A stabilizing control technique for bilateral teleoperation system with time delay

H. W. Kim* and I. H. Suh**

*Department of Electronics Engineering, Hanyang University, Ansan, 426-791, Korea
(Tel: +82-31-400-3717; Fax: +82-31-408-5803; Email:hwkim@incorl.hanyang.ac.kr)
**Graduate School of Information and Communications, Hanyang University, Seoul, 133-791, Korea
(Tel: +82-31-400-5172; Fax: +82-31-408-5803; Email:ihsuh@hanyang.ac.kr)

Abstract: In this paper, a hybrid stabilization approach involving both passivity observer/passivity controller and wave variables is addressed to stabilize a teleoperation system with fixed time delay. To guarantee the stability of master or slave side, passivity observer/passivity controller are applied. But, passivity observer/passivity controller cannot deal with communication delay, and thus even small communication delay cause the system to be unstable. To cope with this problem, wave variables are additionally employed to have robustness to fixed communication delays. To show the validity of our proposed approach, several computer simulation results are illustrated.

Keywords: teleoperation, wave variable, passivity, time delay

1. Introduction

A bilateral teleoperation system may be described by means of the block diagram as shown in Figure 1. The main components of teleoperation system are master, slave, and communication channel. A master robot takes the motions of an operator and generates a desired motion command which a slave robot should follows. While following the desired motion command transmitted from a master side, a slave sends information on its current position or contact force for an operator to feel the environment.

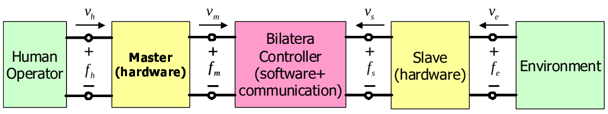
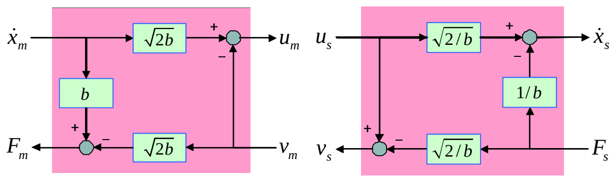


Fig. 1. Two port network model of bilateral teleoperation system

Many research works have been done on the analysis of stability and performance of teleoperation system. Zaad and Salcudean classified operating mode of teleoperation by specifying the transmitted data pair and analyzed the stability conditions and performances for each operating mode[2], [3]. Hannaford and Ryu proposed the time domain passivity observer and passivity controller[4], [5]. The passivity observer checks whether a system is passive or not by measuring energy flows. When the system is detected to be active by a negative value of the passivity observer, the passivity controller makes the system passive by dissipating exactly the net energy output. Although the passivity observer/controller may stabilize a master or slave, instability might be caused by communication delay. Niemeyer and Slotine proposed a physically motivated, passivity-based formalism to provide energy conservation and to ensure stability in the presence of time delay[6], [7]. By transmitting wave variables in place of the power variables(velocity and force), the passivity of time-delayed teleoperation system is guaranteed. Although the concept of characteristic impedance of waves was introduced and an analogy was drawn, there was no research work on the relationship between characteristic impedance and the stability or performance of teleoperation system.

In this paper, a hybrid stabilization approach involving both passivity observer/controller and wave variables is addressed to stabilize the teleoperation system with time delay. To guarantee the stability of a master or slave side, passivity observer/controller are applied. Wave variables are additionally employed to have robustness to communication delay. Furthermore, the minimum value of transmitted impedance from a slave to an operator is used as the performance index of wave-based teleoperation system.



(a) master side (b) slave side

Fig. 2. Structure of wave transform

2. Wave variables

2.1. Definition

Wave variables are defined by encoding of velocity $\dot{\mathbf{x}}$ and force $\mathbf{F}$

$$\mathbf{u} = \frac{b\dot{\mathbf{x}} + \mathbf{F}}{\sqrt{2b}}, \quad \mathbf{v} = \frac{b\dot{\mathbf{x}} - \mathbf{F}}{\sqrt{2b}} \qquad (1)$$

where $\mathbf{u}$, $\mathbf{v}$, and b denote the right moving wave, the left moving wave, and the characteristic wave impedance, respectively.

