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Tracking Control Properties of Human-robot Systems

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Abstract

Human-robot systems including interaction between human operators and robots should be designed with careful consideration for dynamic property and control ability of the human operator. The present paper aims to understand the tracking control properties of human-robot systems using an impedance-controlled robot according to the proficiency of a human operator, the robot impedance, and the human arm impedance. From the experimental results, it is shown that the human operator tries to keep the dynamic property of the overall system as constant as possible by adjusting his or her own impedance property.

1 Introduction

The advanced robot systems which can perform general tasks including interaction with human have been much required for purposes of tending patients and the aged in hospital, assisting a human worker at the office, and so on. In such human-robot systems, the human operator often takes an initiative in executing tasks, while the robot are required to assist him or her movements. Thus, the system should be designed with careful consideration to not only the control accuracy and performance but also the control property and ability of human operators to realize the natural cooperation of the human operator and a robotic device.

Many methods have been proposed for designing and controlling the human-robot systems in the robotics field. Mechanical impedance has been often exploited to express the control properties of the human operator in the human-robot system using the impedance-controlled robots, so that control properties of the whole system can be also described with the mechanical impedance. The systems using an impedance model can be roughly grouped into two types.

The first is a power-assist system which executes a task by the amplified human force [1]–[3]. Kazerooni [1] proposed a power-assist system with a single robot, so far the systems had been constructed with a couple of multiple robots, and estimated the human impedance from frequency responses of the system. Yokokohji et al. [2] and Colgate [3] studied the human impedance property in manipulation of a tele-operation system. Especially, Yokokohji et al. [2] analyzed the system stability by means of the impedance model of the human operator.

The second is a human-robot cooperation system in which robots supplement the assist force to the human operator [4]–[6]. Kosuge et al. [4] estimated the human impedance from frequency responses by the least square method. Al-Jarrah et al. [5] expressed the dynamic property of the human operator with the stiffness, and reported that the system stability is much influenced by the stiffness. Also, Ikeura [6] investigated the impedance property of the human operator who manipulated the slave robot to follow the motion of the master robot controlled by another operator, and reported that the operability of master-slave systems can be improved by applying the estimated human impedance to the impedance control of the slave robot.

Moreover, those studies use two types of hypotheses: human impedance during the operations is constant [1],[2],[4],[6] or variable [3],[5]. However, it has not been discussed in detail how the human operator changes his/her impedance in the operation and adjusts it according to the task and the control property of the system.

On the other hand, it was reported that the human operator can change his/her arm impedance by regulating the arm posture [7],[8] and the muscle contraction levels [9],[10] so as to maintain the system stability even if the robot has an unstable impedance [11]. Also, it has been suggested that the human impedance is much affected by the operator's proficiency in the task. Consequently, it needs to investigate the dynamic properties and the control ability of the human operators according to the control property of the robotic device for designing an effective and safety human-robot system.

In this paper, first, experiments of the tracking control operation are carried out with several healthy subjects by using the human-robot system composed of a one-degree-of-freedom liner robot. In the experiment, the subject is instructed to sit down on the chair and maneuver the impedance-controlled robot with its handle so as to minimize the control error between a hand position and a target signal indicated on the computer display. Then, it investigates how the tracking control property of the human-robot system is changed according to the robot impedance, the proficiency of the operator and the human arm impedance. The experimental results obtained in this paper may be used as basic data for determining the impedance characteristics of power-assist systems and for designing the structure of manual control training devices using the robots such as a master-slave system.

This paper is organized as follows: In Section 2, the structure of the human-robot system and an experimental apparatus are explained. In Section 3 and 4, we analyze the changes of human control property according to the robot impedance and the arm posture of human operator, respectively.

