Proceedings of the 7th Asian Control Conference,
Hong Kong, China, August 27-29, 2009

Network Interpretation of a Human-Machine Interaction System

Hon Fai Lau and Shigeru Yamamoto

***Abstract*— This paper discusses a two-port network interpretation of a human-machine interaction system. Two-port systems are utilized widely in the bilateral teleoperations area, however, most of this large class of interaction control systems consists only of a human and a machine. We will show this human-machine system can be represented in a two-port network system. For the case where there are no force sensors available from the machine when the human is performing tasks, we define a virtual feedback force and virtual input energy in order to formulate a network representation. Stability of the human-machine system is analyzed by utilizing the time domain passivity, and the impedance and the scattering transfer functions with a state space realization in a two-port network. An inverted pendulum system is used to depict a human-machine system for the network representation in the experiment. In the system, the PD controller and the washout controller which are proposed to achieve a superior performance under the stability constraints are examined. Finally, we show the stability constraints can be related to the performance of the inverted pendulum system by monitoring the energy at each port and the maximum singular values of the scattering representation of the network systems in the experiment.**

I. INTRODUCTION

Human-machine interaction systems are coming into wider use today. Before the world can move to a high degree of robotic control, human-robot or human-machine systems that perform tasks cooperatively will play an important role. Currently, humans tend not to rely on robots or automation applications completely for tasks which require high precision. Human-machine interaction systems represent a control level intermediate between humans or robots performing tasks individually.

In many interaction control systems, robots are designed to work with humans cooperatively. The role of robots is to imitate human characteristics in completing tasks. In [1], an impedance control has been developed to determine a manipulator's characteristic variables, damping and stiffness, for cooperative pushing and pulling motions with a human. Rahman, Ikeura and Mizutani characterized various damping and stiffness factors as dependent on time in the logical flow method to characterize the linear motor. However, they focused on performance using only fixed trajectories and without considering any environmental factors.

This work was partially supported by Japan Society for the Promotion Science, Grant-in-Aid for Challenging Exploratory Research (No. 21656107)

H.F. Lau is with Graduate School of Natural Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa, 920-1192 JAPAN. ericlau@moccos.ec.t.kanazawa-u.ac.jp

S. Yamamoto is with Faculty of Electrical and Computer Engineering, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa, 920-1192 JAPAN. shigeru@t.kanazawa-u.ac.jp

Although performance is significant for any interactive situation, stability of the human-machine system with the environment is also paramount. A coupled stability was introduced by Colgate and Hogan [2], [3]. Their control structure consists of three separate systems: controller, active system and state dependent control which is viewed as a controlled network, and a passive environment. They compared several strategies in designing a stable interactive system coupling with passive environments, such as using positive real functions, Nyquist plots, root loci, and Routh stability.

A typical example of a human-machine interaction system in wide use now is bilateral teleoperation which is an interactive control between humans and robots and which consists of master and slave sub-robots. In [4], Hokayem and Spong investigated different approaches to represent a two-port network system in passive based teleoperation. Energy is exchanged inside the interconnection between systems, and the energy passivity is a significant factor in relation to the entire network stability which is also discussed by Ryu, Kwon and Hannaford [5] in the time domain. Matiakis, Hirche and Buss [6], [7] investigated scattering transformations in a networked control system in which the plant and the controller are separated through the communication network when delay is occurred.

In this paper, we extend the notion of passivity, impedance and scattering representations in a human-machine network system with the washout controller that was recently introduced by Takimoto, Yamamoto and Oku [8], [9].

II. REVIEW OF NETWORK

The advantage of using a network approach is to be able to analyze the system stability by checking its passivity. First, it is essential to define the flow and effort at each port. When the energy flowing into the network is greater than the energy flowing out, the network is defined as passive or having positive realness of linear systems. On the other hand, when the network is generating energy, the system becomes active in which case the system is not stable.

