: human-machine system, 2-DOF PID control, collaborater

1. INTRODUCTION

Generally the leading type of a master-slave system is a bilateral type that performs bidirectional communication of a position, speed, and power information between a master and a slave. By transfer delay of the information, degradation of a control performance is caused in such bilateral control, however, the method proposed by Anderson et al. copes with the problem [1], [2], [3]. Their research is the starting point of subsequent master-slave system researches. Against the background of sufficient and substantial infrastructure by maintenance of an information network, and the above-mentioned research result, the problem of information delay is being solved at present. Consequently, expectation of the practical use of master-slave technology to the many fields is growing. However, the chief aim of the conventional research was set to the guarantee of the stability of a master-slave system, and faithful realization of slave manipulator operation by a master manipulator, there are very few research examples for the increase in efficiency of remote work or improvement in operativity. It is required ordinarily that an operator should be an expert of the operation work of master-slave equipment. If an operator is a beginner deficient in experience, naturally it is difficult to obtain the good result. At this time, it cannot be overemphasized that a very great load joins the operator who is a beginner. Moreover, a beginner does not necessarily carry out the best operation agreed for the purpose of work. As a result, there occurs problems. That is, equipment is destroyed by negligence operation of an operator with the shallow degree of skill, or people existing in work environment are damaged. As mentioned above, research on a master-slave system is at the turning point of the paradigm: the system shifts from a research subject called the guarantee of stability to the technical subject thought practically as important.

On the occasion of operating a master-slave system, the skilled operator can perform proper control based on his (her) experience: adjustment of the amount of operations suited to the work purpose and the situation. The prime cause by which an inexperienced person fails in operation in contrast with the skilled operator is the following two points. First, an unripe operator cannot adjust own control characteristic. And it is the second cause that the capability of generating a suitable target about the object is insufficient. If the performance of controlling a system is improvable by some equipment that compensates the shortage of operation of an inexperienced person, the desired control is able to be realized and the operator's load is also able to be mitigated. 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 called "collaborater"[1] in a meaning of what works in cooperation with people. For example, let's consider the work of the master-slave system that draws a circle correctly with a pen attached at the slave side. Although an operator has to draw a circle by the master manipulator correctly, there is a limit in the accuracy of such operation that people can do. Moreover, when the condition that the operation is more high-speed than the muscular reaction is given, the object cannot be attained at all. Here, it is the important point that a gap will arise between an intention of people and operation. Even by the master-slave system that can control manipulators with high precision, since operation of people is imperfect, a slave manipulator cannot realize desired remote control completely. In other words, the operation is accomplished by executing expected slave manipulator action, even if a slave manipulator is not controlled faithfully to the master manipulator. However, note that we don't aim at the automatic controller that neglects people's action. Our aim is to realize cooperation of people and a machine on a higher level.

In this paper, for the purpose of improvement in the practicality of a human-machine system, the collaborater supporting the work which people meant and its design strategy are proposed. In Section 2, the definition, basic functions, and role of collaborater are given systematically. Section 3 describes a human model and its characteristics about the tracking control. Section 4 shows the concrete design procedure of the collaborater. Finally, the validity of the proposal technique is verified through a simulation.

2. BASIC CONCEPT

First of all, let's consider the difference between a beginner and an expert in driving an automobile and clarify the outline of the collaborater. Although an expert can drive an automobile satisfactorily, a beginner cannot do so. What is the difference between the

[1]The coined word " collaborater" is named after "collaborator" who works together with people.

two people? It could be concluded that the difference is the knowledge. A beginner does not have the knowledge: relations between an angle of steering and action of tires, a change of turning radius depending on speed and so on. A beginner cannot drive an automobile as their wish because of lack of knowledge. Unskilled people go to a driving school in order to gain experience of driving and learn the suitable operating method. As the result, they acquire the skill of driving through the experience. For example, a learner acts on instructor's advice at a driving school while steering an automobile (see Fig.1). When the steering is not suitable, the instructor in the driver's assistant seat compensates the driver: steers a car with a learner and gives good advice. Thus, compared with self-education, driving skill can be effectively gained by receiving suitable feedback from an expert.