2 Experimental Methods

2.1 Human-Robot System

Figure 1 shows a block diagram of the human-robot system used in this study, where $r \in \Re^l$ denotes the desired signal, $e \in \Re^l$ the control error, $f \in \Re^l$ the operational force generated by the operator, $x \in \Re^l$ the end-effector position of the robot, and l the dimension of the task space [12]. The human operator is instructed to manipulate the impedance-controlled robot with the hand force f to minimize the control error e which is presented on the display. The motion equation of the end-effector is given by [13], [14]

$$M\ddot{x} + B\dot{x} + K(x - x^e) = f, \quad (1)$$

where $x^e \in \Re^l$ is the equilibrium point of the end-effector, and $M, B, K \in \Re^{l\times l}$ are the inertia, the viscosity and the stiffness matrix, respectively. Here, dynamic property of the human-robot system is determined by not only the robot impedance but also the human impedance which largely depends on the arm posture and the hand position [7]–[10] (See Fig. 1).

The system developed in the present paper is composed of the one-degree-of-freedom linear robot (Nihon Tomson Corp., resolution: 1.0 [μm]) as shown in Fig. 2, where the dimension of the task space is $l = 1$. The robot adopts a moving magnet driving system and can control its driving force (maximum power $\pm 10 \times 9.8$ [N]). In the experiments, the hand force f is measured with the six axis force/torque sensor (BL AUTOTEC, LTD., resolution : force x axis, y axis: 0.05 [N], z axis: 0.15 [N], torque: 0.003 [Nm]) attached at the handle of the robot.

During the experiment, the human operator is instructed to sit down on the chair and operate the robot with its handle (turnable around z axis), in which he/she can voluntarily adjust the grasping power. The sampling rate for the robot control is 1 [kHz] and the one for storing data is 25 [Hz]. The white noise filtered by the second-order Butterworth filter (cut-off frequency, 0.5 [Hz]) is used as a target signal.

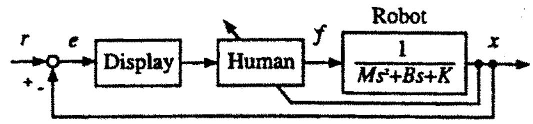


Fig.1: Human-robot system

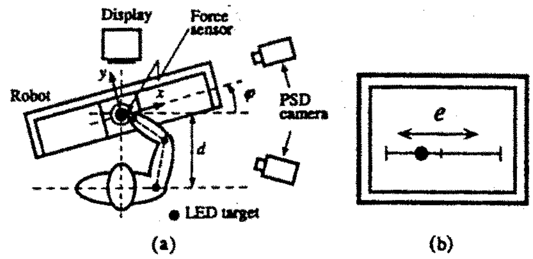


Fig.2: Experimental Apparatus

2.2 Experimental Conditions

Experiments were executed with the eight different stiffnesses of the robot K = -55, -27.5, 0, 27.5, 55, 82.5, 110, 137.5 [N/m], the five different natural frequencies $\omega_n = \sqrt{\frac{K}{M}}$ = 2, 4, 6, 8, 10 [rad/s], and the eight different damping coefficients $\zeta = \frac{B}{2\sqrt{MK}}$ = -0.5, 0, 0.5, 1, 1.5, 2, 2.5, 3. The distance between the operator and the robot handle was set at $d = 0.55$ [m], and the absolute value of the maximum amplitude of the target signal at 0.1 [m]. The equilibrium point x^e was set at the origin of the operational task space that is located in the distance d front on the center line of the body (See Fig. 2). Four male subjects (graduate students) were asked to perform tracking tasks during $t_f = 60$ [s] with enough intermission between trials.

Figure 3 shows an example of the time histories of the target signal r, the hand position x, the control error e, the hand force to the motion direction f_x (= f), and the hand force to the normal direction f_y under $\varphi = 0$ [rad], $\omega_n = 10$ [rad/s], $\zeta = 1.0$, $K = 55$ [N/m].

To evaluate experimental results, the following performance indices are defined as

$$J = \int_0^{t_f} e^2(t)dt \Big/ \int_0^{t_f} r^2(t)dt, \quad (2)$$

$$U = U_x + U_y, \quad (3)$$

$$U_x = \int_0^{t_f} f_x^2(t)dt \Big/ \int_0^{t_f} r^2(t)dt, \quad (4)$$

$$U_y = \int_0^{t_f} f_y^2(t)dt \Big/ \int_0^{t_f} r^2(t)dt, \quad (5)$$

where J is the normalized square sum of positional errors, U the normalized square sum of hand force, U_x

