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*Research Article*

# Stability Problem of Wave Variable Based Bilateral Control: Influence of the Force Source Design

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The wave variable has been proposed to achieve robust stability against the time delay in bilateral control system. However, the influence of the force source on the overall system is still not clear. This paper analyzes this problem and proposes a supplement to the stability analysis for wave variable based bilateral control. Based on the scattering theory, it is pointed out that the design of force source decides the passivity of the two-port network of slave robot. This passivity influences the stability of overall system. Based on the characteristic equation and small gain theorem, it is clear that inappropriate designed force source in encoding the wave variable destroys the stability in the presence of time delay. A wave domain filter makes up for the broken stability. The principle of this reparation is explained in this paper. A reference is also provided by the analysis to design the parameter of the wave domain filter. Experiments prove the correctness and validity.

## 1. Introduction

Bilateral control is investigated for the haptic communication, which expands the range of human beings' activities to perform complex tasks such as telesurgery, space, and undersea exploration [1–3]. There are two robots, the master and the slave, in the system. An operator manipulates the master robot. Meanwhile, the slave one tracks the position of the master and contacts the environment. The force generated from the contact is transmitted to the master side, which makes the operator able to feel the reaction effect from the environment [4]. Therefore, bilateral control makes teleoperation more effective [5].

In the bilateral control system, robust stability is the most important requirement [6]. However, the time delay that exists in the communication channels between the master and the slave always weakens and even destroys the stability [7, 8]. In modern applications of the bilateral control, the networks based on various communication protocols are employed as the communication lines. The network-induced delays, which may be constant, time-varying, or stochastic, packet dropouts, and disorder become the major constraints. In fact, the packet dropouts can be treated in a similar way to network-induced delay because the last received packet (delayed signal) can be used if the packet dropouts occur [9, 10]. Besides, the disordered data can be reordered via buffers, which also turns into the problem of delay. In the situation of long distance or complex network, for example, the Internet, the network-induced delay is inevitable. For normal network control system, robust control algorithms, for example, the $H_\infty$ control, are discussed, which are very effective methods [11–13]. However, the feedback of a robot in the bilateral control system is the other robots, the human beings, and the environment, which means that the dynamics of such a system is more complex. Therefore, the delay of such a system must be specially considered.

To deal with the problem, many synthesis methods were investigated. For example, Natori et al. proposed the communication disturbance observer (CDOB) [14] and applied it in bilateral control system [15–17]. However, the performance of this method is weakened due to the mismatching of the model of slave robot. Besides, the transparency, that is, the index of the control performance, is not satisfying using this method [18]. The $H_\infty$ control and the adaption control were also used to design the system with time delay [19]. However, the stability is limited by the situation of environment. Besides

these researches, the wave variable is one of the famous and the important methods [20], because it provides the system robust stability against arbitrary time delay.

The systemized wave variable method was proposed based on the scattering theory [21]. Then, a more physically motivated reformulation led to the development of wave theory [22], which provides a framework for designing and analyzing bilateral control system. From the proposition of wave variable method to present, many improvements were investigated. A modified Smith predictor was utilized in the wave variable framework [23]. A flexible design and analysis tool has been provided for two-channel teleoperation systems [24]. To avoid the so-called "wave reflection" phenomenon, which leads to the oscillatory behavior of the robots, two remedies have been utilized. One is the impedance matching procedure [22] and the other is the low pass filter in the wave domain [25]. To improve the transparency of wave variable based bilateral control, Aziminejad et al. proposed the idea that force feedback can be improved by designing the force source in encoding the wave variable. Specifically, the design of kinesthetic force-based (KFB) wave variable [26] that was also called directly reflective force wave variable was proposed [27].

On the wave variable methods, past analyses only focused on the passivity of the communication channels; however, they did not consider the overall system, because they assumed that the human-master, slave-environment pairs are passive. Besides, in some works, for example, the KFB method, all past experimental results are obtained with the employment of the wave domain filter. And the cutoff frequency is very low. Then, the stability of the overall system is questionable with high cutoff frequency or without the wave domain filter. There is still no work to point out that what is the influence of designing the force source in encoding the wave variable on the robust stability against time delay. Then, there are following questions.

(Q1) Does the design of force source in encoding the wave variable influence the system stability?

(Q2) What is the effect of the wave domain filter on improving the stability? And how to design the cutoff frequency of such a filter?

This paper answers the above questions and gives useful supplement to the process of designing a bilateral control system. The paper is organized as follows. In Section 2, problem formulation is given. The original wave variable based control and the KFB wave variable method are introduced as two specific situations. In Section 3, the stability of overall system is analyzed. In Section 4, experimental results are illustrated to prove the analysis. Finally, it is concluded in Section 5.

## 2. Problem Formulation

In this section, the problem of time delayed bilateral control system is described via a two-port network model. Then, the control objective is given by a hybrid matrix. Secondly, the algorithm of wave variable encoder is introduced. Finally, the problem of practice design that this paper focuses on is described.

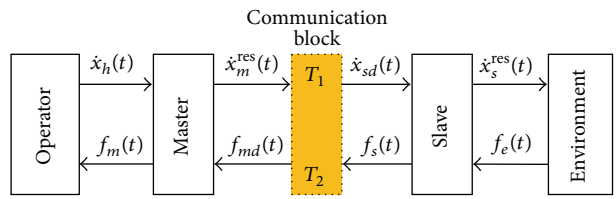



Figure 1: Two-port network model of the teleoperation system.

*2.1. Control Objective by Two-Port Network Model of Teleoperation.* The bilateral teleoperation system is depicted in Figure 1, where $\dot{x}_h(t)$, $\dot{x}_m^{\text{res}}(t)$, $\dot{x}_{sd}(t)$, $\dot{x}_s(t)$, $f_m(t)$, $f_{md}(t)$, $f_s(t)$ and $f_e(t)$, denote the human velocity, the master velocity response, the desired velocity for slave, the slave velocity response, the master force, the desired master force, the slave force, and environment force, respectively. Here, $f_h(t) = -f_m(t)$ means the human force, according to the law of action and reaction.

