

# Operation Force Reflecting Method in Machining Geometry via Bilateral Machining Support System with Variable Connecting Force

Tsuginobu Osada, Norihiko Kato, Ken'ichi Yano and Mustapha. S. Fofana

**Abstract**—Finishing processes such as deburring are performed on a wide variety of products in various quantities by workers on a piece-by-piece basis. Accordingly, the accuracy of the product depends on the worker's skill. To solve this problem, the bilateral control system is applied to a machining support system. The aim of this research is to develop a machining support system via the bilateral control system which can accept various machining theories and to reflect the operation force into the machining geometry. This system has a construction which makes it possible to change the connecting force between a master and a slave robot based on a symmetrical bilateral controller. This construction is useful to change the feature of a system dynamically according to machining condition. The effect of this system is shown by the experiment results.

## I. INTRODUCTION

At present, a great number of working processes are carried out automatically by using industrial robots. Such a production method has been widely adopted for mass production. However, if production is limited to a number of diversified products, deburring these products is difficult because of time and accuracy constraints. For example, a long time is required to prepare CAD data on positioning and configuration of the products. It is difficult to cope with differences in the set position or warping of the products. As a result, these processes have to be carried out manually by workers and require the careful control of force. The absence of skill will cause the machining miss and the increase in cost.

To solve these problems, finish machining systems combined with the bilateral control shown in Fig. 1 have been studied. The bilateral control is one type of a master-slave control method and its control target is both the position and force[1]. The important component for the bilateral control which performs the contact process with objects is how a slave has a stable contact with them. In several researches, this point has been studied and solved by introducing the control method in the controller for a slave robot which realizes the stable contact by correcting its motion[2][3]. As an application example of this method for machining support, Hisatomi et al. investigated the machining process using the bilateral control system constructed by combining a PHANoM1.5/6DOF (SenAble Technologies) and a force display driven by hydraulics[4].

We proposed the teleoperating machining support system via the bilateral control which has a special construction[5].

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Here, the slave robot works automatically during machining because the control signal from the master robot to the slave robot is disconnected for the thrusting direction. As a result, the motion of the slave robot depends only on the controller that the slave robot has independently. In addition, we proposed the control method that makes it possible to perform a deburr process accurately even if the feed speed changes irregularly due to the worker's operation as well. This study achieved a certain result. However, this method is not suitable to apply another field of the machining support because this system has the space to accept the operator's intention only at a start position and a stop position. This problem is caused by the used system that cannot accept the operation toward a thrusting direction during machining. In order to broaden the region of application, this system should be improved to accept the operator's intention by changing the system component during the operation so that the operator can work the machining robot with an arbitrary way.

In this paper, the bilateral control system structured for the machining support system is proposed. This control method makes it possible to change the rate of connecting force given to the master robot or the slave robot. As a result, the slave robot can change the priority to trace the master robot or to achieve the target value such as the target machining force. We will present the design of control proposed newly and the experiment results with the press motion.



Fig. 1. Devices used as bilateral control system

## II. MACHINING SUPPORT SYSTEM

In this study, we used a three-dimensional haptic device (Falcon, Novint) as the master robot. This robot has a parallel link mechanism and outputs position signals and inputs force signals of three axes. As the slave robot, the machining support robot with 6DOF is used[6]. The base side of the slave robot consists of a prismatic joint with 3DOF. Two axes in the middle constitute the fixed rotation joint. The tip side of the robot consists of a rotation joint with 3DOF. A force sensor and a rotating tool are equipped on the hand. The base and tip side of the robot are driven by motors. The base side of the robot uses a prismatic joint made by IAI Co., Ltd. The lead per one rotation of the motor is 0.010 m, resolution is  $2.5 \times 10^{-6}$  m, rated maximum velocity is 0.05 m/s, and maximum thrust force is 1009.7 N. The motor of the tip side of the robot uses a servomotor (Harmonic Drive Systems, Inc.), in which the maximum torque is 11.0 N·m, maximum revolution number is 60.0 rpm, and resolution is  $8.0 \times 10^5$  p/rev. A model of the slave robot is shown in Fig. 2. Here,  $x_i$ ,  $y_i$  and  $z_i$  show the x axis, y axis and z axis on the position where the coordinate  $\Sigma_i$  is set.  $L_i$  show the length between each coordinate position, where  $L_1 = 0\text{m}$ ,  $L_2 = 0.382\text{m}$ ,  $L_3 = 0\text{m}$ ,  $L_4 = 0.212\text{m}$ ,  $L_5 = 0.320\text{m}$ . We used these two robots in combination with a bilateral control system that adjusts the machining support system.