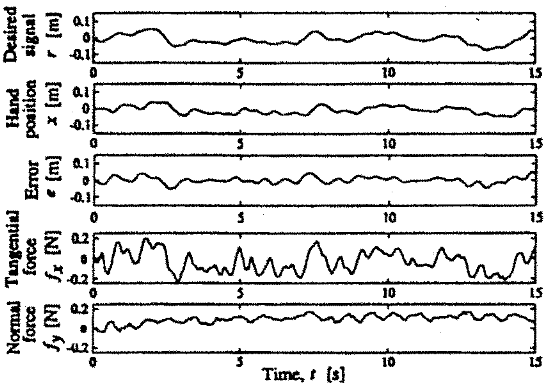


Fig.3: An example of experimental results (K = 55 [N/m], ω_n = 10 [rad/s], ζ = 1, d = 0.55 [m], Subject = A)

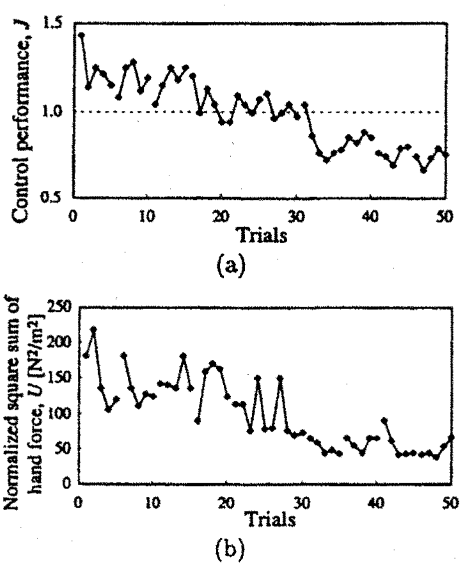


Fig.4: Change of the control performance J and the normalized square sum of hand force U_x depending on the number of trial. Mean values and standard deviation of 10 trials for each subject are shown. (K = 55 [N/m], ω_n = 6 [rad/s], ζ = -0.5, d = 0.55 [m], Subject = B)

and U_y are the normalized square sum of the hand force in the operational direction f_x and in the normal direction f_y (See Fig. 2), respectively.

Figure 4 shows the changes of J and U under ω_n = 6 [rad/s], ζ = -0.5, K = 55 [N/m] with respect to the number of trials, where successive trials are connected by a solid line. The subjects had enough experience for controlling the stable robot, but had never operated the

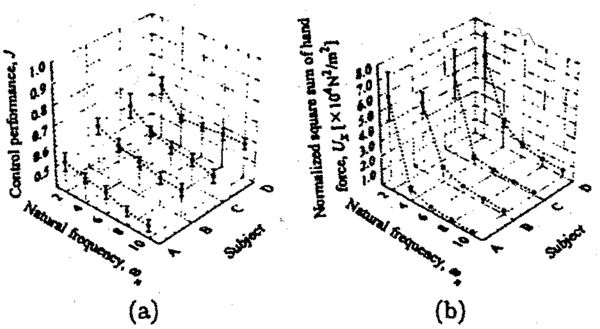


Fig.5: Change of the control performance J and U_x depending on the natural frequency ω_n and subjects. Mean values and standard deviation of 10 trials for each subject are shown. (K = 55 [N/m], ζ = 1, d = 0.55 [m])

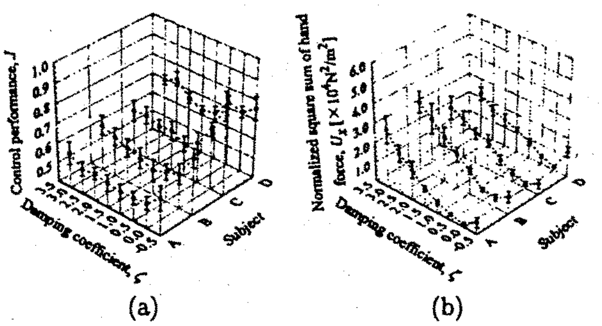


Fig.6: Change of the control performance J and U_x depending on the damping coefficient ζ and subjects. Mean values and standard deviation of 10 trials for each subject are shown. (K = 55 [N/m], ω_n = 4 [rad/s], d = 0.55 [m])

unstable robot (ζ = -0.5). It can be observed that J is almost larger than 1 and U changes greatly during the first 30 trials. After that, however, J is less than 1 and U keeps smaller values. These results show that the human operator can gradually acquire the tracking ability through the repeated operation. In this paper, the dynamic property of skilled operators is analyzed.