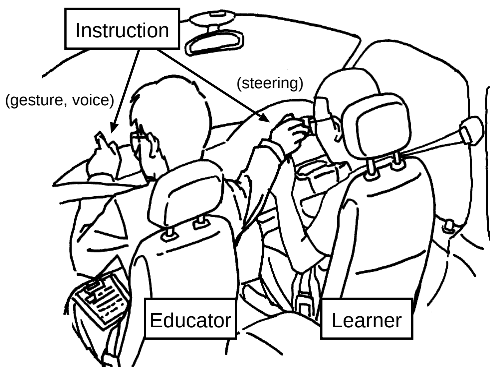

Fig. 1. A scene of a driving school

2.1. Collaborater

Next, we give the definition of the collaborater in order to orient the design strategy. Fig.2 shows the fundamental structure of the human-machine system.

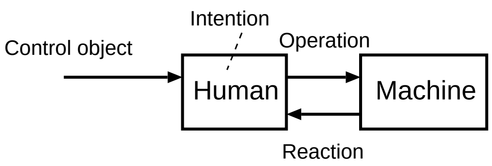

Fig. 2. The human-machine system

It is considered that the act of driving an automobile has the structure similar to Fig.2, where we suppose that neither a human nor a machine is influenced from the environment. Here, we notice that it is necessary to distinguish terms "control object", "intention", and "operation". "Control object", demanded to be achieved in a human-machine system, is the goal of the whole system. "Intention" is the goal generated by the human, in order to realize the control object. And "operation" is regarded as the human output based on the intention. Although the situation where there is no gap in object, intention, and operation is desirable for a good job, such a situation cannot be necessarily satisfied.

Let's consider the case that the control object is different from the operator's intention. A gap of object and intention depends on the concreteness of given object and the capability for an operator to be able to understand. Even if the control object is complicated, an expert can make suitable decision. On the other hand, a beginner takes verbose actions or cannot make a suitable decision. Here, we define a simple object and a complicated object as narrow sense and broad sense, respectively. When the object in the narrow sense is given, the control object is interpreted as the intention and thus support of the operator may not be needed. When the broad control object is given, however, it is possible to support the operator by decomposing the object into the simple target and showing it.

Next, let's consider the case that the intention is different from the operation. A gap of an intention and operation is greatly dependent on an operator's physical ability and the control object: the problem of highly precise target tracking and the operation above muscular dynamics. For example, one of the solutions coping with the problem is to add actuators in order to assist the power.

Based on the above discussion, the collaborater is defined as follows.

Definition (Collaborater)

The system that supports the people's decision and the action in order to realize the given control object is called collaborater.

Here, note that the collaborater is one of the compensator that realizes cooperation work with people and does not work independently and does not disturb human operation.

2.2. Design strategy

According to the above-mentioned examples and the definition of collaborater, the required functions are summarized as follows.

1. **Share of the control object**
   The control object is shared between the human and the mechanical system.
2. **Compensation of the human operation**
   The human operation is assisted in order to achieve the control object.
3. **Detection of the behavior**
   Behavior of the human and the machine is detected.
4. **Grasp and generation of the object**
   The object in the narrow sense is generated from the broad object given to system.
5. **Estimation**
   Behavior of the human and the machine are estimated.
6. **Instruction**
   A variety of information is fed back to the person.

An object in the narrow sense is required in order that the human may take a suitable action. Simultaneously, it is an essential function to achieve cooperation between a human and a machine. Function 1 is derived from the above-mentioned reason. Function 2 means dynamic compensation and assists the human operation when there is a gap between the operation and the intention. Function 3 is an important part to grasp the present situation for the suitable cooperation. An example of the collaborater that has the Function 1-3 is shown in Fig.3. Now, we can see that Function 1, 2, and 3 are basic functions of collaborater that perform dynamic feedback. Therefore, we conclude that all the collaborater only with fundamental functions results in Fig.3.