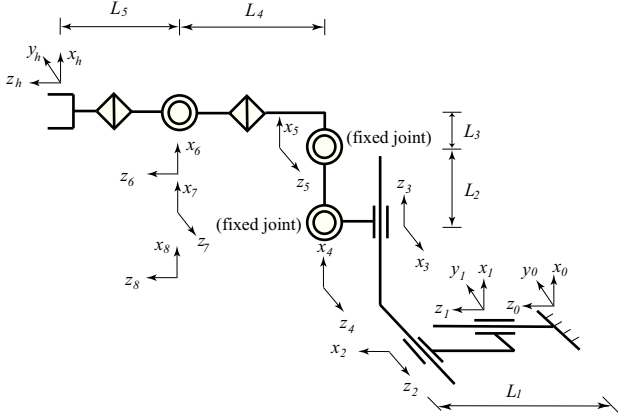


Fig. 2. Modeling of slave robot

## III. DESIGN OF CONTROLLER

In this section, we discuss the concept of a proposed bilateral controller and its application example.

### A. Desired Controller for Machining Support

The desired components in the machining support can be separated into following three conditions.

- 1) The slave robot traces the master robot without making contact.
- 2) The slave robot makes contact with an object and performs machining according to machining theory.
- 3) The operator corrects the tool's trajectory in thrust direction during machining.

In the first condition, the slave robot is required to trace the position of master robot by being given only the connecting force. In the second condition, the slave robot is required to trace the target trajectory precisely calculated with the machining condition equation or others. This time, the force signal measured by the slave robot has to be transferred to master robot so that the operator gets the machining condition such as machining force. In the third condition, the operator corrects the tool's trajectory by adding the operation force when the operator determines that the correction is required. In this research, a symmetrical type bilateral control is adopted in order to present these three conditions as motion equation.

In the symmetrical type bilateral control, the master and the slave robot are considered to be connected by the spring and the damper. This control is able to perform the synchronized motion between the master and the slave robot by connecting them with admittance control via measured value of front edge location or joint angle. Therefore, we can consider that the connecting force generated by the spring damper system is distributed to the master and the slave robot as shown in motion equations (1) and (2).

$$M_m \ddot{q}_m + C_m \dot{q}_m = f_{op} + u_m \quad (1)$$

$$M_s \ddot{q}_s + C_s \dot{q}_s = f_{env} + u_s \quad (2)$$

where  $M_m$  and  $M_s$  show the mass coefficient,  $C_m$  and  $C_s$  show the viscosity coefficient of the master and the slave.  $f_{op}$  and  $f_{env}$  show the force given by the operator or environment,  $u_m$  and  $u_s$  show the connecting force between the master and the slave robot.