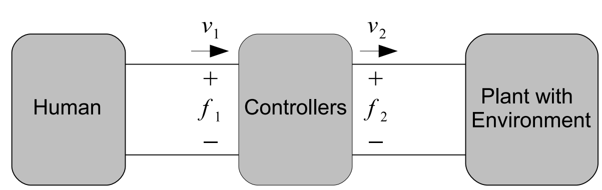

Fig. 1. Two-port network.

978-89-956056-9-1/09/©2009 ACA

In a two-port network system illustrated in Fig. 1, signals with flows and efforts correspond to velocities (currents) and forces (voltages) in mechanical systems (in electric circuits).

Impedance representation which can relate forces to velocities of the two-port network in Fig. 1 can be shown as

$$f = Zv \tag{1}$$

where

$$f = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix},\ v = \begin{bmatrix} v_1 \\ -v_2 \end{bmatrix},\ Z = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix}.$$

To be consistent in the motion of flows between the electrical and mechanical systems, we noted the negative sign of v_2. Nevertheless, the impedance transform is required to either short or open the other port.

A scattering representation is another method to illustrate the network. This can be done by utilizing scattering variables which consist only of the effort-flow pair at each port. Hence, we define the incident waves a_i and reflected waves b_i by

$$a_i = \frac{1}{2}(f_i + v_i), \qquad b_i = \frac{1}{2}(f_i - v_i). \tag{2}$$

Then, we can rewrite (1) as

$$b = Sa \tag{3}$$

where

$$b = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix},\ a = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix},\ S = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}.$$

Furthermore, we can introduce a wave variables representation which is a conceptually similar formulation to the scattering representation if we define wave variables, $\tilde{a}$ and $\tilde{b}$ as

$$\begin{aligned} \tilde{a} &= \frac{1}{\sqrt{2w}}\,(f + wv) \\ \tilde{b} &= \frac{1}{\sqrt{2w}}\,(f - wv)\,. \end{aligned} \tag{4}$$

Instead of exchanging only the incident wave and reflected wave (2) at each port, the wave approach is also comprised of the wave impedance w which can be freely chosen.

The total power definition in a two-port network can be written equivalently in terms of the scattering representation or the wave representation

$$\begin{aligned} Power = f^T v &= \frac{1}{2}a^T a - \frac{1}{2}b^T b = \frac{1}{2}\tilde{a}^T \tilde{a} - \frac{1}{2}\tilde{b}^T \tilde{b} \\ &= P_{in} - P_{out}. \end{aligned} \tag{5}$$

Definition 1. A two-port network with impedance representation (1) is *passive* if there exists a nonnegative storage function $E(t)$ such that

$$\int_0^t f^T(\tau) v(\tau) d\tau \geq E(t) - E(0), \quad \forall t \geq 0 \tag{6}$$

and *lossless* if

$$\int_0^t f^T(\tau) v(\tau) d\tau = E(t) - E(0), \quad \forall t \geq 0 \tag{7}$$

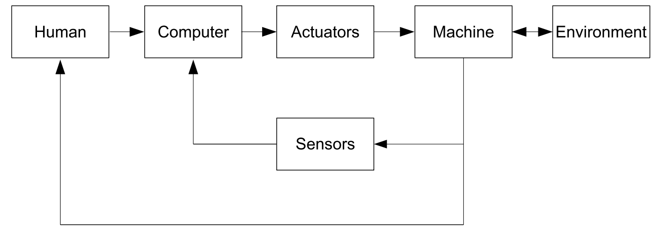

Fig. 2. A human-machine interaction system.

for the initial stored energy $E(0)$ and the *supply rate* $f^T v$.

Equivalently, two-port network with scattering representation (3) is also *passive* if

$$\|S\|_\infty \leq 1, \tag{8}$$

and *lossless* if

$$\|S\|_\infty = 1. \tag{9}$$

III. Interaction network representation

For our perspective, we are interested in utilizing network theory for any interaction systems consisting of a human, controllers, a machine and environment. An example of such an interaction system in mechanical view can be shown in Fig. 2.