3 Tracking Control Properties According to Robot Impedance

3.1 Change of Control Performances by Robot Impedance

Figure 5 shows the changes of J and U_x depending on the natural frequency of the robot ω_n under K =

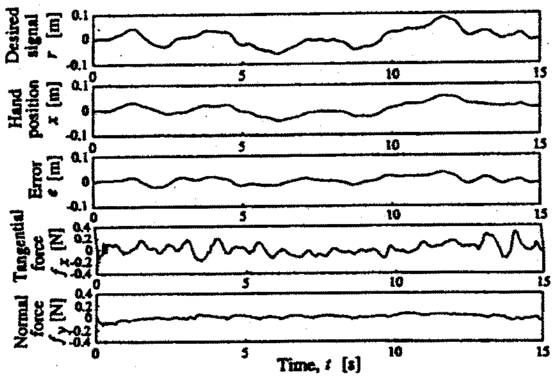
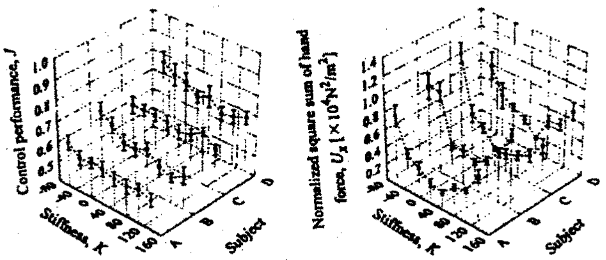


Fig.7: An example of experimental results for an unstable robot impedance (K = 55 [N/m], ω_n = 6 [rad/s], ζ = -0.5, Subject = A)



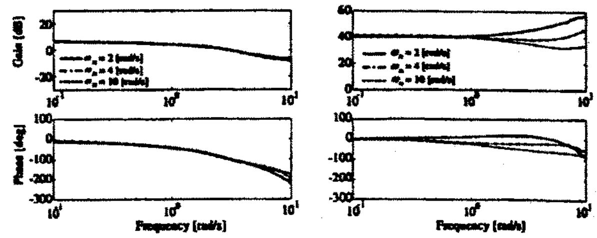
(a) (b)

Fig.8: Change of the control performance J and U_x depending on the stiffness K and subjects. Mean values and standard deviation of 10 trials for each subject are shown. (M = 3.43 [kg], ζ = 0)

55.0 [N/m], ζ = 1.0. Both J and U_x increase with the reduction of ω_n, although there exist some differences among subjects. Since M and B increase as decreasing ω_n, the operator is required large force for the operation.

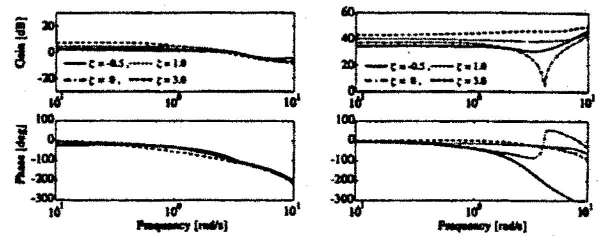
Figure 6 shows the changes of J and U_x depending on the damping coefficient ζ under K = 55.0 [N/m], ω_n = 4 [rad/s]. As increasing the viscosity of robot B, large force is required for the operation. Consequently, J slightly increases and U_x greatly increases with the increase of ζ. Also, J and U_x around ζ = 1.0 are better than other conditions in all subjects. Although J increases under $\zeta < 0$, in which the robot system becomes unstable, the value of J falls in around 0.7 or 0.8. It shows that the subjects followed the target signal by stabilizing the unstable robot. Figure 7 shows an example of experimental results under $\zeta = -0.5$. It can be seen that the hand follows the target signal r very well without divergence.