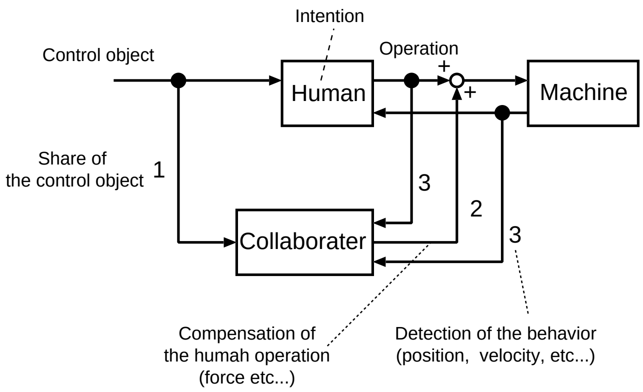

Fig. 3. Basic composition of the collaborater

Moreover, Function 4, 5, and 6 are the extended functions of collaborater. Even if an abstract object is given to the system, the collaborater cannot recognize what it should act. It is expected to decompose the control object into the object in the narrow sense that can be shared with the human, when the broad object is given. If an object is not given to the collaborater (lack of Function 1), a control object is regenerated from the sensing information by the advanced knowledge information technology (Function 4). Function 5 aims at supporting the human operation smoothly by expecting the state, when dead time exists and a part of the data is lost in the transmission of the information. Function 6 is a teaching mechanism that is achieved by offering the information with the image and the sound, or feeding back the physical information to the operator. By adding these extended functions appropriately, the finer bilateral cooperative work becomes possible.

3. HUMAN DYNAMICS

In this section, the inherent characteristic of the human model is clarified. As shown in Fig.3, the collaborater is the compensator to the system that includes the human dynamics and a mechanical system. The characteristics of the whole system are needed to compensate the system effectively. Especially, the human dynamics is needed in order to determine the structure of the collaborater.

3.1. Delayed feed-forward model

Here, the model of the human operation which controls own hand $X(t)$ so as to follow the target $T(t)$ is considered. The DFF (Delayed-Feed-Forward) model was proposed as the model that describes the sensory and motor functions of human [4]. Fig.4 illustrates a signal flow of the model. The model is given as equations (1) and (2), where the parameters of the model are defined in Table 1 and the block diagram is shown in Fig.5.

$$\dot{Y}(t) = \frac{1}{\tau_1}\{T(t-\delta)-X(t-\delta)\}+\gamma\dot{T}(t-\delta) \quad (1)$$

$$\dot{X}(t) = \frac{1}{\tau_2}\{Y(t-\xi)-X(t)\} \quad (2)$$

A close look at Fig.5 reveals that the process in the brain behaves such as the 2-DOF controller. It is seen that a feed-forward block behaves as linear prediction and a feed-back block works to decrease the error between the target and the output. This observation suggests what the structure of the collaborater should be.

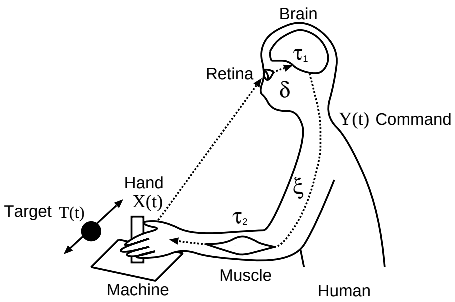

Fig. 4. The sensory and motor functions of human

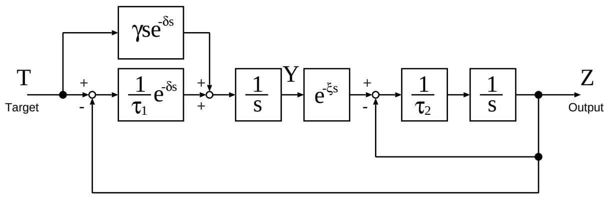

Fig. 5. The block diagram of the DFF model

Table 1. Variables and parameters of the DFF model

Variables and Parameters	Definition
$T(t)$	position of a target
$X(t)$	position of a hand
$Y(t)$	command signal from a brain
δ	daed time from a retina to a brain
ξ	daed time from a brain to muscle
τ_1	time constant of a brain
τ_2	time constant of muscle
γ	feed-forward gain

3.2. Phase compensation of the human model

Fig.6 is a block diagram rearranged from Fig.5. The block diagram shows that the DFF model includes the transfer function $(\tau_1 s+1)/(\tau_2 s+1)$ that is interpreted as a phase compensator. The characteristic of the transfer function depends on relative size of τ_1 and τ_2 and is summarized as follows.