An interaction system is composed of the human who provides position commands, which are usually the desired velocity, to the computer which then generates the voltages to apply to the amplifiers and the motors, and controllers that operate te machine which is imitating the human motion in any environment. The output which will be transmitted back to the controllers and the human can be measured from the sensors in order to regulate the desired position.

The stability of the interaction system can be determined by monitoring energy at each port. In the situation where the human is giving only a single direction command to the controllers, and there is no feedback from the reaction force for the human to feel, we can add a virtual feedback force f_1, when the human intends to move the reference position with the desired velocity v_1 to achieve tasks. Therefore, we can easily define the virtual input energy from the human as the product of the virtual feedback force f_1 and human desired velocity v_1.

The virtual input energy will be input to the controllers which generate a real output energy to the machine through the actuators which then generate real physical energy. The product of the voltage applied to the machine from controllers f_2, and output velocity v_2 can be defined as the real output energy on the other port between the machine and the environment.

IV. Network interpretation of the inverted pendulum system

In this section, we consider an inverted pendulum system as a example of human-machine system as shown in Fig. 3. The inverted pendulum is mounted on a motor driven cart

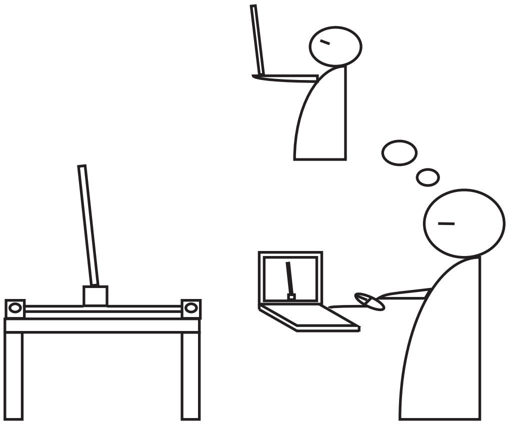

Fig. 3. Human inverted pendulum system.

which is connected from the motor drive. The task for the human is to keep the pendulum in an upright position by moving the mouse. The cart position is manipulated by the human's movement of the mouse. The linearized equations of the inverted pendulum system is given by

$$(M+m)\ddot{x}+ml\ddot{\theta}=F \tag{10}$$

$$ml\ddot{x}+ml^2\ddot{\theta}-mgl\theta=0. \tag{11}$$

This system has a single input which is the voltage applied to the cart motor and two outputs which are the cart position and the angle of the pendulum.

To formulate a two-port network representation, we consider only the major flows and efforts to represent our inverted pendulum system between the human and the pendulum. We can then analyze this information to consider the stability by comparing the virtual input energy and the real output energy at each port. Since the human's objective is to balance the pendulum by controlling the cart position by observing the movement of the pendulum; the desired angular velocities from the human and the measured angular velocities from the pendulum are the most significant informations to illustrate the flows at each port.

The relationship between desired angles and the human commands which depicts the desired cart positions can be derived from (6) as

$$\psi(s)=\frac{x(s)}{\theta(s)}=\frac{-ml^2s^2+mgl}{mls^2}=-l+\frac{g}{s^2}. \tag{12}$$

Hence, the flows and the efforts to represent the human inverted pendulum system are the desired angular velocity from the human $\dot{\theta}_h$, the angular velocity from the pendulum $\dot{\theta}_p$, the virtual feedback force for the human f_h and the actual force for the inverted pendulum system from controllers f_p.

V. Network formulation with controllers

For superior performance, we proposed two controllers implemented inside the network system. One is the PD controller that will convert the desired human command to the output voltage, and the other controller is the washout controller that will suppress undesirable vibrations from the human.

