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On Control Systems for Human-Machine Cooperative Systems with Stable Tool Dynamics

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In this paper, control system design of human-machine cooperative systems (HMCSs) considering maneuverability is investigated. First, the representative past studies are reviewed and essential characteristics of controlled systems are summarized as 4 transfer functions: the tool dynamics, the reaction force transfer function, the maneuver transfer function, and the transfer function of object dynamics variation. Secondly, parametrization of a general structure of control systems stabilizing the tool dynamics is presented. On the basis of the parametrization, it is clarified that the control systems have two degrees of design freedom, and the relationships among those 4 transfer functions are derived and discussed. Thirdly, it is experimentally verified that previous observations by the authors on dynamics self-shaping characteristics of a human operator in a manual control system are also found similar in HMCSs, and that the knowledge can be used for specifying desirable frequency characteristics of the maneuver transfer function. Then, a control design procedure utilizing the full 2 degree of freedom is proposed. An example HMCS is designed so that its maneuver transfer function is shaped suitably corresponding to the dynamics self-shaping characteristics of the operator, as well as the transfer function of object dynamics variation is compensated to have a gain large enough to enable the operator to recognize a small variation. Finally, experiments are carried out to confirm the validity of the proposed design procedure.

Key Words: maneuverability, dynamics self-shaping characteristics of human operator, controller parametrization, maneuver transfer function, object dynamics variation

1. Introduction

This paper deals with control system design for HMCSs considering maneuverability. In such a system, a human operates a motion controlled machine physically and directly in order to manipulate an object, such as for moving or machining. Fig.1 illustrates a simple example of such a system, a human operator is machining with a robot manipulator by operating it directly. In general, control systems of HMCSs are constructed with more than one measurement signal, and have more than one degree of freedom in control. Hence it is important to make clear which transfer characteristics should be considered.

From the point of view of human-oriented system design, maneuverability for human operator is essentially important. So the first point to notice is the mechanical dynamics of *equivalent control object* for the human that includes controlled manipulator and the processing work, that is the transfer function from the operational force to the motion of operational point. In this paper it is called *maneuver transfer function*. The maneuver transfer function has been noticed in past studies not only on HMCSs [1), 2)] but also on tele-manipulation systems [4)] and master-slave systems as the next important design specification to *transparency* [5)~9)]. Add to these, there is also an example where the maneuver transfer function is suitably shaped with dynamic scaling of force and motion in macro-micro bilateral systems [10)]. It follows from past studies that the maneuver transfer function has been regarded as important, but little attention has been given to adaptive characteristics of the operator to the maneuver transfer function, *self-shaping characteristics*, and its relation to maneuverability.

On the other hand, other transfer functions in HMCSs can be specified for determining control performance of the systems, and several investigations were made on different viewpoint of each researcher. For example, a design method specifying the transfer function from human's operational force to the force applied to the object is proposed. As another example, a design method specifying two transfer functions, one is a transfer function from human's operational force to motion of the object at the operational point when the machine is apart from the object, which is called *tool dynamics*, and another is a transfer function from the force imposed on the object to human's operational force when the motion of operational point is restricted, *reaction force transfer function* [11)]. In these studies, however, investigations about maneuverability for

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the operator and class of realizable control system have not been made. We recently proposed a design method that can specify not only maneuver transfer function but also *transfer function of object dynamics variation*, that is how variation of the characteristics of the object is transferred to the human operator [13), 14)]. However, relation between transfer function of object dynamics variation and other important characteristics of the system such as tool dynamics has not been made clear, and design examples that specify both transfer function of object dynamics variation and maneuver transfer function to get good maneuverability have not been given.

In this study, we propose a new design method that considers the maneuver transfer function and the transfer function of object dynamics variation. At first, parametrization of a general structure of control systems of HMCSs stabilizing the tool dynamics is presented, and it is clarified that the systems have two degrees of design freedom. Then, based on parametrization of important transfer functions in the system, relation between transfer functions noticed in our method and those noticed in past studies is examined [15), 16)]. Second, it is experimentally verified that the findings on self-shaping characteristics in manual control systems [19)] also hold similarly in HMCSs and the knowledge can be used for specifying desirable frequency characteristics of the maneuver transfer function. Then, a control design procedure utilizing the full two degree of freedom is proposed. For an example human-machine cooperative task to trace a boundary where object dynamics varies, control system is designed so that its maneuver transfer function is shaped suitably corresponding to the self-shaping characteristics of the operator, as well as the transfer function of object dynamics variation is compensated to have a gain large enough to enable the operator to recognize a small variation. Finally, experiments are carried out to verify that maneuverability is improved greatly and those two transfer functions are specified separately by the design procedure.

2. Past studies on HMCSs

In this section, features of representative past studies are outlined from the viewpoint of control system design.