Such a system can be viewed as a series' cascade of one-port and two-port networks with an effort-flow pair, which is the force-velocity pair for teleoperation robots, being exchanged at each port. The relationship between the forces and velocities at all ports can be represented by the hybrid matrix $H$ as follows:

$$\begin{bmatrix} f_1(t) \\ -\dot{x}_2(t) \end{bmatrix} = \underbrace{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}}_{H} \begin{bmatrix} \dot{x}_1(t) \\ f_2(t) \end{bmatrix}, \tag{1}$$

where the $f_1(t)$, $\dot{x}_1(t)$ pair and the $f_2(t)$, $\dot{x}_2(t)$ pair mean the force source and the velocity flow in each side of a two-port network, respectively [21].

The hybrid matrix describes the kinesthetic feedback between the input and output of a two-port network model. For the robot system, the hybrid matrix can be also used to describe the relationship between environment and human operator by choosing $f_1(t) = f_h(t)$, $f_2(t) = -f_e(t)$, $\dot{x}_1(t) = \dot{x}_m^{\text{res}}(t)$, and $\dot{x}_2(t) = \dot{x}_s^{\text{res}}(t)$.

Then, the control objective is to make $h_{11} = 0$, $h_{12} = 1$, $h_{21} = -1$, and $h_{22} = 0$ when there is no time delay, which means the motion tracking and action-reaction law of the forces as follows:

$$\dot{x}_m^{\text{res}}(t) - \dot{x}_s^{\text{res}}(t) = 0, \tag{2}$$

$$f_h(t) + f_e(t) = 0. \tag{3}$$

With the same initial states, $\dot{x}_m^{\text{res}}(0) = \dot{x}_s^{\text{res}}(0)$, (2) also means $x_m^{\text{res}}(t) - x_s^{\text{res}}(t) = 0$.

*2.2. Wave Variable.* According to the passivity theory, if the master and the slave two-port networks are both passive, the passivity of the communication channel means the system robust stability against arbitrary time delay.

The wave variable approach in bilateral control system stems from scattering theory and theoretically guarantees

stability under arbitrary time delay [24]. The wave variable encoding is described in Figure 2. Instead of directly transmitting the power signals $\dot{x}_m^{\text{res}}(t)$ and $f_s(t)$, the signals are encoded to the wave variables $u_m(t)$ and $v_s(t)$, which are given as follows:

$$u_m(t) = \frac{1}{\sqrt{2b}}\left[b\dot{x}_m^{\text{res}}(t) + f_{md}(t)\right],$$
$$v_s(t) = \frac{1}{\sqrt{2b}}\left[b\dot{x}_{sd}(t) - f_s(t)\right]. \tag{4}$$

These formulations are identical to the scattering formulation, with the only parameter $b$ being the characteristic impedance of the transmission. The transmitted wave variables over the communication channel with time delay are given by the following:

$$u_s(t) = u_m(t - T_1), \qquad v_m(t) = v_s(t - T_2). \tag{5}$$

The reference signals on both sides of the channel are derived as the inverse transformation of the wave variables:

$$\begin{aligned} f_{md}(t) &= b\dot{x}_m^{\text{res}}(t) - \sqrt{2b}v_m(t) \\ &= f_s(t - T_2) + b\left[\dot{x}_m^{\text{res}}(t) - \dot{x}_{sd}(t - T_2)\right], \\ \dot{x}_{sd}(t) &= \frac{1}{b}\left[\sqrt{2b}u_s(t) - f_s(t)\right] \\ &= \dot{x}_m^{\text{res}}(t - T_1) + \frac{1}{b}\left[f_{md}(t - T_1) - f_s(t)\right]. \end{aligned} \tag{6}$$

With the wave variable encoding, the passivity of the communication block can be verified in time domain with zero initial energy storage. The passivity is confirmed if the output energy $E(t)$ of the communication block (7) is less than or equal to the input energy for all time:

$$E(t) = \int_0^t \left[\dot{x}_m^{\text{res}}(\tau) f_{md}(\tau) - \dot{x}_{sd}(\tau) f_s(\tau)\right] d\tau. \tag{7}$$

Obviously, the wave variable method ensures this relationship reasonable as follows:

$$\begin{aligned} E(t) &= \frac{1}{2}\int_0^t \left(u_m^T u_m - v_m^T v_m - u_s^T u_s + v_s^T v_s\right) d\tau \\ &= \frac{1}{2}\int_{t-T_1}^t u_m^T u_m d\tau + \frac{1}{2}\int_{t-T_2}^t v_s^T v_s d\tau \geq 0. \end{aligned} \tag{8}$$

In some past works, the fist-order low pass filters are introduced into the wave transmission to reduce the reflection of signals and improve the performance of the system as illustrated in Figure 2, which is called wave domain filter. However, the important effect of the wave domain filter on stability is not clear. Furthermore, the design principle of such filters is also not clear.

### 2.3. Wave Variable Based Applications

*2.3.1. Original Wave Variable Based System.* For the application of original wave variable, the force source $f_s(t)$ that

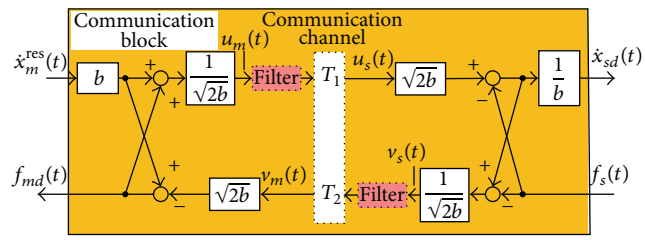



Figure 2: The arithmetic of wave variable.