These equations are restructured to fulfill above three conditions. First condition is shown as (3) and (4).

$$M_m \ddot{q}_m + C_m \dot{q}_m = f_{op} \quad (3)$$

$$\begin{aligned} M_s \ddot{q}_s + C_s \dot{q}_s &= u_s + f_{env} - f_{Aenv} \\ &= u_s \end{aligned} \quad (4)$$

where  $f_{Aenv}$  works to compensate the force given by environment  $f_{env}$ . Generally,  $f_{Aenv}$  is set as  $f_{Aenv} = f_{env}$ . In these motion equations, only the operation force is given to the master robot and only the tracing force toward the master robot is given to the slave robot. Obviously, gravity, friction and other compensations for the master and the slave robot should be considered. However, these problems will be solved by each robot independently. Then, these correcting forces do not affect to the motion of another robot. We don't describe these force inputs in motion equation. The block diagram of this controller is shown in Fig. 3.

Next, the second condition is shown as (5) and (6).

$$M_m \ddot{q}_m + C_m \dot{q}_m = f_{op} + u_m + f_{tenv} \quad (5)$$

$$\begin{aligned} M_s \ddot{q}_s + C_s \dot{q}_s &= f_{env} + f_s - f_{Aenv} \\ &= f_s \end{aligned} \quad (6)$$

where  $f_{tenv}$  shows the force measured by the slave robot and transferred to the master robot.  $f_s$  shows the force given in order to achieve the target position, the target velocity or the

target press force. In these motion equations, not only the operation force but also the force generated by the deviation of position between the master and the slave robot and the force that the slave robot is measuring is given to the master robot. The most important point in this condition is that the slave robot works according to the target value, such as the target press force or the target feed speed. In addition, it is also important that the operator can recognize the force that the slave robot is measuring and the deviation of the position between the master and the slave robot. When  $u_m = 0$ , the master robot is given only  $f_{op}$  and  $f'_{tenv}$ . Then, the operator can recognize the force that the slave is measuring precisely. The block diagram of this controller is shown in Fig. 4.

Finally, the third condition is shown as (7) and (8).

$$M_m \ddot{q}_m + C_m \dot{q}_m = f_{op} + u'_m + f'_{tenv} \quad (7)$$

$$\begin{aligned} M_s \ddot{q}_s + C_s \dot{q}_s &= f_{env} + u'_s + f'_s - f_{Aenv} \\ &= u'_s + f'_s \end{aligned} \quad (8)$$

In these equations, the symbols with dash have the 0 ~ 1 value times to their originals used in (3)~(6). In these motion equations, the operation force, the connecting force and the measured force are given to the master robot. The tracing force toward the target and the connecting force are given to the slave robot. This condition is constructed as the combination of the first and the second condition. The process of transition to the third condition from the first or the second condition should be performed continuously not to lose the stability of the system. The block diagram of this controller is shown in Fig. 5.

From these problem establishments, we find that the three conditions desired to perform the machining support can be shown as the motion equation based on the symmetrical bilateral control.

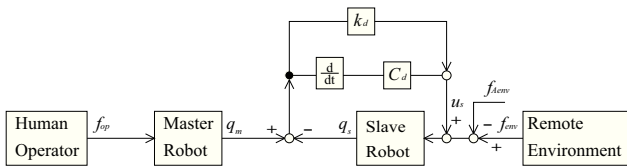


Fig. 3. Block diagram in motion condition 1

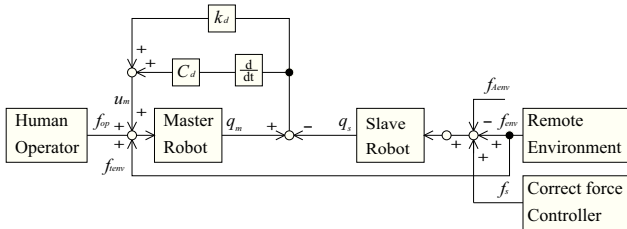


Fig. 4. Block diagram in motion condition 2

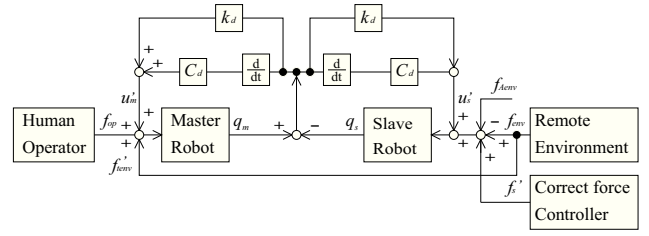


Fig. 5. Block diagram in motion condition 3

### B. Suggestion of bilateral controller for machining support system

In order to realize the conditions shown in the previous section, the new bilateral controller is proposed in this section. This controller has the feature in having the arbitrary variables  $\mu_i$  on the force transfer lines. The motion equations of it are shown as (9) and (10).