Figure 8 shows the changes of J and U_x depending



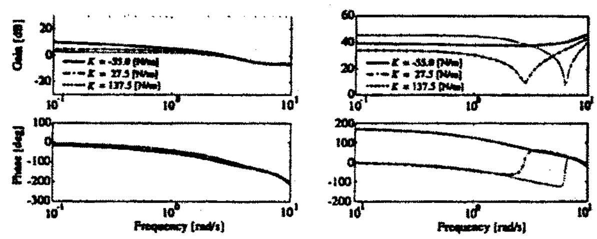
(a) $G(j\omega)$ (b) $H(j\omega)$

Fig.9: Estimated describing functions depending on the natural frequency ω_n (K = 55 [N/m], ζ = 1, Subject = A)



(a) $G(j\omega)$ (b) $H(j\omega)$

Fig.10: Estimated describing functions depending on the damping coefficient ζ (K = 55 [N/m], ω_n = 4 [rad/s], Subject = A)



(a) $G(j\omega)$ (b) $H(j\omega)$

Fig.11: Estimated describing functions depending on the stiffness K (M = 3.43 [kg], ζ = 0, Subject = A)

on the stiffness K under ζ = 0 and M = 3.43 [kg]. U_x much increases since large force is needed to operate the robot as increasing K. On the contrary, both J and U_x increase under $K < 0$ in which the operator has to handle the unstable robot. It can be found that the subjects can manipulate the unstable system and follow the target signal very well within the range of K = 0 ~ 137.5 [N/m].

3.2 Analysis of Dynamic characteristics

Dynamic property of the human-robot system was analyzed by estimating describing functions of the system from the observed experimental results. Since the

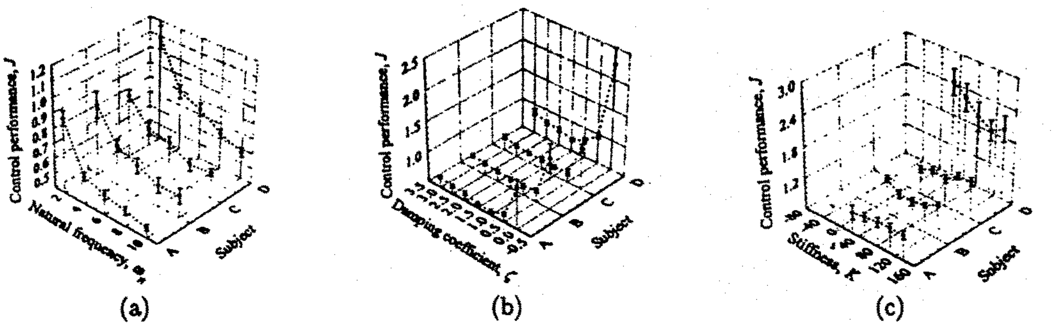


Fig.12: Change of the control performance J depending on the natural frequency ω_n, the damping coefficient ζ and the stiffness K, in which the robot does not move. Mean values and standard deviation of 10 trials for each subject are shown.

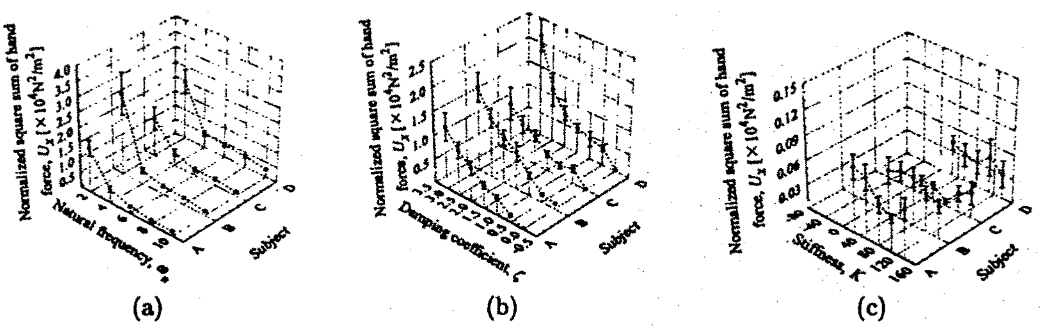


Fig.13: Change of the control performance U_x depending on the natural frequency ω_n, the damping coefficient ζ and the stiffness K, in which the robot does not move. Mean values and standard deviation of 10 trials for each subject are shown.

human arm impedance depends on the hand position as shown in Fig. 1, the describing functions should be dealt with as a first approximation. The open-loop describing function from the error e to the robot position x, $G(j\omega)$, and the human describing function from e to the hand force f_x, $H(j\omega)$, are obtained by using the subspace method [15].