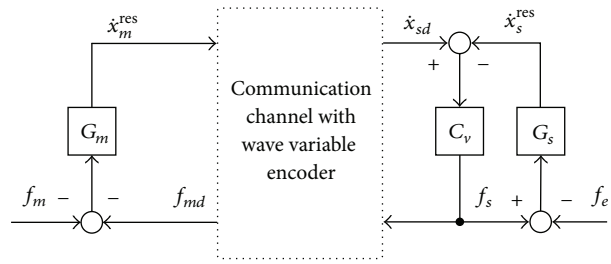



Figure 3: Original wave variable application.

participates in the wave variable encoding is designed as follows:

$$f_s(t) = K_v\left[\dot{x}_{sd}(t) - \dot{x}_s^{\text{res}}(t)\right] + K_p\int_0^t \left[\dot{x}_{sd}(\tau) - \dot{x}_s^{\text{res}}(\tau)\right] d\tau. \tag{9}$$

In this situation, the $f_s(t)$ is the control effect generated by the controller in the slave robot. $K_v$ denotes the velocity gain and $K_p$ denotes the position gain. The structure of this application method is described in Figure 3. Here, $C_v$ is the velocity controller, which is a PI control as $C_v = K_p/s + K_v$ in Laplace domain. $G_m$ and $G_s$ are the transfer functions of the master and the slave, respectively.

*2.3.2. Kinesthetic Force-Based (KFB) Wave Variable.* For this application approach, the force effect in the wave variable encoder is directly designed as the environment force, which realizes the direct force reflection as follows [26]:

$$f_s(t) = f_e(t). \tag{10}$$

The structure of this KFB method is described in Figure 4. The difference between the two methods is the design of the force source in wave variable encoding. Although this design does not influence the passivity of communication block with wave transmission, it influences the passivity of the slave part and also the robust stability of the overall system. This problem is analyzed in the next section.

## 3. Passivity and Stability

This section gives out the relationship between the human force and master motion and the relationship between the environment force and slave motion by human and environment impedances. Then, the stability of both the original and

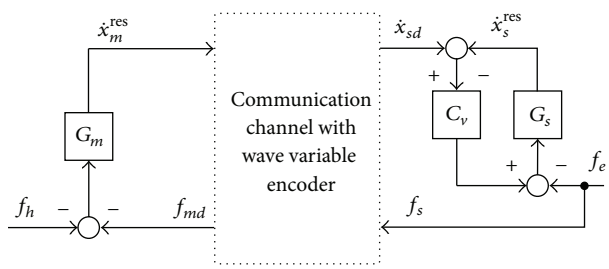



Figure 4: Kinesthetic force-based wave variable.

KFB wave variable applications is analyzed. It is pointed out that the latter one is not stable for some situations of high frequency and hard environment.

*3.1. Relationship between Passivity and Force Source Design.* The passivity of a two-port network can be judged by the scattering matrix $\mathbf{S}(s)$ that is defined as

$$\mathbf{S}(s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} [\mathbf{H}(s) - I] [\mathbf{H}(s) + I]^{-1}, \tag{11}$$

where $\mathbf{H}(s)$ is the Laplace transformation of the hybrid matrix in (1). There is following theorem.

**Theorem 1** (see [21]). *A system is passive if and only if its scattering matrix satisfies the following condition:*

$$\sup_{\forall\omega>0} \lambda^{1/2} [\mathbf{S}^*(\omega j) \mathbf{S}(\omega j)] \leq 1. \tag{12}$$

The relationship between the passivity and the design of force source is investigated using this theorem.

In the original wave variable, the force source that participates in encoding the wave variable is designed as the control force of the slave robot. The two-port network of the slave robot is shown as Figure 5(a). According to this figure, the hybrid matrix in frequency domain $\mathbf{H}(s)$ is calculated as follows:

$$\mathbf{H}(s) = \begin{bmatrix} \dfrac{C_v(s)}{1 + C_v(s) G_s(s)} & \dfrac{C_v(s) G(s)}{1 + C_v(s) G_s(s)} \\ -\dfrac{C_v(s) G(s)}{1 + C_v(s) G_s(s)} & \dfrac{s}{1 + C_v(s) G_s(s)} \end{bmatrix}. \tag{13}$$

In the situation of KFB wave variable, the force source is designed as the environment force as shown in Figure 5(b). Correspondingly, the hybrid matrix is calculated as follows:

$$\mathbf{H}(s) = \begin{bmatrix} 0 & 1 \\ -\dfrac{C_v(s) G(s)}{1 + C_v(s) G_s(s)} & \dfrac{s}{1 + C_v(s) G_s(s)} \end{bmatrix}. \tag{14}$$

Then, the passivity can be investigated by substituting the hybrid matrices into (11) and calculating the eigenvalue in (12) for the passivity judgement of specific design.

In practice, velocity controller $C_v(s)$ is usually designed as a PI controller. For linear motor driven 1-DOF (degree-of-freedom) robot, the transfer function of the slave robot $G_s(s)$ is a nominal model that is an integration element as $G_s(s) = 1/(M_s s)$, where $M_s$ is the inertial mass. In practice, the dynamics can be guaranteed by using disturbance observer (DOB) based robust internal loop control [28, 29]. Therefore, the nominal model of the robot is available in the analysis. For the robot used in the experiment of this paper, the parameter $M_s$ is unity. The left part of the passivity condition, the inequality (12), is calculated and plotted as shown in Figure 6 with different gains of the controller $C_v(s)$.

Obviously, the passivity condition (12) is satisfied in the original wave variable design. However, the design of the KFB wave variable does not guarantee the passivity of the two-port model of the slave robot. This discloses that the force source cannot be designed arbitrarily. The broken passivity of the slave two-port model can not guarantee the robust stability of the whole system under communication delay between the master and the slave.