2.1 Control system of the Extender

Kazerooni et al. named manipulator system expanding human's force the Extender, and have done pioneering research on HMCSs [3)]. Control system of the Extender is illustrated as Fig.2 [1), 2)], where $E_x(s)$ is transfer function of

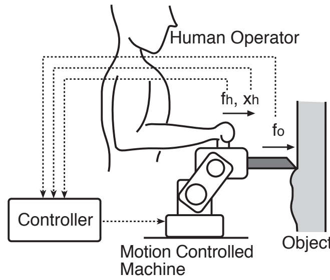


Fig. 1 Simple example of HMCSs.

the Extender, and the Extender is suitably position controlled so as to be able to ignore operator's force f_{eh} and the force imposed on the Extender from the environment f_{en}. They take up two transfer functions, from f_{eh} to f_{en} and from operational motion y_e to f_{eh}. Because there is a relationship $f_{en}(s) = -E_n^{-1}(s)\, y_e(s) + f_{ext}(s)$, these two transfer functions are not independent, and treated separately on design problem, that is, only one design freedom of control system is utilized.

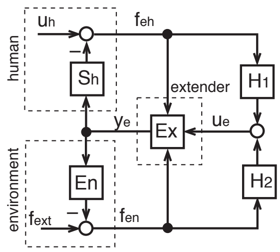


Fig. 2 Dynamics of extender, human, environment and compensators [1)].

2.2 Control based on virtual tool dynamics

Kosuge et al. proposed a method of controlling the human-machine system based on virtual tool dynamics [11)]. In this method, a robot manipulator is nonlinearly controlled and compensated so that an equation, $M_v\,\ddot{x} + D_v\,\dot{x} = Q\,F_h - F_e$, holds. In that case, the HMCS can be considered as three separated parts, humnan operator, environment (object) and virtual tool as Fig.3, and it is possible to discuss stability of the system based on passivity. In this method, two transfer functions are treated. One is the *tool dynamics*, a transfer function from $f_h(t)$ to motion of the object at the operational point, $\dot{x}$, when the machine is apart from the object ($F_e = 0$), and another is augmentation ratio of $F_e(t)$ to $F_h(t)$ when the motion of operational point is restricted ($\ddot{x} = \dot{x} = 0$). Although it is argued that these two transfer functions can be specified independently, maneuverability on the condition that the manipulator is in contact with the object is not discussed. For that reason this method is valid only for relatively simple tasks like peg-in-hole task that does not require delicate operation with movement of the object.

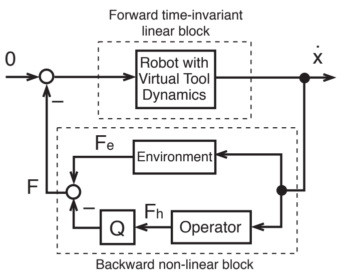


Fig. 3 Man-machine system based on virtual tool dynamics [11].

2.3 Control system to ease recognition of object dynamics variation

We have investigated design method of control system of HMCS aiming to ease skillful work [14]. In this method *maneuver transfer function* $G(s)$, the transfer function from the operational force f_h to the motion of operational point x_h while the manipulator is contact with the object, is specified, and its sensitivity function $S(s)$ to object dynamics variation is also specified, where $S(s)$ is defined as $S(s) = \frac{\Delta_G(s)}{\Delta_P(s)}$ and it is assumed that the variations of $P_O(s)$ and $G(s)$ are multiplicative, that is, $\tilde{P}(s) = P_0(s)\,(1 + \Delta_P(s))$ and $\tilde{G}(s) = G_0(s)\,(1 + \Delta_G(s))$. The system's block diagram is illustrated as Fig.4. Proposed method is applied to an example task that requires recognition of small variation of object dynamics, and experimental results show validity of the method [13].

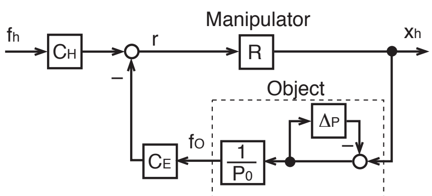


Fig. 4 Block diagram of a control system for a HMCS considering object dynamics variation [13].

In contrast to two prior methods, this method has distinctive feature in terms of making use of multiple degree of design freedom and noticing both maneuver transfer function and its sensitivity function. However, relation between these two functions and design specifications of prior methods has not been made clear, and it has not been concretely discussed how maneuver transfer function should be specified to get good maneuverability. So in the following sections general structure of control systems for HMCSs is presented and investigation into these problems based on the structure is made.

3. A general structure of control systems of HMCSs and essential controlled characteristics

In this section, a general configuration of control systems for HMCSs with three measured signals, and essential controlled characteristics of the systems are classified into four characteristics.