$$\begin{aligned} M_m \ddot{q}_m(t) + C_m \dot{q}_m(t) + C_{mp} \dot{q}_m(t - \tau_{m1}) &= f_{op}(t) + \mu_{m1} u_m + \mu_{m2} f_m \\ &+ \mu_{m3} f_{tenv}(t - \tau_{s2} - \tau_{tr}(t)) \quad (9) \\ M_s \ddot{q}_s(t - \tau_{s1}) + (C_s + C_{sp}) \dot{q}_s(t - \tau_{s1}) &= f_{env}(t - \tau_{s2}) - f_{Aenv}(t - \tau_{s2}) \\ &+ \mu_{s1} u_s + \mu_{s2} f_s \\ &+ \mu_{s3} f_{top}(t - \tau_{m2} - \tau_{tr}(t)) \quad (10) \end{aligned}$$

where  $q_m$  and  $q_s$  show the position of the master and the slave robot.  $M_i$ ,  $C_i$  and  $C_{ip}$  ( $i = m, s$ ) show the mass, viscosity and virtual viscosity coefficient of each robot.  $f_i$  show the tracing force toward the target value.  $f_{top}$  and  $f_{tenv}$  show the force signal transferred from another robot. The angle errors of each joint of the slave robot are compensated by PID controller and we assume that the slave robot will move according to reference signal accurately. Then, we set the virtual impedance model for the slave robot and give the arbitrary impedance attribution. It is set so that the tool can make stable contact with object. Although the system used in this research doesn't cause the transfer time delay, we estimate the condition that the time delay exists by the reproduction of it by using the software's function so as to show the effectiveness of the proposed system. Then, the motion equation is described by containing the time delay components.  $\tau_{m1}$  and  $\tau_{s1}$  show the time delay caused by the filter for position encoders of each robot,  $\tau_{m2}$  and  $\tau_{s2}$  show the time delay caused by the filter for a force sensor and  $\tau_{tr}$  shows the transfer time delay between the master and the slave robot. As a filter, we use the lowpass filter and set  $\tau_{m1} = \tau_{s1} = 0.05s$ ,  $\tau_{m2} = \tau_{s2} = 0.1s$ .  $u_i$  and  $f_i$  are shown as (11)~(14).

$$\begin{aligned} u_m(t) &= k_d (q_s(t - \tau_{s1} - \tau_{tr}(t)) - q_m(t - \tau_{m1})) \\ &+ C_d (\dot{q}_s(t - \tau_{s1} - \tau_{tr}(t)) - \dot{q}_m(t - \tau_{m1})) \\ &+ O_3 (q_s(t - \tau_{s1} - \tau_{tr}(t)) - q_m(t - \tau_{m1}))^3 \end{aligned} \quad (11)$$

$$\begin{aligned}
u_s(t) &= k_d (q_m(t - \tau_{m1} - \tau_{tr}(t)) - q_s(t - \tau_{s1})) \\
&+ C_d (\dot{q}_m(t - \tau_{m1} - \tau_{tr}(t)) - \dot{q}_s(t - \tau_{s1})) \\
&+ O_3 (q_m(t - \tau_{m1} - \tau_{tr}(t)) - q_s(t - \tau_{s1}))^3
\end{aligned} \tag{12}$$