*3.2. Stability of Overall System under Time Delay*

*3.2.1. Relationship between Force and Motion.* To analyze the stability of the whole system, the relationship between force and motion is discussed first of all. In a human-machine interaction-like system, the bilateral teleoperation, the human force, and the environment force relate to the motion of the master and the slave robots through the human and the environment impedances. Considering the spring-damping impedance models [30], this relationship is described as follows:

$$\begin{aligned} F_h &= K_h \left(X_m^{res} - X_h^{des}\right) + D_h s X_m^{res} = Z_h X_m^{res} - K_h X_h^{des}, \\ F_e &= K_e \left(X_s^{res} - X_e^{int}\right) + D_e s X_s^{res} = Z_e X_s^{res} - K_e X_e^{int}, \end{aligned} \tag{15}$$

where $K_h$, $D_h$, $K_e$, and $D_e$ are human stiffness, human damping, environment stiffness, and environment damping, respectively. $F_h$, $F_e$, $X_m^{res}$, and $X_s^{res}$ are the Laplace transformations of $f_h$, $f_e$, $x_m^{res}$, and $x_s^{res}$, respectively. $X_h^{des}$ is the desired position by human. $X_e^{int}$ is the initial position of environment. $Z_h = K_h + D_h s$ and $Z_e = K_e + D_e s$ denote the human and environment impedances, respectively.

Without losing generality, $X_e^{int}$ can be assumed as zero. Then, the only input value is $X_h^{des}$, and the outputs are $X_m^{res}$ and $X_s^{res}$ for the bilateral teleoperation system. Also without losing generality, the input $X_h^{des}$ can be seen as zero when the stability is considered for the control system itself.

*3.2.2. The Situation of Original Wave Variable.* The wave inverse transmission (6) can be rewritten in the frequency domain expressions as follows:

$$\begin{aligned} F_{md} &= F_s e^{-T_2 s} Q(s) + b\left(s X_m^{res} - s X_{sd} e^{-T_2 s} Q(s)\right), \\ s X_{sd} &= s X_m^{res} e^{-T_1 s} Q(s) + \frac{1}{b}\left(F_{md} e^{-T_1 s} Q(s) - F_s\right). \end{aligned} \tag{16}$$

Here, $Q(s)$ is the wave domain filter. In the situation of the original wave variable method, there is no wave domain filter

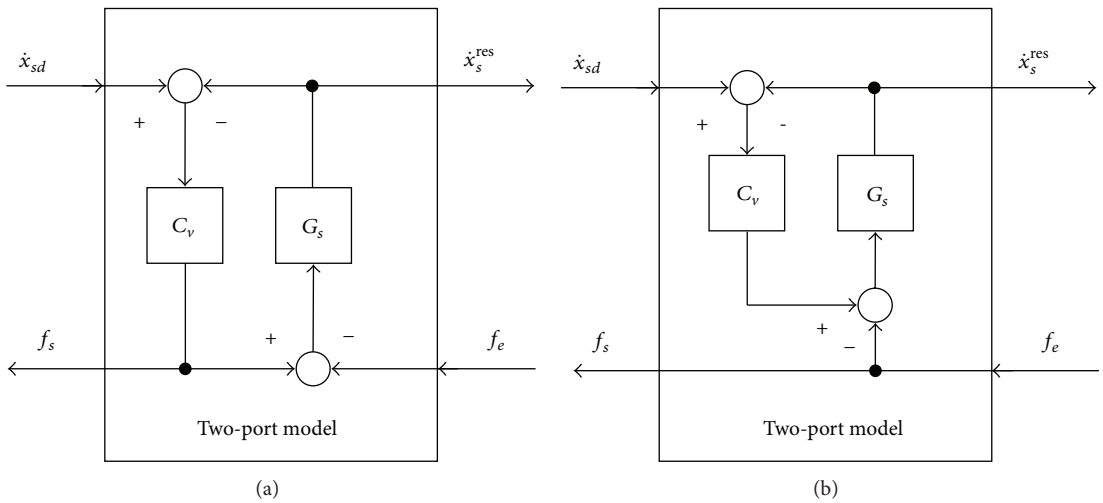



Figure 5: The two-port model of two different designs: (a) original wave variable; (b) KFB wave variable.

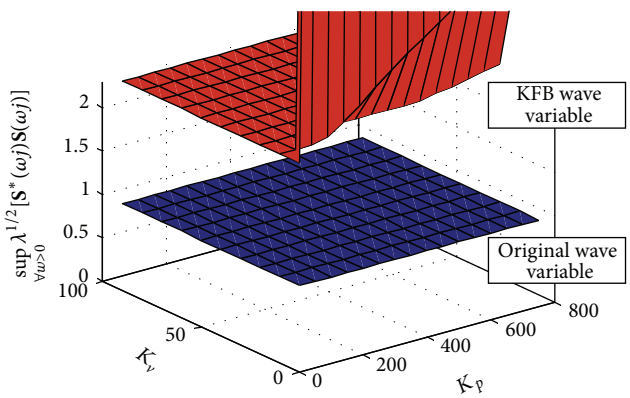



Figure 6: The passivity judgement.

in the sense of $Q(s) = 1$. Besides, the control relationship of the following obtained according to Figure 3:

$$G_m^{-1} s X_m^{res} = -F_h - F_{md},$$
$$G_s^{-1} s X_s^{res} = F_s - F_e. \tag{17}$$

Considering the dynamics of the human operator and the environment, the characteristic equation of the overall system can be calculated as (18) considering $Q(s) = 1$ according to (16) and (17):

$$\left(G_m^{-1}s + bs + Z_h\right)\left(\frac{C_v + b}{b}G_s^{-1}s + sC_v + \frac{C_v + b}{b}Z_e\right) - \left(\frac{bs - G_m^{-1}s}{b}C_v - \frac{C_v}{b}Z_h\right) \times \left(bs + \frac{b - C_v}{C_v}G_s^{-1}s - \frac{C_v - b}{C_v}Z_e\right)e^{-(T_1+T_2)s} = 0. \tag{18}$$

In fact, (18) is also the characteristic equation of the unit feedback system of $S_1(s)S_2(s)e^{-(T_1+T_2)s}$. $S_1(s)$ and $S_2(s)$ are described as follows:

$$S_1(s) = \left(\frac{bs - G_m^{-1}s}{b}C_v - \frac{C_v}{b}Z_h\right) \times \left(bs + \frac{b - C_v}{C_v}G_s^{-1}s - \frac{C_v - b}{C_v}Z_e\right),$$
$$S_2(s) = \left[\left(G_m^{-1}s + bs + Z_h\right) \times \left(\frac{C_v + b}{b}G_s^{-1}s + sC_v + \frac{C_v + b}{b}Z_e\right)\right]^{-1}. \tag{19}$$

Therefore, the stability of the system in Figure 3 is equivalent to the unit feedback system of $S_1(s)S_2(s)e^{-(T_1+T_2)s}$.