3.1 General configuration of a control system for a HMCSs and 4 essential controlled characteristics

Including prior studies mentioned above, a configuration of control systems for HMCSs is generalized as Fig.5. In this configuration three signals, the operational force $f_h(t)$, the force acting on the object $f_o(t)$ and the motion of the operational point $x_m(t)$, are measured and used as inputs for compensators. These signals are vector valued and x_h is usually velocity or position depending on intended task. It is assumed that nonlinearities of and interference between the motion coordinates of the machine are compensated by using these measurements [11] so that the characteristics of the machine can be expressed by a linear transfer function matrix $P_M(s)$.

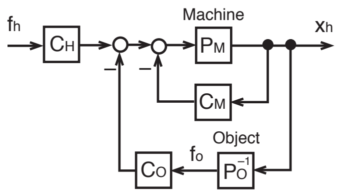


Fig. 5 General configuration of a control system for a HMCSs.

As mentioned in previous section, one or two controlled characteristics are noticed on each design procedure. These characteristics are classified into following four characteristics based on the general configuration, Fig.5.

<u>*Tool dynamics*</u> $G_T(s)$: transfer function from human's operational force, f_h, to motion of the object at the operational point, x_h, when the machine is apart from the object.

<u>*Reaction force transfer function*</u> $G_F(s)$: transfer function from the reaction force $f_o(t)$ to the operational force $f_h(t)$ when the motion of the object at the operational point is fully constrained.

Maneuver transfer function $G(s)$: transfer function from the operational force $f_h(t)$ to the motion of operational point $x_m(t)$ when the machine contacts and moves with the object.

Transfer function of object dynamics variation $G_\Delta(s)$: transfer function represents how variation of the object impedance affects the maneuver impedance from the viewpoint of the human operator.

In the Extender project by Kazerooni et al., only $G(s)$, is noticed in spite of the design freedom of two. In the method based on virtual tool dynamics by Kosuge et al., $G_T(s)$ and $G_F(s)$ are simultaneously noticed. In contrast, in the previous method of the authors, $G(s)$ and $G_\Delta(s)$ are simultaneously considered, where $G_\Delta(s)$ is extended version of $S(s)$ in previous study [13] and defined as follows.

$$G_\Delta(s) \equiv \Delta_{G^{-1}} \, (\Delta_{P_O^{-1}})^{-1} \tag{1}$$

Where it is assumed that variations of $P_O^{-1}(s)$ and $G^{-1}(s)$ are multiplicative.

$$\begin{cases} \tilde{P}_O^{-1}(s) = P_O^{-1}(s)\,(I + \Delta_{P_O^{-1}}) \\ \tilde{G}^{-1}(s) = G^{-1}(s)\,(I + \Delta_{G^{-1}}) \end{cases} \tag{2}$$

3.2 General structure of control systems for HMCSs stabilizing their tool dynamics and parametrization of 4 essential transfer functions

Now let us consider the class of all control systems with stable transfer functions from $f_h(t)$ and $f_o(t)$ to $x_m(t)$ when the machine is apart from the object $P_O(s)$. This requirement of stability seems reasonable for safety of the system.

If compensators $C_H(s)$ and $C_M(s)$ are linear rational transfer functions, the system of Fig.5 can be depicted as Fig.6 based on YJBK parameterization of all stabilized linear control systems, where $N(s)$ is derived from a right coprime factorization of the machine $P_M(s)$,

$$P_M(s) = N(s)\,D^{-1}(s),\ (N(s), D(s) \in RH_\infty), \tag{3}$$

and $K_H(s)$, $K_O(s) \in RH_\infty$ are free parameters (RH_∞ is the set of stable and proper transfer function matrices). Fig.6 illustrates *a general structure of the all control systems for HMCSs with stable tool dynamics.* Note that the structure has two design freedom with $K_H(s)$ and $K_O(s)$.

According to the general structure 4 essential transfer functions in previous section are parameterized by $K_H(s)$ and $K_O(s)$ as follows.

Tool dynamics

$$G_T(s) = N(s)\,K_H(s) \tag{4}$$

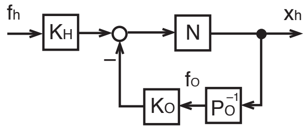


Fig. 6 Structure of the all control systems for HMCSs with stable tool dynamics.

Reaction force transfer function

$$G_F(s) = K_H^{-1}(s)\,K_O(s) \tag{5}$$

Maneuver transfer function

$$\begin{aligned} G(s) &= \left(I + N(s)\,K_O(s)\,P_O^{-1}(s)\right)^{-1} N(s)\,K_H(s) \\ &= \left(I + G_T(s)\,G_F(s)\,P_O^{-1}(s)\right)^{-1} G_T(s) \end{aligned} \tag{6}$$

Transfer function of object dynamics variation

$$\begin{aligned} G_\Delta(s) &= \left(I + N(s)K_O(s)P_O^{-1}(s)\right)^{-1} \\ &\qquad N(s)K_O(s)P_O^{-1}(s) \\ &= G(s)G_F(s)P_O^{-1}(s) \end{aligned} \tag{7}$$

It has been made clear that 2 transfer functions can be specified independently among of 4 essential transfer functions.