At the master side, the measured velocity $\dot{\mathbf{x}}_\mathbf{m}$ and the left moving wave $\mathbf{v}_\mathbf{m}$ provide both the right moving wave $\mathbf{u}_\mathbf{m}$ and the force feedback $\mathbf{F}_\mathbf{m}$.

$$\mathbf{u}_\mathbf{m} = \sqrt{2b}\dot{\mathbf{x}}_\mathbf{m} - \mathbf{v}_\mathbf{m}, \quad \mathbf{F}_\mathbf{m} = b\dot{\mathbf{x}}_\mathbf{m} - \sqrt{2b}\mathbf{v}_\mathbf{m} \qquad (2)$$

Together with the observed slave force $\mathbf{F}_\mathbf{s}$, the right moving wave $\mathbf{u}_\mathbf{s}$ is decoded into a velocity command $\dot{\mathbf{x}}_\mathbf{s}$ and the feedback wave $\mathbf{v}_\mathbf{s}$.

$$\mathbf{v_x} = \mathbf{u_s} - \sqrt{\frac{2}{b}}\mathbf{F_s}, \quad \dot{\mathbf{x}}_\mathbf{s} = \sqrt{\frac{2}{b}}\mathbf{u_s} - \frac{\mathbf{F_s}}{b} \tag{3}$$

Figure 2 shows the wave transformation at each side and the wave-based bilateral teleoperation system is shown in Figure 3.

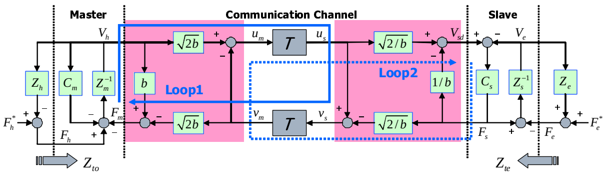


Fig. 3. Wave variable-based teleoperation system

2.2. Passivity of wave variables

A one port system is passive if the total energy delivered to the system is non-negative [9]

$$E(t) = \int_0^t P_{in} d\tau + E_{store}(0) \geq 0, \ \forall t \geq 0 \tag{4}$$

where $E_{store}(0)$ denotes the energy stored in the system at time t=0.
The power input to a one port system can be computed as following wave form

$$P_{in} = \dot{\mathbf{x}}^\mathbf{T}\mathbf{F} = \frac{1}{2}\mathbf{u}^\mathbf{T}\mathbf{u} - \frac{1}{2}\mathbf{v}^\mathbf{T}\mathbf{v} \tag{5}$$

where $\frac{1}{2}\mathbf{u}^\mathbf{T}\mathbf{u}$ is the power flowing into the system and $\frac{1}{2}\mathbf{v}^\mathbf{T}\mathbf{v}$ is the power flowing back.
In the wave domain, the passivity condition Eq.(4) becomes

$$\int_0^t \frac{1}{2}\mathbf{v}^\mathbf{T}\mathbf{v} d\tau \leq \int_0^t \frac{1}{2}\mathbf{u}^\mathbf{T}\mathbf{u} d\tau + E_{store}(0), \ \ \forall t \geq 0 \tag{6}$$

and a system is passive if the returning energy is smaller than the sum of provided energy and initially stored energy.
The total power input into the communication channel at any point in time is given by

$$P_{in} = \dot{\mathbf{x}}_\mathbf{m}^\mathbf{T}\mathbf{F_m} - \dot{\mathbf{x}}_\mathbf{s}^\mathbf{T}\mathbf{F_s} \tag{7}$$

where the minus sign appears because power is considered positive while flowing in the main direction from left to right.
Substituting Eq.(1) into Eq.(7), power input can be computed as

$$P_{in} = \frac{1}{2}\mathbf{u_m^T u_m} - \frac{1}{2}\mathbf{v_m^T v_m} - \frac{1}{2}\mathbf{u_s^T u_s} + \frac{1}{2}\mathbf{v_s^T v_s} \tag{8}$$