If $S_1(s)$ and $S_2(s)$ are $L_2$ stable, according to the small gain theorem, to make the system stable under arbitrary time delay in the signal transmission, which is the target of wave variable method, the following equation should be satisfied:

$$\left\|S_1(\omega j)S_2(\omega j)e^{-(T_1+T_2)\omega j}\right\|_\infty < 1. \tag{20}$$

By substituting (19) into (20), to make the system stable under any time delay, the following equation should be satisfied:

$$\sup_{\forall\omega>0}\left|\frac{(G_m^{-1}s - bs + Z_h)[\alpha G_s^{-1}s - bsC_v + \alpha Z_e]}{(G_m^{-1}s + bs + Z_h)[\beta G_s^{-1}s + bsC_v + \beta Z_e]}\right|_{s=j\omega} < 1, \tag{21}$$

where $\alpha = C_v - b$ and $\beta = C_v + b$.

The dynamics of the master robot is the same as the slave one, which is $G_m = 1/(M_m s)$, where $M_m$ is the inertial mass of the master robot. In order to verify the stability of

such a system, quantitative analysis can be implemented. The employed parameters in the quantitative analysis are shown in Table 1.

The situation of great environment stiffness, $K_e = 10^6$ N/m, denotes that the environment is a hard object and $K_e = 10^{-6}$ depicts the free motion. The parameters are designed for the experimental devices in Section 4. Such designed $K_p$ and $K_v$ make the control of slave robot have the unity damping to avoid oscillation. The wave impedance $b$ is designed as a great value to reduce the oscillation of system responses [31]. In the quantitative analysis, it is assumed that the human operator does not apply any effect on the system to consider the stability of only the controlled robots. The values of damping of the environment and the human operator simulate the viscous friction in both the two robots. According to Figure 7, the values of $|S_1||S_2|$ are less than one. The system is stable for either free motion or hard contact under any time delay in whole frequency domain. According to the above subsection, the design of the force source in the wave variable guarantees the passivity of the two-port model of slave. The passivity of the overall system is then guaranteed. The system performs strong robustness against the time delay in the signal transmission.

*3.2.3. The Situation of KFB Wave Variable.* Following the same line of above analysis, the KFB wave variable method is also analyzed, which has different design on the force source.

According to (20), condition (22) should be satisfied to make the system have robustness against any time delay:

$$\sup_{\forall\omega>0}\left|\frac{(G_m^{-1}-bs+Z_h)[bsG_s^{-1}+bsC_v+(bs-C_v)Z_e]}{(G_m^{-1}+bs+Z_h)[bsG_s^{-1}+bsC_v+(bs+C_v)Z_e]}\right|_{s=j\omega}<1. \tag{22}$$

The quantitative analysis is also implemented. With the same parameters in Table 1, the values of $|S_1||S_2|$ are shown in Figure 8. According to the result, (22) is not satisfied in the situation of hard contact. Because the passivity is broken in the two-port model of the slave, the stability of overall system is also not guaranteed in the presence of time delay. It is proved that the design of force source influences the robust stability of the overall system. The design of the force source should make any two-port model be passive in the system.

In fact, direct application of the KFB wave variable approach was not implemented in past works. There always exists a wave domain filter in the transmission line as shown in Figure 2. However, it is not clear enough what is the most important effect and how to design the wave domain filter. With the filter, the values of $|S_1||S_2|$ are calculated as shown in Figure 9. The first-order filter $g/(s+g)$ is employed. The cutoff frequency $g$ is set as 550.0 rad/s and 31.4 rad/s, respectively. According to the results, the wave domain filter reduces the values of $|S_1||S_2|$. In practice, the wave domain filter strengthens the robust stability of overall system in the presence of time delay. If the design of force source breaks the stability of overall system, wave domain filter can make up for this problem only when the cutoff frequency is appropriate. The analysis process in this paper is quite necessary in the design of a wave variable based bilateral control system. The analysis does not only show the stability of overall system, but also provides a reference to design the system parameters for some newly proposed wave variable based system.

Table 1: Parameters for stability analysis.

| Parameters | Mark | Value |
|---|---|---|
| Master mass | $M_m$ | 1.0 (kg) |
| Slave mass | $M_S$ | 1.0 (kg) |
| Position gain | $K_p$ | 400.0 ($s^{-2}$) |
| Velocity gain | $K_v$ | 40.0 ($s^{-1}$) |
| Wave impedance | $b$ | 50.0 |
| Environment damping | $D_e$ | 2.0 (Nm/s) |
| Human damping | $D_h$ | 2.0 (Nm/s) |
| Human stiffness | $K_h$ | $10^{-6}$ (N/m) |

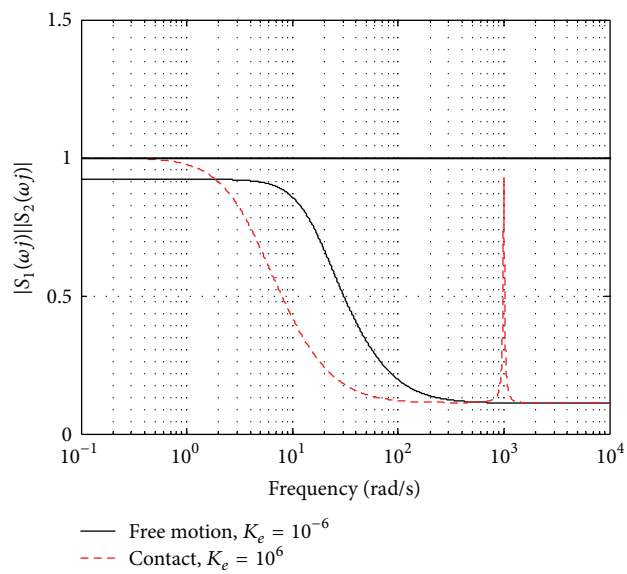



Figure 7: The stability of the overall system with the original wave variable.