3.3 Constraints on transfer function of object dynamics variation

As mentioned later, if transfer function of object dynamics variation $G_\Delta(s)$ is shaped suitably, variation of object dynamics will be recognizable and it makes a sort of difficult task easy. However, there must be design constraints on $G_\Delta(s)$ from robust stability and so on.

For considering robust stability condition of $G(s)$, block diagram of the system Fig.7 (a), which includes variation of object impedance, collapses to block diagram (b), where

$$\begin{aligned} M(s) &= -\left(I + N(s)\,K_O(s)\,P_O^{-1}(s)\right)^{-1} \\ &\qquad N(s)\,K_O(s)\,P_O^{-1}(s) \\ &= -G_\Delta(s). \end{aligned} \tag{8}$$

robust stability condition of the system is identical to stability of $\left(I - M(s)\,\Delta_{P_O^{-1}}\right)^{-1}$, and its sufficient condition is

$$\|M\,\Delta_{P_O^{-1}}\|_\infty = \|G_\Delta\,\Delta_{P_O^{-1}}\|_\infty < 1. \tag{9}$$

This means that the smaller $\Delta_{P_O^{-1}}$, the larger $G_\Delta(s)$ is allowed, and we can say that the constraint on $G_\Delta(s)$ from robust stability is not so tight.

On the other hand, there is a constraint on $G_\Delta(s)$ from stability of tool dynamics. From equation (4), (6) and (7), $G_T(s)$ can be expressed as

$$G_T(s) = (I - G_\Delta(s))^{-1}\,G(s). \tag{10}$$

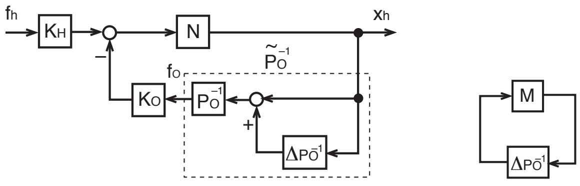


Fig. 7 Block diagram of the control system considering variation of the object dynamics.

Assuming $G(s)$ is stable, stability of $(I - G_\Delta(s))^{-1}$ is required, and its sufficient condition is

$$\|G_\Delta\|_\infty < 1. \tag{11}$$

Practically, this condition is more tight than inequality (9). Actually, on design example in our past study [13), 14)], tool dynamics was not stable. To combine stability of $G_T(s)$ and large gain of $G_\Delta(s)$, some scheme such as controller switching may be needed. Because above discussion is based on sufficient condition, there are more than a few case that the condition need not to be so tight according to selecting of $G(s)$ and $G_\Delta(s)$.

4. Self-shaping characteristics of human operator in HMCSs and maneuverability

In this section, it is experimentally verified that the findings on self-shaping characteristics of a human operator in a manual control system are also found similarly in HMCSs, and the knowledge can be used for specifying desirable frequency characteristics of the maneuver transfer function.

4.1 Self-shaping characteristics of a human operator on manual control systems

Self-shaping characteristics of a human operator on manual control systems based on especially visual feedback is well known as crossover model [17)]. This model says that the human operator shapes his own dynamics with characteristics listed below.

- Slope of Bode plot of open-loop transfer function is −20 [dB/dec] near the gain crossover frequency.
- Crossover frequency is fixed at his own value.
- Crossover frequency is lowered if high frequency information are unnecessarily displayed.

We have pointed out that success of self-shaping has great relevance to maneuverability, and proposed a design method of compensators of manual control system [18)]. In addition, we also found out self-shaping characteristics on hand position control in manual control systems with only motion sensation feedback [19)] (Fig.8). Likewise crossover model, the operator in in manual control systems based on motion sensation tries to make the slope of Bode plot of open-loop transfer function to be −20 [dB/dec] around crossover frequency. In addition, there are the following distinctive features.

- In comparison with visual sensation case, the crossover frequency obtained becomes higher, but varies according to object dynamics.
- Achievable class of self-shaping is limited, moreover, maneuverability has direct connection with if self-shaping is made successfully.
- Considering output of the system to be operator's hand position, obtained crossover frequency becomes higher when the object dynamics has first order integral property at the frequencies near gain crossover.

From the above, the self-shaping characteristics in HMCSs with motion sensation has great relevance to maneuverability. It means that the transfer function of the equivalent control object $G_E(s)$ should be selected properly considering the characteristics.

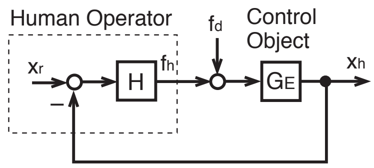


Fig. 8 Manual control system based on motion sensation.

4.2 Outline of experiments

From the viewpoint of the operator, HMCSs can be regard as the configuration of Fig.8.