When the time delay exists in communication channel, wave variables are transmitted via

$$\mathbf{u_s}(t) = \mathbf{u_m}(t-T), \ \mathbf{v_m}(t) = \mathbf{v_s}(t-T) \tag{9}$$

Substituting into Eq.(8), power input becomes

$$\begin{aligned} P_{in} =& \frac{1}{2}\mathbf{u_m^T}(t)\mathbf{u_m}(t) - \frac{1}{2}\mathbf{u_m^T}(t-T)\mathbf{u_m}(t-T) + \\ & \frac{1}{2}\mathbf{v_s^T}(t)\mathbf{v_s}(t) - \frac{1}{2}\mathbf{v_s^T}(t-T)\mathbf{v_s}(t-T) \\ =& \frac{d}{dt}\int_{t-T}^t \left(\frac{1}{2}\mathbf{u_m^T}(\tau)\mathbf{u_m}(\tau) + \frac{1}{2}\mathbf{v_s^T}(\tau)\mathbf{v_s}(\tau)\right) d\tau \end{aligned} \tag{10}$$

Integrating Eq.(10), all input power is stored according to

$$\begin{aligned} E_{store}(t) =& \int_0^t P_{in} d\tau \\ =& \int_{t-T}^t \left(\frac{1}{2}\mathbf{u_m^T u_m} + \frac{1}{2}\mathbf{v_s^T v_s}\right) d\tau \geq 0 \end{aligned} \tag{11}$$

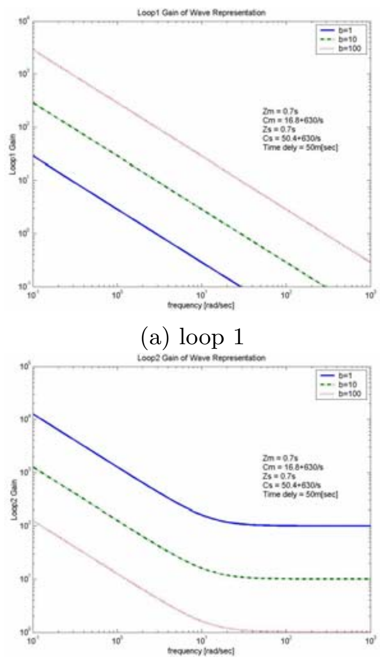
assuming zero initial conditions. Should the returning wave get delayed then energy is only temporarily stored in the communication channel and released later, still satisfying the passivity condition. And this is independent of time delay T.

3. Characteristic impedance-based stability and performance analysis of teleoperation system using wave variables

To learn the effect of characteristic impedance b on stability, loop gains are obtained from Figure 3 as

$$Loop\ 1: \ \frac{2be^{-2sT}}{Z_m}, \quad Loop\ 2: \ \frac{2C_s e^{-2sT}}{b} \tag{12}$$

Figure 4 shows the plot of loop gains with different b. Both loops are positive feedback and the gain of loop 2 is much larger than that of loop 1 when b is small, thus increasing b that decreases the gain of loop 2 is desirable to stabilize a slave side.



(a) loop 1

(b) loop 2

Fig. 4. Plot of loop gains with different b

In Figure 3, the output from the master side is a velocity and the input to the master side is a feedback force. This input-output relation can be matched with four channel architecture[1], where channel 3 and 4 are not used in Figure 5. The only difference between two architectures is that velocity and force information are transmitted via independent channel in four channel architecture. But, communication channels are coupled each other in wave-based architecture, performance analysis is relatively difficult.