Figure 9 shows the changes of $G(j\omega)$ and $H(j\omega)$ depending on the natural frequency of the robot ω_n, where the solid line is in the case with $\omega_n = 2$ [rad/s], the dotted line with $\omega_n = 4$ [rad/s] and the broken line with $\omega_n = 10$ [rad/s], respectively. Each result expresses the mean value of 10 trials. The gain of $G(j\omega)$ is almost constant without respect to the change of the natural frequency ω_n, while the gain of $H(j\omega)$ increases in the high frequency band with the reduction of ω_n. It follows that the human subject actively changes his/her own impedance property according to the robot impedance.

Figure 10 shows the changes of $G(j\omega)$ and $H(j\omega)$ depending on the damping coefficient of robot ζ. In the figures, the solid line is in the case with ζ = -0.5, the dotted line with $\zeta = 0.0$, the alternate long and short dashed line with $\zeta = 1.0$ and the broken line with $\zeta = 3.0$. Dynamic property of the system does not change so much except for the case with ζ = -0.5. It can be found that the gain under ζ = -0.5 is smaller than other conditions. These results indicates that it is difficult for the subjects to adjust their dynamic property when the robot is extremely unstable.

Figure 11 shows the changes of $G(j\omega)$ and $H(j\omega)$ depending on the robot stiffness K. In the figures, the solid line in the case with K = -55.0 [N/m], the broken line with K = 27.5 [N/m], and the dotted line with K = 137.5 [N/m]. It can be seen that the subjects adjust their own dynamic characteristics according to K so that the control property of the whole system is held in some degree even if K is negative or very large.

In ordinary man-machine system, the human operator tries to maintain the control property of the whole system by adjusting his/her own control property even if the control property of the system remarkably changes [16]. The similar feature can be observed in the constructed human-robot system under the natural frequency $\omega_n = 2 \sim 10$ [rad/s], the damping coefficient $\zeta = 0.0 \sim 3.0$, and the robot stiffness K = -55.0 $\sim$ 137.5 [N/m].

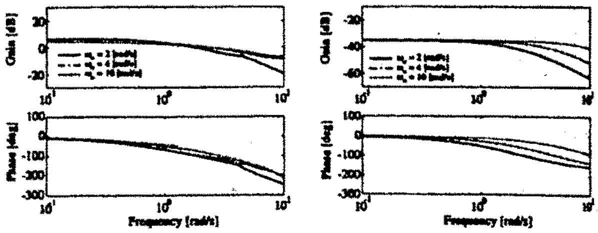
4 Tracking Control Properties According to Human Impedance

Experiments were carried out with the fixed robot handle to maintain the hand position even if the subject applies the hand force to the robot. The subjects were asked to minimize the error e between the virtual position of robot handle x and the target signal r shown on the display as small as possible. In the tracking operation, x is calculated from the dynamics of impedance-controlled robot defined in (1) with the measured hand force f_x. This experimental condition corresponds to that the human operator carries out tracking control in ordinary man-machine system with a second-order controlled element [16].

Figures 12 and 13 show the changes of J and U_x with the four skilled subjects depending on the natural frequency ω_n, the damping coefficient ζ, and the stiffness of robot K, respectively. Experimental conditions and subjects are the same in Figs. 5, 6, 8. The control performance J in Fig. 12 remarkably increases than one in which the robot handle allows to move in the operation (Figs. 5 (a), 6 (a), 8 (a)). On the other hand, U_x considerably decreases as shown in Fig. 13. It can be found that the subjects could not increase their own gain in order to follow the target signal with the fixed robot handle. Especially, the system is not controlled under the unstable impedance condition with a negative damping coefficient any longer (Fig. 12 (b) ; ζ = -0.5). Although the system is not unstable under ζ =0, the subjects hardly follow the target signal (Fig. 12 (c)).