From the viewpoint of the operator, the HMCSs can be also regarded as a manual control system of Fig.8. So if there holds the self-shaping characteristics based on motion sensation in the system, the knowledge can be used for specifying desirable frequency characteristics of the equivalent maneuver transfer function $G_E(s)$. To confirm this, experiments are carried out as follows.

In the same way as the virtual tool method by Kosuge et al. and other past studies, tool transfer function is shaped as mass-damper system. Assuming the object dynamics to be mass-damper-spring system, the equivalent maneuver transfer function becaomes mass-damper-spring system as equation (12). Notice that the velocity of the operational point is chosen as $x_h(t)$.

$$G_E(s) = \frac{s}{M\,s^2 + D\,s + K} \tag{12}$$

The experimental system consists of an industrial robot manipulator with a force sensing grip (Fig.9). In this experiments, the operation is restricted to a straight-line motion in right and left direction of the operator. Dynamics of the specified $G_E(s)$ and disturbance $f_d(t)$ are simulated by a personal computer, and the position reference signal to the controller of the robot manipulator is calculated based on measured operational force $f_h(t)$. The human operator is directed to keep his/her hand motion $x_h(t)$ as small as possible against the disturbance only by voluntary operation without visual information.

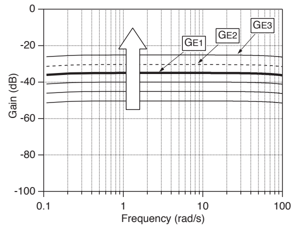
Fig. 9 Experimental system.

4.3 Experimental results

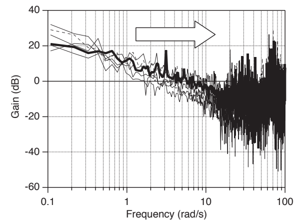
In this study, we think of getting good maneuverability as operating the way he/she want. This means that the wider control band of manual control system8, the better maneuverability. So we can regard the crossover frequency as an index of maneuverability.

Experiments are carried out for 3 adult men after enough practice. There are indeed some differences among their results, but self-shaping characteristics have common properties. In this paper, we will discuss based on results of representative one.

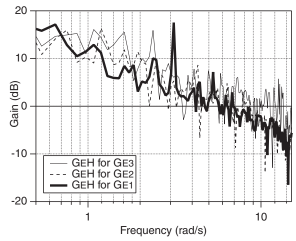
As mentioned in subsection 4.1, the equivalent control object $G_E(s)$ should have a suitable viscosity for good maneuverability. Since the output of the manual control system $x_h(t)$ is chosen to be the velocity, frequency characteristics of $G_E(s)$ should have a almost flat gain. At first, experiments for examining self-shaping characteristics of the operator for such $G_E(s)$ as shown Fig.10(a) are carried out. Fig.10(b) shows analysis results of a subject, Subject A, and it is found that open loop characteristics $G_E(s)\,H(s)$ are shaped integral characteristics around its crossover frequencies by operator's self-shaping. It is also found that the crossover frequency increases as gain of $G_E(s)$ is increased. There is, however, a limit of the gain (plotted in thick line), and when the gain exceeds the limit, the crossover frequency is also limited and the maneuverability is extremely spoiled. Fig.10(c) shows that crossover frequencies for three $G_E(s)$s with higher gain are almost same, and Fig.10(d) shows that if gain of $G_E(s)$ is insufficiently large, the coherence between f_d and f_h is lowered. This means that there is the optimum gain, and the thick line in Fig.10 (a), $G_{E1}(s)$, shows the optimum $G_E(s)$ for Subject A.



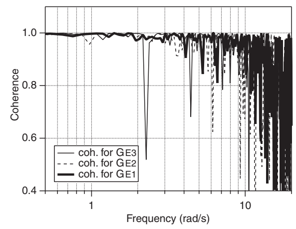
(a) Frequency responses of $G_E(s)$.



(b) Frequency responses of $G_E(s)\,H(s)$s for $G_E(s)$s in (a).



(c) Frequency responses of $G_E(s)\,H(s)$s for $G_{E1,2,3}(s)$ in (a) (enlarged around the crossover frequencies).



(d) Coherences between $f_d(t)$ and $f_h(t)$ for $G_{E1,2,3}(s)$ in (a) (enlarged around the crossover frequencies).

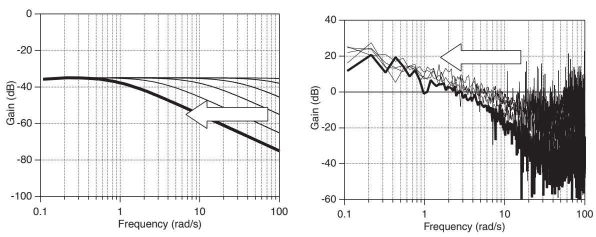
Fig. 10 Loop-shaping characteristics of a human operator for various $G_E(s)$ dominated by viscosity.