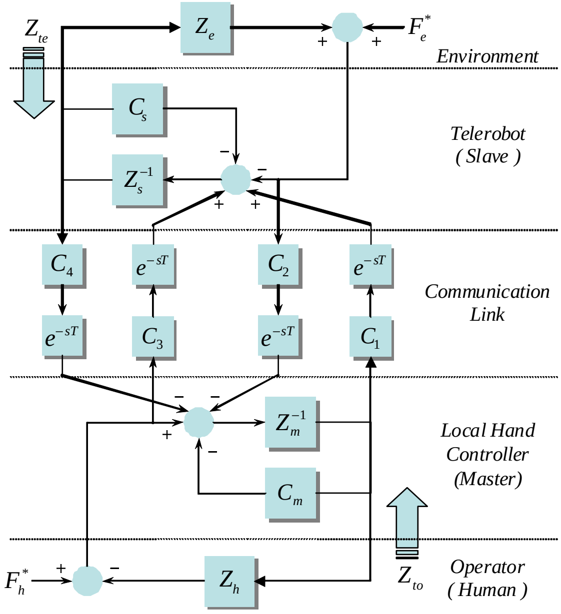


Fig. 5. Block diagram of a 4 channel teleoperation architecture after Lawrence

In this paper, two port network theory is used to analyze the effect of wave impedance b on the performance of wave-based teleoperation architecture.
If (V_h, F_e) and $(F_h, -V_e)$ are chosen as the input and output of communication channel, two port network can be represented as a hybrid model[9]

$$\begin{pmatrix} F_h \\ -V_e \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} V_h \\ F_e \end{pmatrix} \tag{13}$$

When the velocity channel from master to slave and the force channel from slave to master are used in Figure 5, hybrid parameters can be calculated as

$$\begin{aligned} h_{11:4Ch} &= Z_{cm} \\ h_{12:4Ch} &= C_2 e^{-2sT} \\ h_{21:4Ch} &= -\frac{C_1 e^{-sT}}{Z_{cs}} \\ h_{22:4Ch} &= \frac{1}{Z_{cs}} \end{aligned} \tag{14}$$

The hybrid parameters of wave-based two port network can be derived as

$$\begin{aligned} h_{11:W} &= Z_{cm} + \frac{(2\Gamma-1)\{bC_sZ_s(2\Gamma-1)-b^2Z_{cs}\}}{bZ_{cs}-C_sZ_s(2\Gamma-1)} \\ h_{12:W} &= \frac{2e^{-sT}}{1+e^{-2sT}}\left(1-\frac{bZ_s-C_sZ_s(2\Gamma-1)}{bZ_{cs}-C_sZ_s(2\Gamma-1)}\right) \\ h_{21:W} &= -\frac{2bC_s(1-\Gamma)e^{-sT}}{bZ_{cs}-C_sZ_s(2\Gamma-1)} \\ h_{22:W} &= \frac{b-C_s(2\Gamma-1)}{bZ_{cs}-C_sZ_s(2\Gamma-1)} \end{aligned} \tag{15}$$

where $Z_{cm} = Z_m + C_m$, $Z_{cs} = Z_s + C_s$, and $\Gamma = e^{-2sT}(1 + e^{-2sT})^{-1}$.
The performance of teleoperation system can be evaluated as transparency, that is a match between environment impedance(Z_e) and the transmitted impedance to the operator(Z_{to}). In ideal case, perfect transparency means that the transmitted impedance is equal to the environment impedance.

$$Z_{to} = \left.\frac{F_h}{V_h}\right|_{F_h^*=0} = \frac{h_{11}+(h_{11}h_{22}-h_{12}h_{21})Z_e}{1+h_{22}Z_e} \tag{16}$$

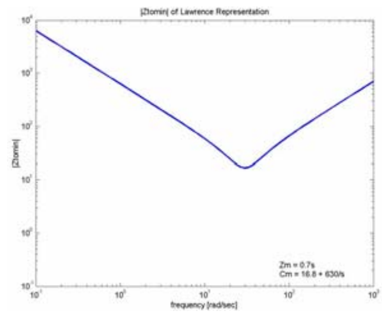
The minimum value of transmitted impedance can be defined as Eq.(17) when slave moves freely without any contact with environment.