Case1 ($\tau_1 << \tau_2$) The transfer function $(\tau_1 s+1)/(\tau_2 s+1)$ behaves like a phase lag system.

Case2 ($\tau_1 >> \tau_2$) The transfer function $(\tau_1 s+1)/(\tau_2 s+1)$ behaves like a phase lead system.

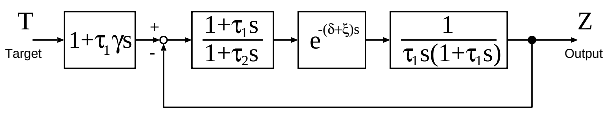

Fig. 6. Phase -lead or -lag transfer function in DFF model

The transfer function is considered as a phase-lag system, when the time constant of deciding the motion is shorter than the time constant of moving a hand. Generally, a phase-lag factor increases steady-state accuracy and a phase margin. On the other hand, the transfer function is considered as a phase-lead system, when the time constant deciding the motion is longer than the time constant moving a hand. The lead-compensated system will generally be much faster in its time response than the uncompensated plant. That is, the factor behaves so as to compensate the delay of operation caused by the delay of instructions. We could conclude that control strategy of human is denoted from a viewpoint of phase characteristics. These indicate that degradation of the performance in a human-machine system is caused when human cannot attain the intentional characteristics. Therefore, improving the shortage of the characteristics by the collaborater, the desired control can be realized. For example, it can be said that the collaborater can raise the tracking performance by acting as the phase-lead compensator.

4. SCHEME FOR DESIGNING COLLABORATER

In this section, we set up a problem for designing a collaborater and show a basic scheme to design it based on the strategy proposed in section 2.

4.1. Problem setting

Now, we consider the next problem.

Problem setting

Consider the human-machine system whose position is controlled by a human. Design a collaborater that aims at improving control performance of the system.

$$G_m = \frac{1}{Ms^2 + Ds + K} \quad (3)$$

M : a mass of the system
D : a damping coefficient
K : a stiffness of the spring

Where the target is given visually and the machine is the damped mass-spring system G_m.

If we assume the following assumptions, the collaborater can be constructed by a basic composition shown in Fig.3.

Assumption

1. Human dynamics does not change during operation.
2. The disturbance signal is not inputted into a system and system parameters do not change during operation.

Since it is important to indicate the scheme to design a collaborater, we do not take into consideration about the concrete actuator for realizing the collaborater.

Step1: Determination of the structure of a human-machine system

The block diagram of a human-machine system is shown in Fig.7. Since a DFF model is a transfer function from visual target to the position of a hand, we have to consider the characteristic impedance G_i in order to apply it to a human-machine system. The control object is to manipulate a machine so that a position of hand $Z(t)$ traces a target signal $T(t)$. An operator makes a lot of progress in controlling the machine by knowing characteristics of the system G_m from experience. Such a process means to adjust parameters γ, τ_1. That is, since the beginner has not adapted the parameters in the brain yet, he (she) cannot achieve a good performance so that an expert manipulates. Therefore, the structure that compensates the insufficiency of adjustment of parameters in the brain acts as collaborater that we propose.

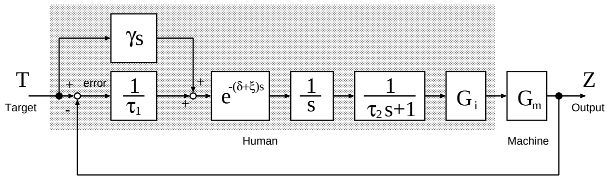

Fig. 7. The block diagram of a human-machine system

Step2: Determination of the structure of a human-machine system

Now, let's arrange the block diagram of a human-machine system (see Fig.8). We could consider that the portion enclosed with a dashed line is a virtual plant G_v. And the block diagram is regarded as a system composed of a virtual plant G_v and a virtual 2-DOF controllers $1/\tau_1$ and γs. Therefore, an external compensator that is equivalent to adjusting the parameter within a brain appropriately is regarded as collaborater that improves the total performance of a human-machine system. Moreover, various adjustment rules for a dead time system have been established based on the PID control [5]. Since signal processing within a brain is a 2-DOF controller and includes dead time, a compensator of the same type is considered using PID control law. Thus the control elements C_1,C_2 are designed as follows.