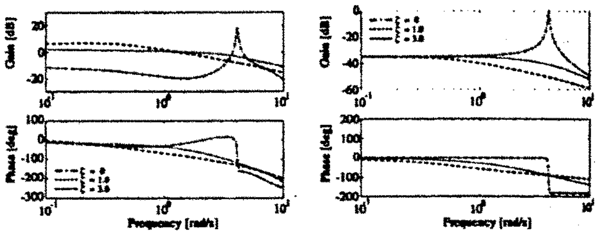
The observed features arise from the influence of human arm impedance on the impedance property of whole system, because the human operator can regulate his/her hand impedance unconsciously in the arm motion [7]-[9]. Namely, the operator can keep the dynamic property of the system almost constant by changing his own impedances when the arm allows to move with the robot handle. On the contrary, when the handle is fixed, the human arm impedance can not be utilized to regulate the dynamic property of the system any longer. It can be confirmed that the control property of human-robot systems is much affected by not only the robot impedance but also the human arm impedance. This point is the major difference between the human-robot system and the ordinary man-machine system [16].

Figures 14, 15 and 16 show the dynamic properties of the estimated human-robot system by the subspace method [15] according to the natural frequency of robot ω_n, the damping coefficient ζ and the stiffness K, respectively. Each of the figures corresponds to Figs. 9, 10, 11. It can be observed from Fig. 14 (a) that the gain of $G(j\omega)$ considerably decreases in the high frequency band under $\omega_n = 2$. Besides, the dynamic property of the whole system is not changed so much according to the damping coefficient ζ as shown in Fig. 15, except for $\zeta = 0$ in which the gain considerably decreases than other conditions. It can be found that the human operator can not adjust his arm impedance sufficiently to maintain the dynamic property of the whole system because $G(j\omega)$ is quite similar to $R(j\omega)$ as shown in the figures.



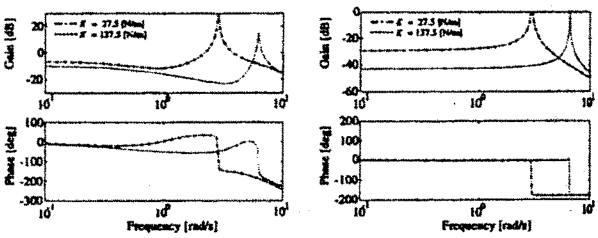
(a) $G(j\omega)$ (b) $R(j\omega)$

Fig.14: Change of the dynamic properties of the human-robot system depending on the natural frequency ω_n (K = 55.0 [N/m], ζ = 1.0, d = 0.55 [m], R = 0.1 [m], Subject = A)



(a) $G(j\omega)$ (b) $R(j\omega)$

Fig.15: Change of the dynamic properties of the human-robot system depending on the damping coefficient ζ (K = 55.0 [N/m], ω_n = 4 [rad/s], d = 0.55 [m], R = 0.1 [m], Subject = A)



(a) $G(j\omega)$ (b) $R(j\omega)$

Fig.16: Change of the dynamic properties of the human-robot system depending on the stiffness K (M = 3.43 [kg], ζ = 0, d = 0.55 [m], R = 0.1 [m], Subject = A)

5 Conclusions

The present paper has analyzed the control property of human-robot system according to the robot impedance, the proficiency of operators, and the impedance property of human arm. Through the experimental results, we have found the following distinctive characteristics:

1. The control property of a human operator considerably depends on the robot impedance.
2. The control property of a human-robot system is almost invariable against the change of robot impedance within some ranges.
3. The control performance of the whole system slightly decreases when the robot is unstable or the operator has to generate a large operational force.
4. The flexible adjustment of human arm impedance is realized by utilizing the arm redundancy, and fulfills the important role in the system stability.

By way of conclusion, we have found that the human operator tries to keep the dynamic property of the overall system as constant as possible by adjusting his or her own impedance property according to the robot impedance and the given task. The experimental results may be useful as a basic material for the design of impedance characteristic of a power assist robot and the composition problem of manual control training with robots.

The results obtained in this paper will be applied to develop a new control method of the multiple degrees of freedom robot for human assists.

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