$$Z_{to\,\min} = Z_{to}|_{\,Z_e=0} = h_{11} \tag{17}$$

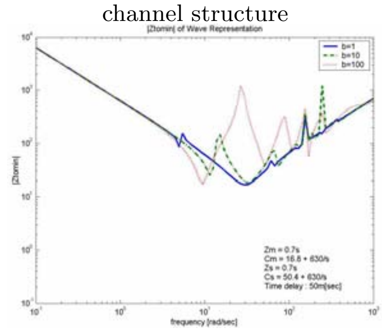
Substituting Eq.(15) and Eq.(16) into Eq.(17) and after some manipulation, the minimum values of Z_{to} become

$$Z_{to\,\min\,:\,4Ch} = Z_{cm} \tag{18}$$

$$\begin{aligned} Z_{to\,\min\,:\,W} =& Z_{cm} \\ &+ \frac{(2\Gamma-1)\{bC_sZ_s(2\Gamma-1)-b^2Z_{cs}\}}{bZ_{cs}-C_sZ_s(2\Gamma-1)} \end{aligned} \tag{19}$$



(a) velocity-force mode of 4 channel structure



(b) wave-based structure

Fig. 6. Plot of Z_{to} minimum

The two minimum values of Z_{to} differ by

$$\frac{(2\Gamma-1)\{bC_sZ_s(2\Gamma-1)-b^2Z_{cs}\}}{bZ_{cs}-C_sZ_s(2\Gamma-1)}$$

Thus, the performance of wave-based teleoperation system will be degraded if b grows, which cause the growth of Z_{to} minimum value at high frequency range over 10rad/sec.
Figure 6(a) shows the $Z_{to\,\min}$ plot of four channel architecture, where velocity-force mode is used, and Figure 6(b) shows the $Z_{to\,\min}$ plot when the wave variables are applied in teleoperation system with different b. When the value of b is 1, the performances of four channel and wave-based system look similar. When the value of b is 100, the minimum value of Z_{to} is increased by 50 times.

4. Hybrid stabilizing control method using passivity controller and wave variables

Figure 7 shows the structure of proposed hybrid stabilizing method. Wave variables are applied at communication channel to guarantee the stability of time-delayed teleoperation system and the passivity controller is applied at the environment to guarantee the passivity of a slave.
The control commands to master and slave are given as Eq.(20) and Eq.(21), respectively.

$$master: \quad U_m = F_h - (b + C_m)V_h + \sqrt{2b}\mathbf{v_m} \tag{20}$$

$$slave: \quad U_s = \frac{\sqrt{2b}C_s}{b + C_s}\mathbf{u_s} - F_e^{'} - \left(\alpha + \frac{bC_s}{b + C_s}\right)V_e \tag{21}$$

where $F_e^{'}$ is a measured force at the environment and a PI controller is used at the master and slave.

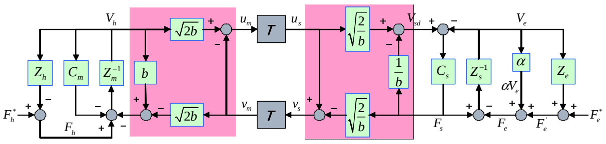


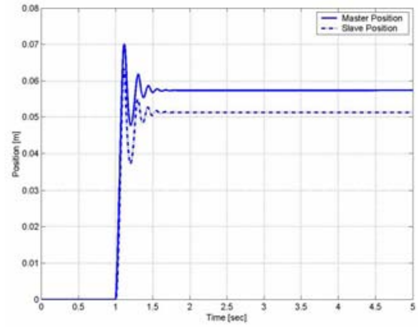
Fig. 7. Structure of the proposed hybrid stabilization approach

5. Simulation results

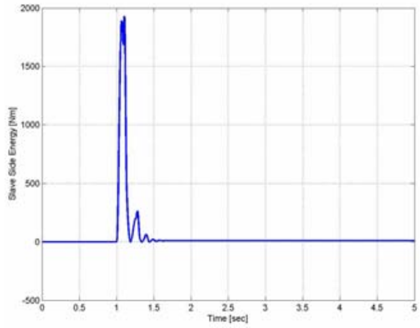
Figure 8 shows a simulation result when no time delay exists in communication channel. The parameters used in simulation given as

$$\begin{aligned} Z_m{=}0.7s, \quad C_m &= 16.8 + \frac{630}{s} \\ Z_s{=}0.7s, \quad C_s &= 50.4 + \frac{630}{s} \end{aligned} \tag{22}$$