## 4. Experiments

The experiments are implemented to prove above analyses in this paper. In Section 4.1, the experimental setup is illustrated. Then, the experimental results are shown in Section 4.2.

*4.1. Experimental Setup.* In the experiments, two single DOF robots are utilized as the master and the slave, respectively. The structure and devices of experimental system are shown in Figure 10. The original wave variable based system and the KFB wave variable method are both implemented by programming in Linux RTAI. Wide bandwidth sensorless force measurement is realized by the reaction force observer (RFOB) [32]. An aluminium cube is used as a hard environment that is put in the side of slave.

An internal loop robust controller, the disturbance observer, is employed to compensate model uncertainties and guarantee that the dynamics of the robots performs as the

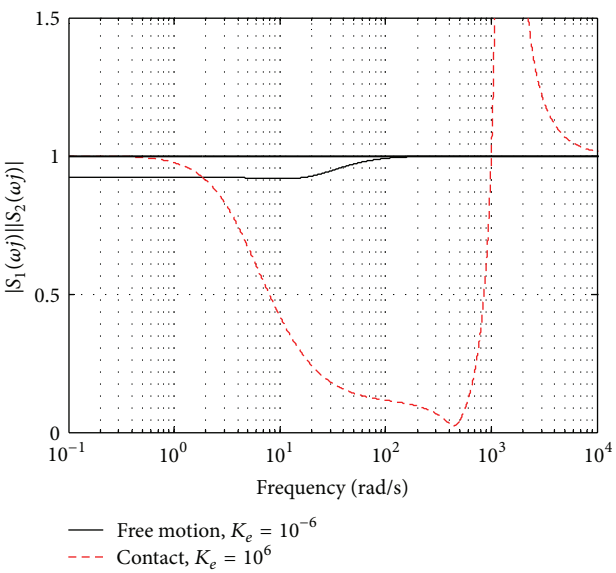



Figure 8: The stability of the overall system with the KFB wave variable.

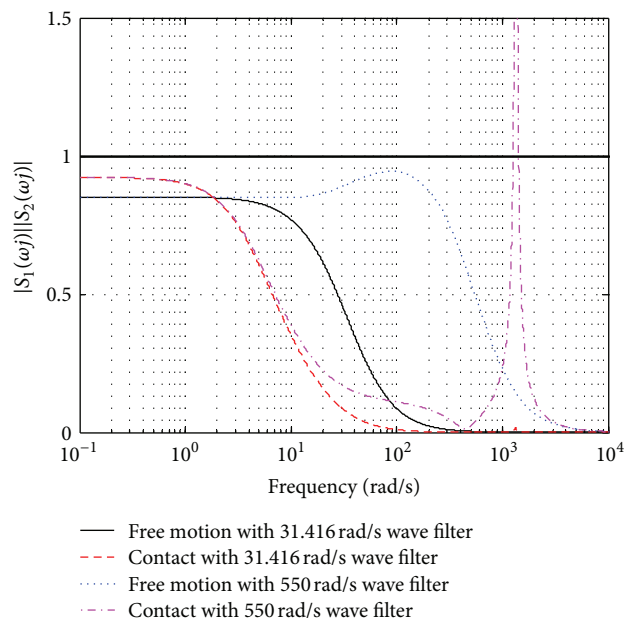



Figure 9: The stability of the overall system with the KFB wave variable and wave domain filters.

one in the analysis [33]. The structure of the internal loop is illustrated in Figure 11. The equivalent disturbance that contains the external disturbances and dynamics uncertainties are compensated within the bandwidth of the DOB. $g_{\text{dis}}$ is the cutoff frequency. Greater $g_{\text{dis}}$ means stronger robustness against the equivalent disturbance. In practice, major influence of the disturbances and uncertainties is in the low frequency domain. Therefore, with the DOB, the dynamics of the robot is guaranteed to be similar to the model that is used in the analysis. Then, the wave variable based approach is verified with little influence of other factors.

The experiments are composed of 4 cases. Case 1 is the situation of original wave variable based control. Case 2 is the situation of KFB wave variable based control without the wave domain filter. Case 3 and Case 4 are the KFB wave variable based system with the wave domain filter. The cutoff frequency of the filter is set highly in Case 3 as 550 rad/s and lowly in Case 4 as 31.416 rad/s. All the results are plotted into figures with $x_m^{\text{res}}$, $x_s^{\text{res}}$, $f_h$, and $-f_e$. The experimental parameters are shown in Table 2. Here, the cutoff frequencies of RFOB and DOB are smaller in Case 2 to extend the working time because the system is seriously instable in this case according to the above analysis.

*4.2. Experimental Results.* Figure 12 illustrates the position and force responses of the original wave variable based control system that corresponds to Case 1. It can be found that the system is stable for both free motion and contact operation even with the round-trip time delay of 1000 ms.