$$\begin{aligned}
f_m(t) &= a_{mf} (f_{op}(t - \tau_{m2}) - f_{mt}(t)) \\
&+ a_{mp} (q_{mt}(t) - q_m(t - \tau_{m1})) \\
&+ a_{mv} (v_{mt}(t) - \dot{q}_m(t - \tau_{m1}))
\end{aligned} \tag{13}$$

$$\begin{aligned}
f_s(t) &= a_{sf} (f_{env}(t - \tau_{s2}) - f_{st}(t)) \\
&+ a_{sp} (q_{st}(t) - q_s(t - \tau_{s1})) \\
&+ a_{sv} (v_{st}(t) - \dot{q}_s(t - \tau_{s1}))
\end{aligned} \tag{14}$$

where  $f_{it}$ ,  $q_{it}$  and  $v_{it}$  show the target force, the target position and the target velocity.  $a_{if}$ ,  $a_{ip}$  and  $a_{iv}$  show coefficients which are determined to define the trace performance toward each target values.  $k_d$  and  $C_d$  show the spring and the damper coefficient between the master and the slave robot. By changing the  $\mu_i$ , we can change the connecting condition between the master and the slave robot and control the feature of the system. For example, the slave robot will be affected by both the connecting force  $u_s$  and the tracing force  $f_s$  in the condition of  $\mu_{s1} = 0.5$  and  $\mu_{s2} = 0.5$ . The slave robot will be affected only by the tracing force  $f_s$  and perform to achieve the target value in the condition  $\mu_{s1} = 0$  and  $\mu_{s2} = 1$ . By calculating  $f_{ts}$ ,  $q_{st}$ ,  $v_{st}$  with machining condition equation[5], we can control the slave robot according to the machining condition or the cutting theory.

### C. Robot control model

The slave robot has the arbitrary character by being added the virtual impedance model as shown in the previous section. In this research, the impedance model of the slave robot has  $M_s = 1.0 \times 10^2 \text{kg}$ ,  $C_s + C_{sp} = 6.0 \times 10^3 \text{Ns/m}$ . These parameters are set so that the slave robot contacts the object with stability. Then, these values are higher than those of the master robot. The parameters for connecting force between the master and the slave robot are set as  $K_d = 2.4 \times 10^4 \text{N/m}$ ,  $C_d = 1.0 \times 10^2 \text{Ns/m}$ .  $O_3$  is set in order to reduce the rapid deviation of position if it becomes larger. Then,  $O_3$  is set as  $1.0 \times 10^2 \text{N/m}^3$  not to affect the connecting force when the deviation is small. In addition, the master robot has  $C_{mp} = 8.0 \text{Ns/m}$  so as to stabilize its motion. This value is determined so that the master robot which has  $K_d = 2.4 \times 10^4 \text{N/m}$  and the initial deviation 10cm stops without an overshoot in the condition that the motion of the master robot becomes most unstable, that is, the operator lets go his grip of the master robot.

The coefficients  $\mu_{mi}$  and  $\mu_{si}$  can be rewritten as the product with a new coefficient  $\mu$ . In this research, these coefficients are set as  $\mu_{m1} = \mu \times 0.10$ ,  $\mu_{m2} = 0.0$ ,  $\mu_{m3} = \mu \times 1.0$ ,  $\mu_{s1} = 1.0 - \mu$ ,  $\mu_{s2} = \mu$ ,  $\mu_{s3} = 0.0$ . By controlling this coefficient  $\mu$  dynamically, the character of the system can be changed as the change of one coefficient. The difference of the impedance parameter between the master and the slave robot is very large. The motion of these robots will become

unstable if the connecting force is given to each robot in the same condition. Then,  $\mu_{m1}$  is set as  $\mu_{m1} = \mu \times 0.10$ .

## IV. EXPERIMENT WITH PRESS MOTION

In order to perform the practical machining works, the slave robot should realize the stable contact motion and the according target value motion. In this section, the control algorithm for an arbitrary variable  $\mu$  is shown and applied to the bilateral controller proposed in the previous section. The effectiveness of this control method is shown through the operation experiment.