As shown in Figure 8, the slave followed the master motion exactly and the monitored energy at environment satisfied the passivity condition. The position difference between master and slave at steady state was caused by the fact that slave contacted the virtual wall located at 5cm.
To show the effectiveness of the passivity controller when the master or slave was unstable, 30msec time delay was assumed to exist in the slave in the following simulation. The position response of master and slave and monitored energy at the slave are shown in Figure 9.
The energy monitored at the slave is negative, which violates the passivity condition, system is unstable and as a result master and slave robot oscillate severely.
Simulation result when the passivity controller is applied to the above situation is shown in Figure 10. We can find that the passivity controller stabilize the slave by consuming the generated energy.
Next simulation is to check whether wave variable method can stabilize the teleoperation system with time delay in communication channel. Communication time delay is assumed 50msec and the passivity controller is applied to the slave.
As shown in Figure 11, the position of master and slave oscillate and the passivity controller which is applied at slave cannot deal with the communication delay.

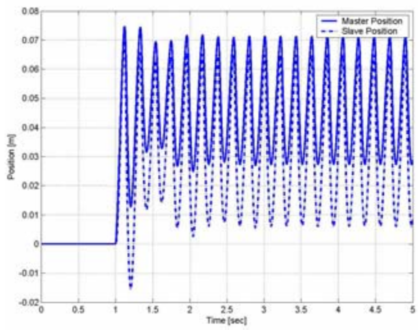


(a) position response

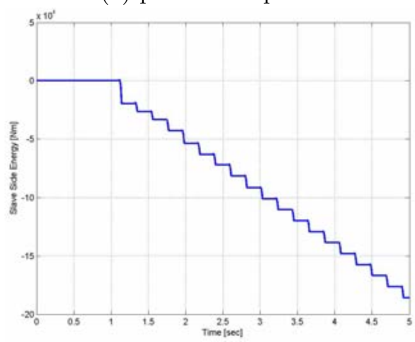


(b) energy monitored at the slave

Fig. 8. Position response and monitored energy for the case without time delay in the communication channel

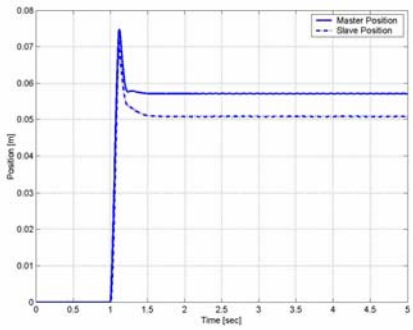


(a) position response

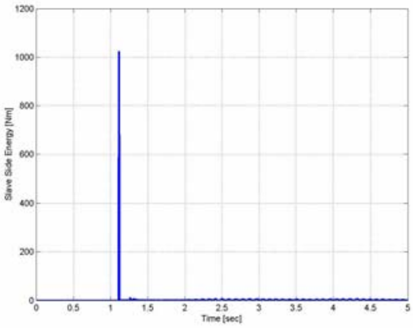


(b) energy monitored at the slave

Fig. 9. Position response and monitored energy for the case with 30msec delay in slave dynamics incorporating with environment

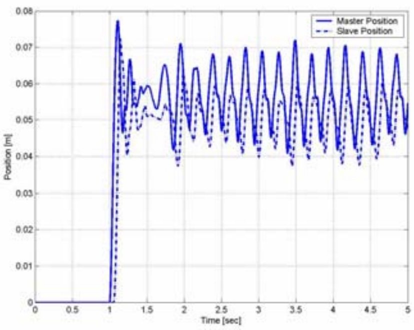


(a) position response

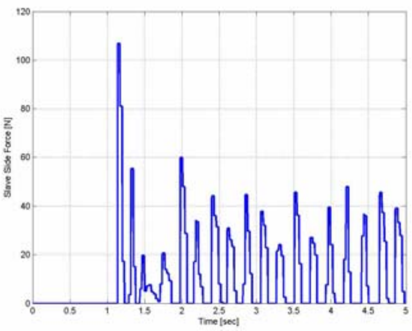


(b) energy monitored at the slave

Fig. 10. Position response and monitored energy for the case that the passivity controller is applied at the slave