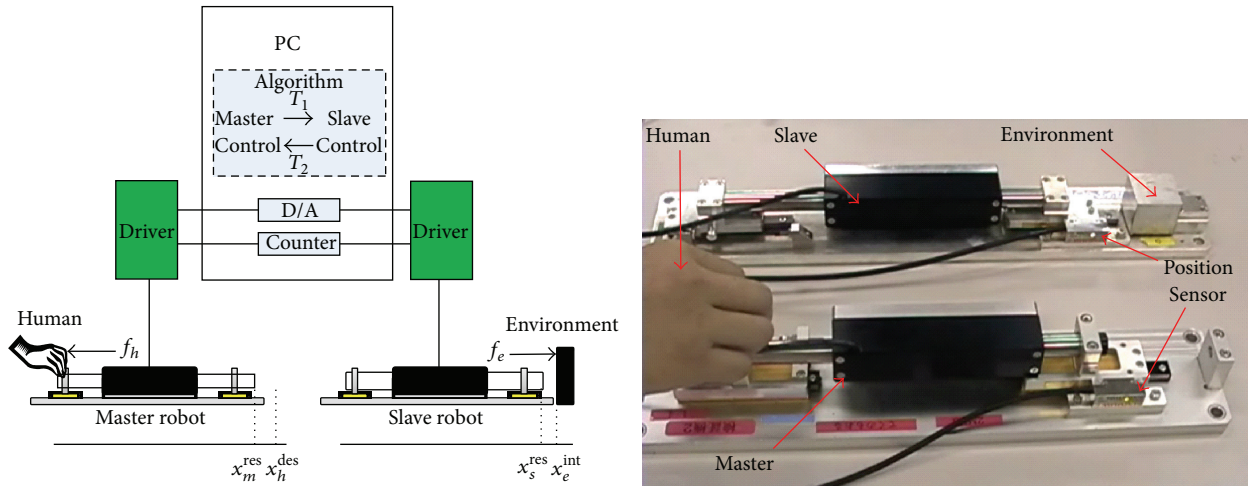
Figure 13 illustrates the results of KFB wave variable based control system that corresponds to Case 2. Without the wave domain filter, the system is unstable, especially when contact occurs. The force responses are obviously emanative. At about 3.3 s, the system stops for protection. This is in agreement with the theoretical analysis.

Table 2: Experimental parameters.

| Parameters | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| Wave impedance $b$ | 50.0 | 50.0 | 50.0 | 50.0 |
| Position gain $K_p$ ($s^{-2}$) | 400.0 | 400.0 | 400.0 | 400.0 |
| Velocity gain $K_v$ ($s^{-2}$) | 40.0 | 40.0 | 40.0 | 40.0 |
| Cutoff frequency of DOB (rad/s) | 500.0 | 50.0 | 500.0 | 500.0 |
| Cutoff frequency of RFOB (rad/s) | 500.0 | 50.0 | 500.0 | 500.0 |
| Cutoff frequency of wave filter (rad/s) | — | — | 550.0 | 31.416 |
| Time delay (ms) | $T_1 = T_2 =$ 500 | $T_1 = T_2 =$ 500 | $T_1 = T_2 =$ 500 | $T_1 = T_2 =$ 500 |

Figure 14 illustrates the results of KFB wave variable approach with the wave domain filter that corresponds to Case 3. Although there is the wave filter, the system is also unstable, especially when contact occurs according to Figure 8. The theoretical analysis shows that the system stability is not guaranteed if the cutoff frequency of this filter is not appropriately designed. The experimental results prove the analysis.

Finally, the results of Case 4 are shown in Figure 15. The system is stable when the cutoff frequency of the wave domain filter is small enough for the KFB based control. Compared with the original wave variable method, the design of KFB wave variable deduces the oscillation of the slave robot in the




(a) Structure of experimental setup

(b) The experimental setup

Figure 10: The experimental setup.

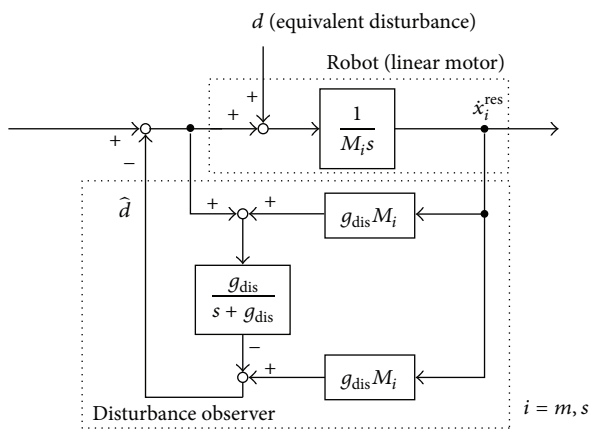
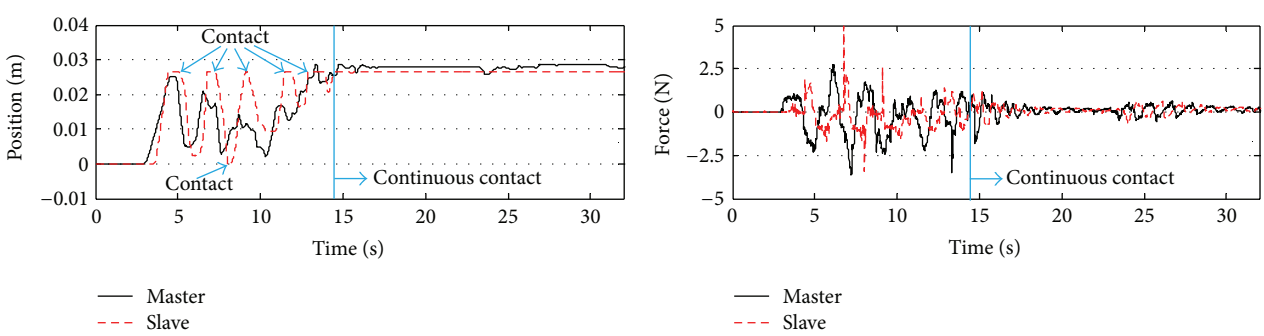



Figure 11: The structure of DOB based internal loop robust control.




(a)

(b)

Figure 12: Experimental results of original wave variable application method.

state of free motion. The experimental results illustrated the place of improvement by the KFB wave variable and proved the correctness of the analysis process in this paper.