Then, the influence of inertia M on self-shaping characteristics has been examined using $G_E(s)$s in Fig.11 (a), and it is found that the maneuverability is spoiled and the crossover frequency of $G_E(s)\,H(s)$ becomes low when the gain of $G_E(s)$ is not flat around the crossover frequency as shown in Fig.11 (b). Similarly, the influence of the elasticity K has been examined, and the results are shown in Fig.11 (c). It is also found that the maneuverability is spoiled when the gain of $G_E(s)$ is not flat around the crossover frequency like the influence of inertia M. However, from Fig.11 (d) that is open loop frequency responses for two subjects, Subject A and B, with same large K, it is newly found that the influence of the elasticity in lower frequencies depends on the subject.

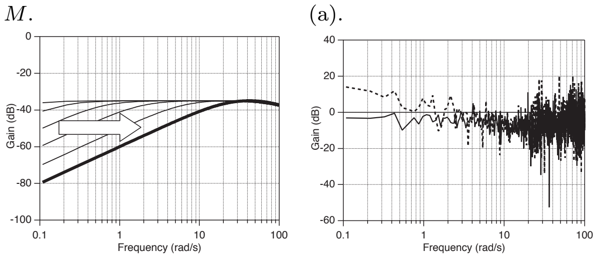
From above experiments, when the operating velocity is regarded as the system output x_h, It is found that the frequency response of the equivalent object $G_E(s)$ should have a flat gain over a sufficiently wide frequency range for good maneuverability. As mentioned in section 4.1, that the crossover frequency is lowered if high frequency information are unnecessarily displayed to the operator. This is one of properties of manual control system with visual sensation, but there probably be the same kind of lowering of the crossover frequency in the system with motion sensation, too. And furthermore, it is necessary to make clear to what extent $G_E(s)$ should be compensated to have flat gain over low-frequency range for decreasing gain with elasticity of the object.

Thus $G_E(s)$ has to be suitably narrowed its bandwidth without spoiling maneuverability. From results shown in Fig.11, it is found that the bandwidth can be narrowed so much as Fig.12(a) without lowing the crossover frequency. Now it remains to search an optimal gain of flat part of $G_E(s)$. From experimental results shown in Fig.12, it can be verified that the relationship between the gain and self-shaping characteristics are unchanged from wide bandwidth case, Fig.10. Consequently a desirable frequency response of $G_E(s)$ for Subject A is chosen as the thick line in Fig.12(a), and its parameters are as follows: $M = 0.56$ [kg], $D = 56$ [Ns/m] and $K = 33$ [N/m]. The open loop frequency responses of $G_E(s)\,H(s)$ for the desirable $G_E(s)$ is the thick line in Fig.12 (b).

Thus it is confirmed that there also exist self-shaping characteristics of a human operator in a HMCS based on motion sensation, its relevance to maneuverability, and a class of $G_E(s)$ for good maneuverability.

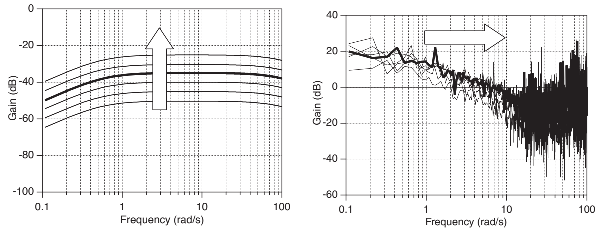


(a) Frequency responses of $G_E(s)H(s)$ with increasing M. (b) Frequency responses of $G_E(s)H(s)$s for $G_E(s)$s in (a).



(c) Frequency responses of $G_E(s)\,H(s)$ with increasing K. (d) Frequency responses of $G_E(s)\,H(s)$ for $G_E(s)$s plotted with the thick line in (c).

Fig. 11 Influences of M and K on the Loop-shaping characteristics.



(a) Frequency responses of $G_E(s)$. (b) Frequency responses of $G_E(s)\,H(s)$s for $G_E(s)$s in (a).

Fig. 12 Loop-shaping characteristics of a human operator for various $G_E(s)$ that have flat gain over moderate frequency range.

5. Design method specifying both the maneuver transfer function and the transfer function of object dynamics variation

In this section, a design method specifying both the maneuver transfer function $G(s)$ and the transfer function of object dynamics variation $G_\Delta(s)$ is proposed.