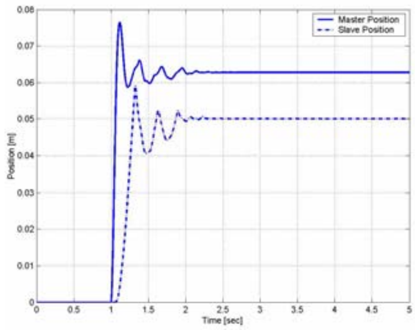


(a) position response

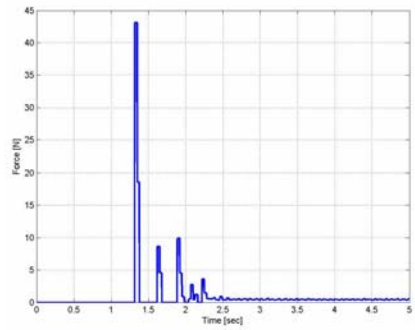


(b) force response of the slave

Fig. 11. Position response and force response for the case with 50msec time delay in the communication channel



(a) position response



(b) force response of the slave

Fig. 12. Position response and force response of slave when wave variables are applied

Figure 12 shows the simulation result when the proposed hybrid stabilization method is applied. It can be seen that the position responses of the master and slave are settled down, even 50msec time delay exists in communication channel.

6. Concluding Remarks

A hybrid stabilization technique involving both passivity controller and wave variables was proposed to stabilize the bilateral teleoperation system with fixed time delay. To stabilize a master or slave side, the passivity controller was applied and wave variables were additionally employed to guarantee the stability of the teleoperation system with communication delay. By use of two port network theory and the minimum value of transmitted impedance, the stability and performance of wave-based teleoperation system were also evaluated qualitatively.

References

[1] D. A. Lawrence, "Stability and Transparency in Bilateral Teleoperation," *IEEE Transactions on Robotics and Automation*, Vol. 9, No. 5, pp. 624–637, 1993.

[2] K. Zaad and S. E. Salcudean, "Analysis and Evaluation of Stability and Performance Robustness for Teleoperation Control Architectures," *IEEE International Conference on Robotics and Automation*, pp. 3107–3113, 2000.

[3] K. Zaad and S. E. Salcudean, "Transparency in Time-Delayed Systems and the Effect of Local Force Feedback for Transparent Teleoperation," *IEEE Transactions on*

Robotics and Automation, Vol. 18, No. 1, pp. 108–114, 2002.

[4] B. Hannaford and J. H. Ryu, "Time-Domain Passivity Control of Haptic Interfaces," *IEEE Transactions on Robotics and Automation*, Vol. 18, No. 1, pp. 1–10, 2002.

[5] J. H. Ryu, D. S. Kwon and B. Hannaford, "Stable Teleoperation with Time Domain Passivity Control," *IEEE International Conference on Robotics and Automation*, Vol. 3, pp. 3260–3265, 2002.

[6] G. Niemeyer and J. E. Slotine, "Using Wave Variables for System Analysis and Robot Control," *IEEE International Conference on Robotics and Automation*, pp. 1619–1625, 1997.

[7] G. Niemeyer and J. E. Slotine, "Designing Force Reflecting Teleoperators with Large Time Delays to Appear as Virtual Tools," *IEEE International Conference on Robotics and Automation*, pp. 2212–2218, 1997.

[8] J. E. Colgate and J. M. Brown, "Factors Affecting the Z-width of a Haptic Display," *IEEE International Conference on Robotics and Automation*, pp. 3205–3210, 1994.

[9] S. S. Haykin, "Active Network Theory," *Addison-Wesley*, 1970.