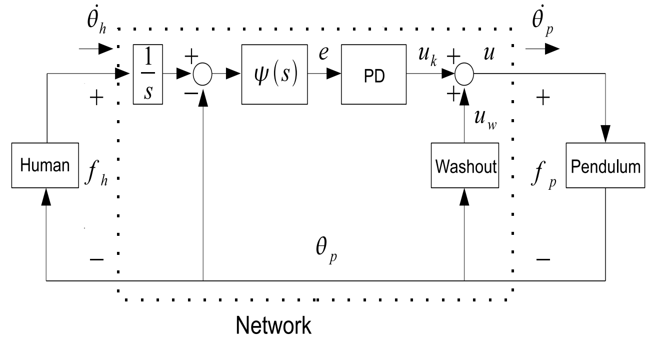

Fig. 4. Network representation with PD controller and washout controller.

The proposed network representation is shown in Fig. 4. The network outputs are the angle from the pendulum system θ_p to the human and the torque u to the motor. The network inputs are the mouse position from the human x_h and the measurements from the pendulum system y, pendulum angle θ_p and cart position x_p.

The PD controller is given by

$$u_k(s)=PD(s)e(s) \tag{13}$$

where

$$PD(s)=K_p+K_ds$$
$$e=x_h-x_p.$$

The washout controller is also given by

$$u_w(s)=\widehat{K}(s)\theta_p(s) \tag{14}$$

where it has a state space realization

$$\begin{aligned}\dot{z}&=\widehat{A}z+\widehat{B}\theta_p\\ u_w&=\widehat{C}z+\widehat{D}\theta_p,\end{aligned} \tag{15}$$

with the constraints det $\widehat{A}\neq 0$ and $\widehat{D}-\widehat{C}\widehat{A}^{-1}\widehat{B}=0$.

The force that generated from the controllers to the plant can be derived as the following

$$\begin{aligned}u(s)=&f_p(s)=u_w(s)+u_k(s)\\ =&\widehat{K}(s)\theta_p(s)+PD(s)e(s)\\ =&\widehat{K}(s)\theta_p(s)+PD(s)\left\{x_h(s)-x_p(s)\right\}\\ =&\frac{1}{s}\left\{\widehat{K}(s)-PD(s)\psi(s)\right\}\dot{\theta}_p(s)\\ &+\frac{1}{s}PD(s)\psi(s)\dot{\theta}_h(s).\end{aligned}$$

Then, the impedance matrix of the network system can be shown as

$$\begin{bmatrix}f_h(s)\\ f_p(s)\end{bmatrix}=\begin{bmatrix}\alpha z_{11}(s) & \alpha z_{12}(s)\\ z_{21}(s) & z_{22}(s)\end{bmatrix}\begin{bmatrix}\dot{\theta}_h(s)\\ -\dot{\theta}_p(s)\end{bmatrix} \tag{16}$$

where α is a weighting factor which is assumed to be $(0\leq\alpha\leq 1)$,

$$z_{11}(s) = z_{21}(s) = \frac{gPD(s) - K_p l s^2 - K_d l s^3}{s^3}$$
$$z_{12}(s) = z_{22}(s) = \frac{1}{s}\widehat{K}(s) - \frac{gPD(s) - K_p l s^2 - K_d l s^3}{s^3}.$$

A state space realization of the transfer function for impedance matrix $Z(s)$ can be obtained as

$$Z(s) = \begin{bmatrix} \alpha z_{11}(s) & \alpha z_{12}(s) \\ z_{21}(s) & z_{22}(s) \end{bmatrix} = \left[\begin{array}{c|c} \widetilde{A} & \widetilde{B} \\ \hline \widetilde{C} & \widetilde{D} \end{array}\right] \quad (17)$$

where

$$\widetilde{A} = \begin{bmatrix} \widehat{A} & \widehat{B} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \ \widetilde{B} = \begin{bmatrix} 0 & 0 \\ 0 & -1 \\ 0 & 0 \\ 0 & 0 \\ 1 & 1 \end{bmatrix}$$
$$\widetilde{C} = \begin{bmatrix} \alpha\widehat{C} & \alpha\widehat{D} & \alpha K_p g & \alpha K_d g & -\alpha K_p l \\ \widehat{C} & \widehat{D} & K_p g & K_d g & -K_p l \end{bmatrix}$$
$$\widetilde{D} = \begin{bmatrix} -\alpha K_d l & -\alpha K_d l \\ -K_d l & -K_d l \end{bmatrix}.$$

The impedance matrix of the human-machine system is critical to introducing the scattering matrix for our human-machine system to check the stability of the network system.