According to the analysis and the experiment, the following results are proved. Firstly, the design of force source in wave variable influences the stability of overall system. Secondly, the analysis process proposed in this paper helps researchers to judge the robust stability of bilateral system against time delay. If the system is unstable, the wave domain filters strengthen the stability. The proposed analysis process

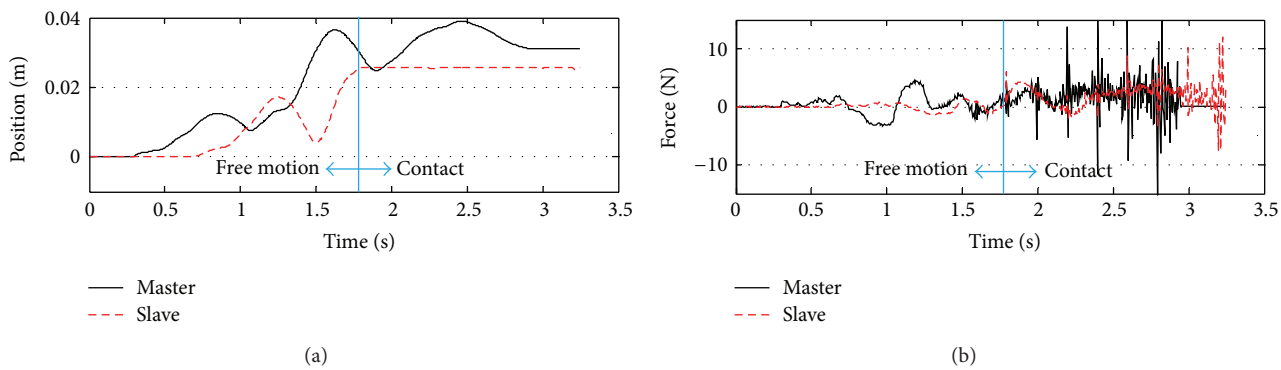



Figure 13: Experimental results of KFB wave variable method without wave domain filter.

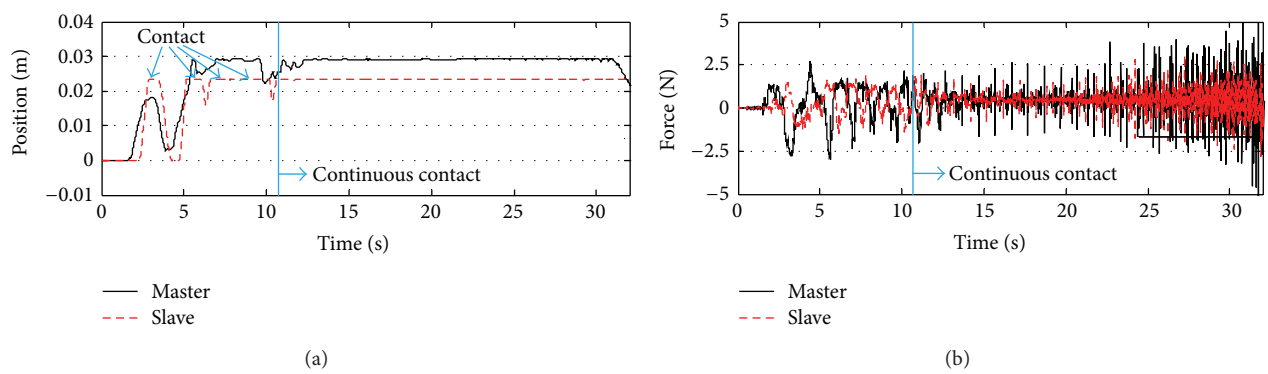



Figure 14: Experimental results of KFB wave variable method with wave domain filter of 550 rad/s cutoff frequency.

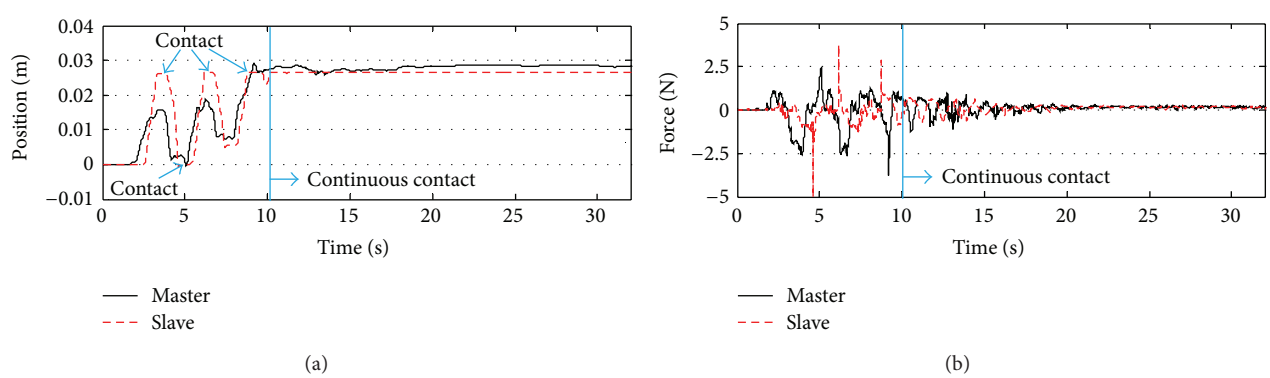



Figure 15: Experimental results of KFB wave variable method with wave domain filter of 31.416 rad/s cutoff frequency.

is useful in the design of the cutoff frequency of the wave domain filters.

## 5. Conclusion

This paper focused on the problem of stability caused by the design of the force source in encoding the wave variable in the delayed bilateral control system. The influence of the force source design is analyzed for the original wave variable based system and the kinesthetic force-based wave variable method specifically.

It is pointed that the design of the force source may destroy the stability of the two-port network in slave and then break the robust stability of the control system. The overall bilateral control structure is considered including the human and the environment impedances in frequency domain. Analysis illustrates that appropriately designed wave variable based system has robust stability against any time delay. However, this stability is broken if the design of the force source is not appropriate in encoding the wave variable. In the unstable situation, adding a wave domain filter improves the robust stability. The analysis in this paper

clearly illustrates the reason and provides a reference for the design of the wave domain filter.

Experimental results in practical system prove the analyses. This paper is helpful to understand the remarkable problem on the design of the force source in wave variable based bilateral control.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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