$$C_1 = K_D s^2 + K_P s + K_I \quad (4)$$
$$C_2 = \beta s^2 + \alpha s \quad (5)$$

Where K_P, K_I, and K_D are proportional gain, integral gain and differential gain in C_1, respectively. α and β are proportional gain and differential gain in C_2. Since a human model has an integral element, we applied differential type PID control method. The example of a gain tuning is shown in section 5.

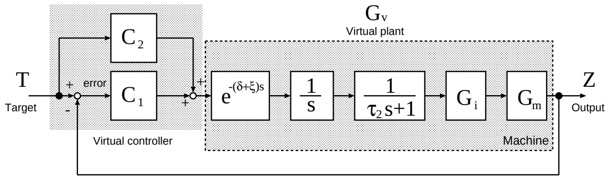

Fig. 8. The block diagram of the system that is composed of a virtual plant and controllers

C_1 and C_2 are the controllers to a virtual plant G_v, and C_1' and C_2' are compensators included in it (see Fig.9). Therefore, the following equation is derived.

$$C_1' = C_1 - \frac{1}{\tau_1} \quad (6)$$
$$C_2' = C_2 - \gamma s \quad (7)$$

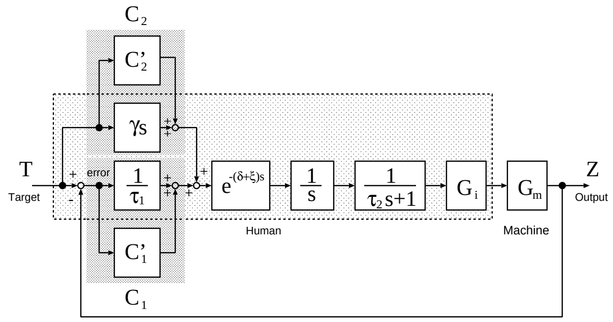

Fig. 9. Compensator in the human function

Step3: Derivation of the collaborater

We decided C_1' and C_2' in step2. But C_1' and C_2' are located in the brain, so these cannot be realized as a physical device. Accordingly, the block diagram is arranged so that the signal is connected outside of human function. Consequently, using 2-DOF PID controller that is designed for the virtual plant, collaborater is obtained as C_1'' and C_2''.

$$C_1'' = \frac{K_D s^2 + K_P s + (K_I - \frac{1}{\tau_1})}{\tau_2 s^2 + s} G_i e^{-(\delta+\xi)s} \quad (8)$$

$$C_2'' = \frac{\beta s^2 + (\alpha - \gamma)s}{\tau_2 s^2 + s} G_i e^{-(\delta+\xi)s} \quad (9)$$

According to the design strategy, the basic collaborater is designed. The collaborater includes the function1-3: share of the control object, compensation of the human operation and detection of the behavior. Since the collaborater is designed on the condition that dynamics of a human and a machine are known well, it is very important to model a human appropriately and identify the parameter correctly.

5. SIMULATION

In this section, we show a simple example. We design a collaborater about a human-machine system shown in Fig. 7. The control object is to manipulate a machine so that the machine follows the target given visually.

5.1. Design of a collaborater

First, we set parameters of a human model (1), (2) and a machine (3): $\delta = 0.05$, $\xi = 0.05$, $\tau_1 = 0.1$, $\tau_2 = 0.1$, $\gamma = 1.5$, $M = 2$ [kg], $D = 40$ [Ns/m] and $K = 400$ [N/m]. Next, design a compensator C_1 and C_2 to the virtual plant G_v. Here, we apply the ultimate sensitivity method as a parameter tuning method [6]. The proportional gain until the closed loop system reaches the stability limit K_c and the corresponding period T_c of the oscillation are determined by the simulation of step response: $K_c = 6.905$, $T_c = 0.575$. And the PID parameters are then determined as follows.