5.1 Proposed method

In HMCSs, $G_E(s)$ is correspond to maneuver transfer function $G(s)$ or tool dynamics $G_T(s)$, so we can increase maneuverability if these functions are properly specified. If only $G_T(s)$ is shaped to the desirable frequency response, maneuverability would be spoiled because $G_E(s)$ is depend on the object dynamics. From parameterization mentioned in section 3.2, although we can make $G(s) = G_T(s)$ with the compensator $K_O(s) = 0$, but this means the reaction force $f_o(t)$ not be transferred to the operator and $G_\Delta(s) = 0$. This results in losing advantages of HMCSs. In this way, there is trade-off between maneuverability with the object dynamics variation and ease of recognition of the variation. In this study, we aim at making HMCSs in which the operator can manipulate the object skillfully as he feels the reaction force from it. So, we specify nominal maneuver transfer function $G(s)$ first, and the rest of the design freedom is used for shaping $G_\Delta(s)$ to ease recognition of the object dynamics variation. Indeed, there are differences among individuals in desirable frequency response of $G_E(s)$, but desirable frequency response of $G_\Delta(s)$ depends on operating task and the differences are not so large. It is one of features of proposed method that $G(s)$ can be adjusted according to the operator keeping $G_\Delta(s)$ specified.

5.2 Design procedure

For simplicity, it is assumed that the motion freedom of cooperative task is 1 and the transfer functions of the machine $N(s)$, the nominal object $P_O^{-1}(s)$ and the object with variation are represented as follows

$$N(s) = \frac{1}{M_N s + D_N} \quad (13)$$

$$P_O(s) = \frac{s}{M_P s^2 + D_P s + K_P} \quad (14)$$

$$\tilde{P}_O(s) = \frac{s}{\tilde{M}_P s^2 + \tilde{D}_P s + \tilde{K}_P}. \quad (15)$$

Choose desirable $G(s)$ as

$$G(s) = \frac{s}{M_G s^2 + D_G s + K_G} \quad (16)$$

according to the results in the previous subsection, and $G_\Delta(s)$ is considered as a 2nd order low-pass filter,

$$G_\Delta(s) = \frac{K_\Delta}{M_\Delta s^2 + D_\Delta s + K_\Delta}. \quad (17)$$

From equation (10), $G_T(s)$ is represented as next equation, and it is stable if its parameters are positive.

$$G_T(s) = \frac{M_\Delta s^2 + D_\Delta s + K_\Delta}{M_G s^2 + D_G s + K_G} \cdot \frac{1}{M_\Delta s + D_\Delta} \quad (18)$$

To get robust stability of $G(s)$, stability of net equation is required, and this restricts parameter K_Δ.

$$\left(1 + G_\Delta(s)\,\Delta_{P_O^{-1}}\right)^{-1} = \frac{L(s)}{L(s) + K_\Delta\ (\Delta M_P s^2 + \Delta D_P s + \Delta K_P)} \quad (19)$$

where

$$L(s) = (M_\Delta s^2 + D_\Delta s + K_\Delta) \cdot (M_P s^2 + D_P s + K_P) \quad (20)$$

$$\Delta M_P = \tilde{M}_P - M_P,\ \Delta D_P = \tilde{D}_P - D_P,\ \Delta K_P = \tilde{K}_P - K_P. \quad (21)$$

From equations (6) and (7), compensators that achieve transfer functions $G(s)$ and $G_\Delta(s)$ are obtained as follows.

$$K_H(s) = \frac{(M_N s + D_N)(M_\Delta s^2 + D_\Delta s + K_\Delta)}{(M_G s^2 + D_G s + K_G)(M_\Delta s + D_\Delta)} \quad (22)$$

$$K_O(s) = \frac{(M_N s + D_N) K_\Delta}{(M_P s^2 + D_P s + K_P)(M_\Delta s + D_\Delta)} \quad (23)$$

These compensators are stable, so the control system surely belongs to the general structure of Fig.6.

6. Example cooperative task and experiments

In this section, a design example of the control system based on design procedure proposed in section 5. 2 is presented, and validity of the procedure is confirmed.

6. 1 Example task settings

As an example, we assume a task to trace a boundary where object dynamics varies as shown in Fig. ??. In this task, it is important that $G(s)$ has desirable frequency response for the maneuverability, and also $G_\Delta(s)$ has a gain large enough for operator to sense the variation

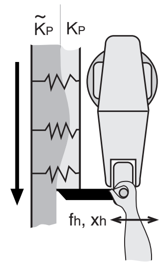


Fig. 13 Example cooperative task to trace a boundary line of object dynamics variation.

of the object dynamics.

In this example, we assume an elastic object represented as

$$P_O^{-1}(s) = \frac{K_P}{s}. \quad (24)$$

Where the elastic parameter K_P varies from $K_P = 33$ [N/m] to $\tilde{K}_P = 165$ [N/m] over a zone of ±5 [mm] on the boundary which is unknown to the subjects. The parameters of $N(s)$ are assumed to be $M_N = 0.56$ [kg] and $D_N = 56$ [N s/m].

6. 2 Settings of desired $G(s)$ and $G_\Delta(s)$

Parameters in desired $G(s)$, equation (16), are taken as $M_G = 0.56$ [kg], $D_G = 56$ [N s/m] and $K_G = 33$ [N/m], according to results in section 4. 3. For desired $G_\Delta(s)$, equation (17), M_Δ and D_Δ are fixed as $M_\Delta = 0.56$[kg], $D_\Delta = 56$ [N s/m], and influence of K_Δ on maneuverability is examined.