### A. Control algorithm for $\mu$

The operation experiment with proposed bilateral controller is performed. In this experiment, the slave robot is pressed toward the object so that the contact force becomes the target force (5N). In order to prove the effectiveness of the proposed method, the operation experiment with the master-slave control method is also performed as the previous method. The arbitrary variable  $\mu$  is controlled as following equations (15), (16) and (17).

$$\mu = \begin{cases} 0 & (\mu_1 - \mu_2 < 0) \\ \mu_1 - \mu_2 & (0 \leq \mu_1 - \mu_2 \leq 1) \end{cases} \tag{15}$$

$$\mu_1 = \begin{cases} 0 & (f_{env} < 0) \\ f_{env}/3 & (0 \leq f_{env} < 3) \\ 1 & (f_{env} \geq 3) \end{cases} \tag{16}$$

$$\mu_2 = \begin{cases} 0 & (|q_m - q_s| < 0.03) \\ \frac{|q_m - q_s| - 0.03}{0.02} & (0.03 \leq |q_m - q_s| < 0.05) \\ 1 & (|q_m - q_s| \geq 0.05) \end{cases} \tag{17}$$

By using this control method, the motion mode of the slave robot can change from the contact motion to the pressing motion with the target force continuously. In addition, the tracing motion toward the master robot will appear again by broadening the deviation of the position between the master and the slave robot. As a result, this system enables the slave robot to transition into a stable contact condition and provides the operation force to the slave robot in this condition.

### B. Operation verification

First, we performed the contact experiment with the master-slave control by setting the  $\mu$  as  $\mu = 0$  ( $\mu_{m1} = 0.00$ ,  $\mu_{m3} = 0.0$ ,  $\mu_{s1} = 1.0$ ,  $\mu_{s2} = 0.0$ ,  $\mu_{m2} = \mu_{s3} = 0$ ). The experiment result is shown in Fig. 6. In case 1 (between 20s and 43s), the contact motion between the slave robot and the object was performed. In case 2 (between 45s and 55s), the pressing force toward the object was increased and decreased. In case 3 (between 60s and 98s), the operator moved the slave robot toward tangential direction adjusting the pressing force to become as the target force. From experiment results, we can find that it is difficult for the master-slave control to keep the contact or press force constant. Especially, this result was seen prominently in case 3. In the master-slave control, it is impossible for the operator to

feel the pressing force. Then, the operator has to control the robot monitoring the measured force value displayed on a computer screen. However, the marginal operation force will cause the large difference of the contact force because both the slave robot and the object have the high stiffness. As a result, these results are observed. On the other hand, the common bilateral control will cause that the slave robot will be flipped from the object because the large change of the contact force will be transferred to the master robot directly. Then, it is very difficult to realize the stable contact motion or pressing motion. Moreover, if the operator controls the robot so as not to be flipped, he is required to control the robot with extreme discretion and the system can't accomplish the purpose of the machining support.

Next, we performed the experiment with the proposed method. The experiment result is shown in Fig. 7. In case 1 (between 12s and 20s), the contact motion between the slave robot and the object was performed. In case 2 (between 28s and 51s), the operator moved the master robot toward the normal direction during the contact motion. In case 3 (between 57s and 70s), the contact and the separate motion were repeated. In case 4 (between 75s and 83s), the operator moved the robot toward tangential direction with the pressing motion. In case 5 (between 85s and 97s), the operator pushed the robot toward normal direction during performing as case 4. Comparing with the experiment result with the master-slave control, the slave robot worked in order to accomplish the target force precisely. Especially, this phenomenon was observed when the slave robot was moving toward tangential direction clearly. When the master robot is moved toward object during working, the slave robot continued the contact motion with the constant force due to the small operation force as seen in case 4 and was effected by the large operation force as seen in case 5. In addition, the repulsive force yield in onset of the contact between the slave robot and the object became large in case 1 and case 4. This force didn't affect the motion of the slave robot and the press motion with the target force was accomplished quickly. In this controller, the contact yield at the onset of contact force between the slave robot and the object is transferred to the master robot and the operator feels the repulsive force as the previous experiment. However, the motion condition for the slave robot is changed as the condition 2 shown in the previous section. Then, the operator is not required to control the robot carefully. Furthermore, larger impedance parameters of the slave robot set to have stable contact with the object are one of the reasons for these results.