Table 2. Parameters of C_1 and C_2

	Gain	
K_P	$(= 0.6K_c)$	4.143
K_I	$(= \frac{K_P}{0.5T_c})$	14.41
K_D	$(= 0.125K_P T_c)$	0.298
α	$(= -0.63K_P)$	-2.61
β	$(= -0.70K_D)$	-0.208

According to the design scheme proposed in section 4, compensators C_1'' and C_2'' are determined as follows.

$$C_1'' = \frac{0.298s^2 + 4.143s + 4.41}{0.1s^2 + s} e^{-0.1s} \quad (10)$$

$$C_2'' = \frac{-0.208s^2 - 4.11s}{0.1s^2 + s} e^{-0.1s} \quad (11)$$

5.2. System characteristics

The Bode diagram of the human-machine system is shown in Fig.7. The broken line expresses a frequency response of the closed loop of the human-machine system without a collaborater, and the solid line with a collaborater.

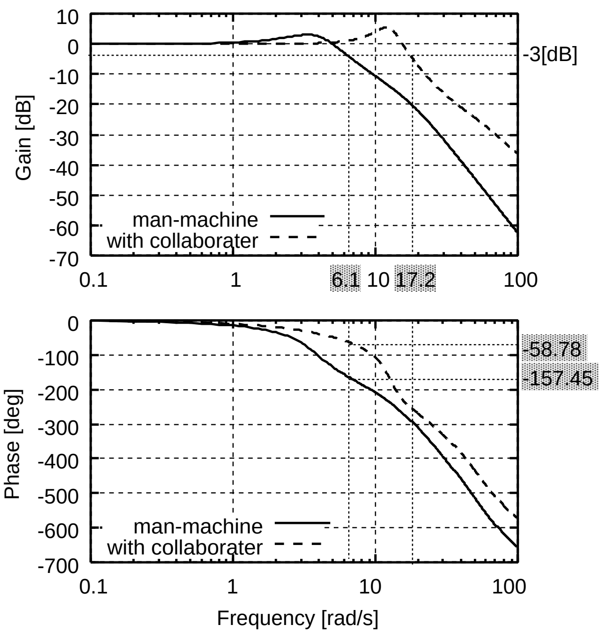

Fig. 10. The Bode diagram of the human-machine system

There are several characteristics of the system that can be read directly from the Bode diagram. First, we focus on the human-machine system. The low frequency gain is 0 [dB], however, the phase lag is -157.45 [deg] at the bandwidth frequency (6.1 [rad/s]) so that human cannot track even the target moving slowly. On the other hand, the bandwidth of the system with collaborater is 17.2 [rad/s] and the phase lag is -58.78 [rad/s] at 6.1 [rad/s]. Consequently, the frequency characteristic of the human-machine system is improved by a collaborater. Perhaps you should have a question to the increase of bandwidth not being so wide. However, we do not design the automatic controller but the compensator that works together with people. That is, even if the broad bandwidth is kept, the frequency is above the range which people can detect, it cannot be said to be the situation where the machine is controlled by human consciously.

Next, let's consider a step response of the system. Fig.11 shows a step response with the magnitude 0.1. The reference signal is inputted into the system at the time of 1 [s]. The characteristics analyzed from a simulation are shown in Table 3. By adding the collaborater to the man-machine system, the overshoot is removed, the delay time and the settling time is reduced. Although the step response is improved on the whole, a little vibration is observed in transient response.

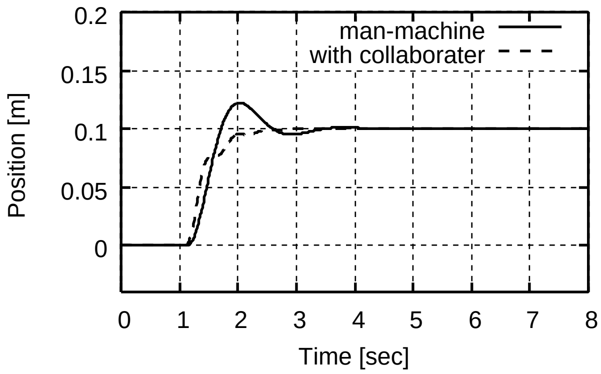

Fig. 11. Step responce of the human-machine system

Table 3. Characteristics of the step response

Transient Response	Human-machine system	Human-machine system with collaborater
Overshoot [%]	22.3%	0%
Delay time [sec]	0.47	0.35
Peak time [sec]	1.03	—
Settling time [sec]	1.48	1.21