To ease recognition of variation of the object dynamics, $G_\Delta(s)$ has enough gain on frequency range of operating motion, so, K_Δ needs to be large. Although it is confirmed from equation (19) that $G(s)$ is robustly stable regardless of K_Δ, but unnecessarily large K_Δ is undesirable in terms of stability margin. Two K_Δs, $K_\Delta = 33$ and 660 [N/m], are taken for below experiments, and frequency responses of $G_\Delta(s)$ are plotted in Fig.14. From the plot for $K_\Delta = 33$, broken line, the gain of $G_\Delta(s)$ is decreased at 7 [rad/s], prospective crossover frequency for Subject A, and there is the possibility that the operator hardly recognize the object dynamics variation. On the other hand, for $K_\Delta = 660$, bandwidth of $G_\Delta(s)$ is sufficiently wide, good recognition of the variation is expected.

6. 3 Experimental results and discussion

Experiments are carried out with $K_\Delta = 33$ and $K_\Delta = 660$. A subject is directed to trace the boundary of the object dynamics variation without visual sensation. The experimental results are shown in Fig. 15.

In each figures, the thick line represents hand position, and the variation of the elastic parameter K_P occurs in

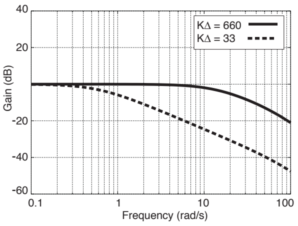
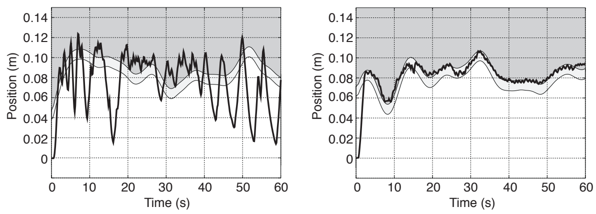


Fig. 14 Frequency responses of $G_\Delta(s)$.

the boundary zone between thin lines. The elastic parameter is taken as $K_P = 33$ in white zone and $\tilde{K}_P = 165$ in gray zone. The results show that the subject can hardly recognize the boundary and the tracing task is not achieved with $K_\Delta = 33$, but the task is achieved very well with $K_\Delta = 660$.

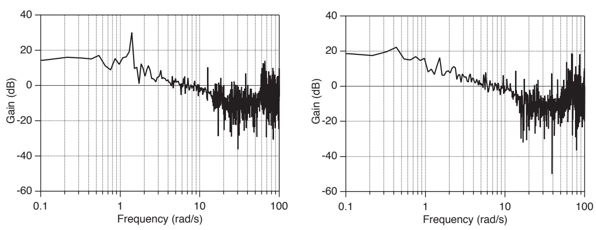


(a) $K_\Delta = 33$ (b) $K_\Delta = 660$

Fig. 15 Results of tracing experiments.

Additional experiments are carried out to make sure that $G(s)$ can be specified independently of $G_\Delta(s)$. Self-shaping characteristics are examined with disturbance rejection task the same as section 4. 3, and results are shown in Fig.16. From the results, it is found that almost same crossover frequency is achieved in spite of different $G_\Delta(s)$. And this means that $G(s)$ is independence from $G_\Delta(s)$ and good maneuverability can be achieved.

As mentioned above, it is confirmed that the proposed method is very valid for the task in which recognition of the object dynamics variation is important.



(a) $K_\Delta = 33$ (b) $K_\Delta = 660$

Fig. 16 Frequency responses of $G(s)\,H(s)$ for different settings of $G_\Delta(s)$.

7. Conclusion

In this paper, the we have investigated control system design of HMCSs considering maneuverability, and the following results have been obtained.

- A general structure of control systems for HMCSs stabilizing their tool dynamics was found, and it was made clear that design freedom of the system is 2.
- 4 essential transfer functions were parameterized, and relevance of maneuver transfer function and transfer function of object dynamics variation to the functions noticed in past studies was made clear.
- It was experimentally verified that there exists self-shaping characteristics of a operator in HMCSs with mass-damper-spring type equivalent maneuver transfer function, and maneuver transfer function must be shaped so that the operator easily achieves self-shaping for increasing maneuverability.
- A control design procedure that can specify both the maneuver transfer function according to self-shaping characteristics and the transfer function of object dynamics variation to ease recognition of the object dynamics variation was proposed.
- Validity of the proposed design procedure was confirmed by experiments on a cooperative task to trace a boundary of object dynamics variation, and it is confirmed that maneuverability was remarkably increased.

As future studies, the authors are interested in expansion of the motion freedom of the cooperative task and development of a control scheme adaptable to differences of the desirable maneuver transfer function among individuals.

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