### C. Operation verification with time delay

We performed the operation verification with the transfer time delay. The time delay was set as constant value 0.1s. The impedance model of the slave robot and other values were set as they were used in the previous experiment. The experiment via the master-slave control and the experiment via the proposed method were performed. The experiment results are shown in Fig. 8 and 9.

In the experiment via the master-slave control, it became

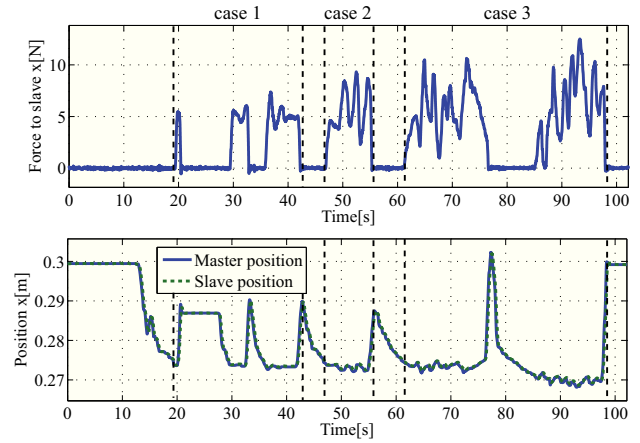


Fig. 6. Experiment result via master-slave control

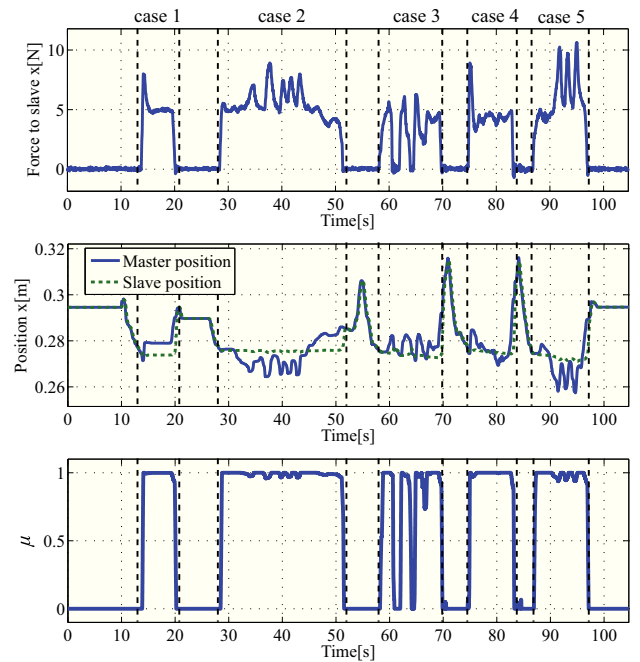


Fig. 7. Experiment result via proposed control

more difficult to control the slave robot with the constant press force comparing with the experiment without time delay. This phenomenon is considered to happen due to the debasement of the operability because the slave robot traces the master robot with the motion delay. On the other hand, it is known that the stability of the motion between the master and the slave robot debases if the time delay exists[7]. In this experiment, the same parameters used in the experiment without time delay were used and the overshoot was yielded when the slave robot converges to the position of the master robot. This is considered as another reason for this phenomenon.