Fig.12 shows the power, when a step input is applied. Lines from no.1 to no.4 are the power added to the machine when we apply the collaborater. Line no.1-4 show the power generated by human, the outputs of C_1'', the output of C_2'' and the summation of power, respectively. Line no.5 expresses the power generated by a person, when he (she) operates a machine without a collaborater.

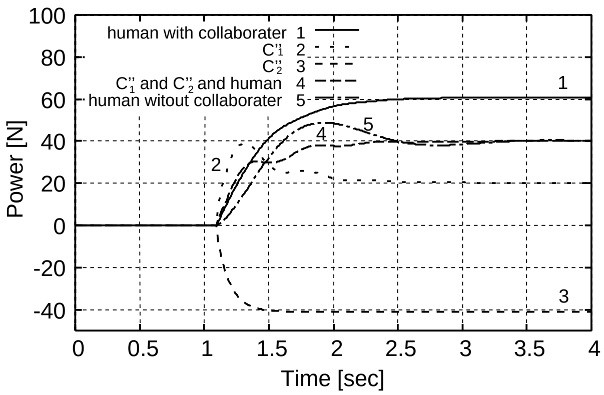

Fig. 12. The power of a human and a collaborater

Collaborater C_1'' is a factor which compensates a time constant in a brain. It is thought that C_1'' compensates human action with being added in the same direction as the power which people apply so that the time constant in the brain may be made small. Since a gain is adjusted by the ultimate sensitivity method, C_1'' is a high gain, and vibration is seen in the input. C_2'' is added to reverse direction of C_1'' in order to increase the robustness. Although the power which people apply increases as a result, the phenomenon of oscillation of power does not appear.

From the simulation result, it is concluded that the proposed compensator called "collaborater" supports a human action.

6. CONCLUSION

In this paper, a concept and a design strategy of a compensator which is called "collaborater" has been proposed. In position control of a man-machine system, the collaborater can extend the bandwidth of the system and decrease the phase lag. As a result, it improves the operativity of human-machine system. The simulation is executed on the assumption that human dynamics does not change during operation. However, human has excellent ability to adapt, and if environment changes, he (she) can change own dynamics by acquiring knowledge. That is, there are possibilities that human adapts own dynamics to the environment that includes the collaborater, when he (she) manipulates a mechanical system. Therefore, the following step is removing the assumptions and making it automatic tuning system which does not disturb people's actions. Although the proposed method uses a technique to support a signal processing in a brain, it is also the method to design so that the dynamics of muscles may be improved.

Our future work is to extend the design strategy to other human-machine system like the master-slave system by developing further functions.

REFERENCES

[1] Mark W. Spong Robert J. Anderson, "Asymptotic stability for force reflecting teleoperators with time delay," *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*, pp. 1618–1625, 1989.

[2] Mark W. Spong Robert J. Anderson, "Bilateral control of teleoperators with time delay," *Proceedings of the 27th Conference on Decision and Control*, pp. 167–173, 1988.

[3] Mark W. Spong Robert J. Anderson, "Bilateral control of teleoperators with time delay," *IEEE Transactions on Automatic Control*, vol. 34, no. 5, pp. 494–501, 1989.

[4] Y. Sawada F. Ishida, "Quantitative studies of phase lead phenomena in human percept-motor control system," *Transactions of the Society of Instrument and Control Engineering*, vol. 39, no. 1, pp. 59–66, 2003 (in Japanese).

[5] Suda Nobuhide, "Pid control," *Asakura-shoten*, 1992 (in Japanese).

[6] J.G. Ziegler and N.B. Nichols, "Optimum settings for automatic controllers," *Trans. ASME*, vol. 64, pp. 759–768, 1942.