In the experiment via proposed method, the press motion with the constant force was performed better than the experiment via the master-slave control. The position and force signal measured by the slave robot and another position and force signals transferred from the master robot are used

to control  $\mu$ . Then, the transition from the condition 1 to the condition 2 was performed in the same way which doesn't have the time delay. Then, the press motion and the movement toward tangential direction were performed successfully even if there are the transfer time delay components. However, the operability was not so good because the signal measured by the slave robot was transferred with the time delay and the trace capability of the master robot toward the slave robot degrades. It is required to improve the system by changing the connection force between the master and the slave robot or increasing the viscosity coefficient of each robot based on the time delay component. In addition, the correction of the force signal transferred from the slave robot will be required because this signal has a very important task for the operator to recognize the condition of machining surface.

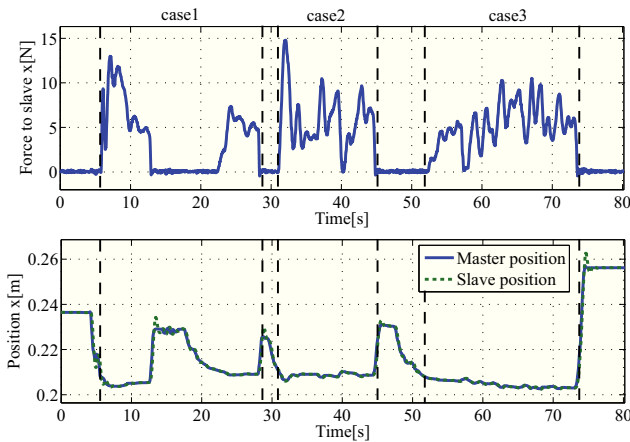


Fig. 8. Experiment result via master slave control with time delay 0.1s

## V. CONCLUSION

In this study, the control methods and the motion equations which are required during machining were shown. From these conditions, the bilateral controller which can change the connecting force between the master and the slave robot dynamically was proposed. This system makes it possible to reflect the motion of the master robot in the motion of the slave robot which is controlled based on the machining theory. As a result, the machining trajectory is corrected by the operator. The effectiveness of this system was shown via the experiment result. In addition, the experiment was performed with the transfer time delay so as to show the effectiveness of this system in other working support. As a future works, we have to discuss the force feedback method for the operator in order to transfer the machining states such as the machining force or others precisely even if there are the transfer time delay components. In addition, we have to show the effectiveness of this system as the machining support system by performing the machining experiments with the proposed method.

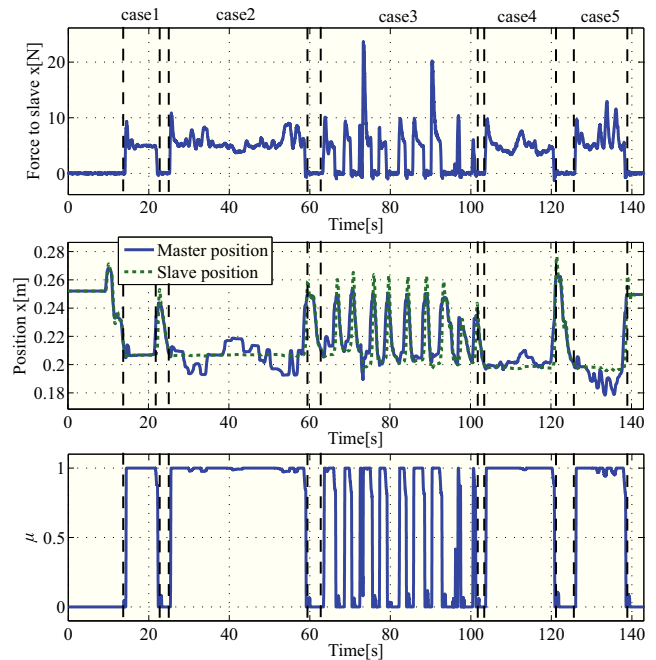


Fig. 9. Experiment result via proposed control with time delay 0.1s

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