VI. Stability Conditions

In this section, we discuss the time domain passivity and the scattering approaches to the stability of the human-machine system. First, considering the time domain, we can define the stability definition of the inverted pendulum system in terms of the energy at each port.

Theorem 1: Assume that the the human and the inverted pendulum with environment are both passive. Then, the overall system is passive if and only if, for all $t \geq 0$,

$$\int_0^t \left(\alpha f_h^T(\tau)\dot{\theta}_h(\tau) - f_p^T(\tau)\dot{\theta}_p(\tau) \right) d\tau \geq E(t) - E(0), \quad (18)$$

where $E(t)$ is a nonnegative storage function, and $E(0)$ is the initial stored energy that can be calculated from the difference of the initial angle $\theta_p(0)$ and the equilibrium angle θ_{eq} as

$$E(0) = \frac{1}{2} m(\theta_p(0) - \theta_{eq})^2. \quad (19)$$

Monitoring energy at each port reveals whether the human is able to balance the inverted pendulum in an upright position or not.

Alternative approach is to utilize the bounded real lemma to check the stability of the scattering state space realization which represents the network system.

By defining the reflected waves and the incident waves as

$$\begin{bmatrix} b_h \\ b_p \end{bmatrix} = \begin{bmatrix} (f_h - \dot{\theta}_h)/2 \\ (f_p + \dot{\theta}_p)/2 \end{bmatrix}, \ \begin{bmatrix} a_h \\ a_p \end{bmatrix} = \begin{bmatrix} (f_h + \dot{\theta}_h)/2 \\ (f_p - \dot{\theta}_p)/2 \end{bmatrix} \quad (20)$$

We have the scattering matrix which can be described as

$$\begin{bmatrix} b_h(s) \\ b_p(s) \end{bmatrix} = \begin{bmatrix} s_{11}(s) & s_{12}(s) \\ s_{21}(s) & s_{22}(s) \end{bmatrix} \begin{bmatrix} a_h(s) \\ a_p(s) \end{bmatrix}. \quad (21)$$

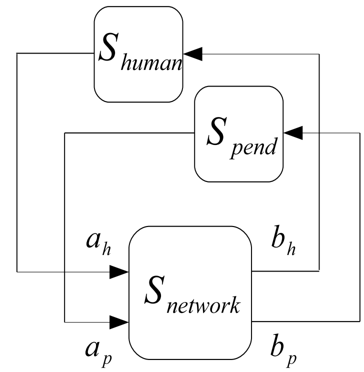

Fig. 5. Scattering transformation for the human inverted pendulum system.

To utilize the relationship between the scattering and impedance matrix with the impedance wave w.

$$S(s) = (Z(s) - wI)(Z(s) + wI)^{-1}$$
$$= \begin{bmatrix} s_{11}(s) & s_{12}(s) \\ s_{21}(s) & s_{22}(s) \end{bmatrix} = \left[\begin{array}{c|c} \mathfrak{A} & \mathfrak{B} \\ \hline \mathfrak{C} & \mathfrak{D} \end{array}\right] \quad (22)$$

where

$$\mathfrak{A} = \begin{bmatrix} \widetilde{A} & -\widetilde{B}(\widetilde{D} + wI)^{-1}\widetilde{C} \\ 0 & \widetilde{A} - \widetilde{B}(\widetilde{D} + wI)^{-1}\widetilde{C} \end{bmatrix}, \ \mathfrak{B} = \begin{bmatrix} \widetilde{B}(\widetilde{D} + wI)^{-1} \\ \widetilde{B}(\widetilde{D} + wI)^{-1} \end{bmatrix}$$
$$\mathfrak{C} = \begin{bmatrix} \widetilde{C} & -(\widetilde{D} - wI)(\widetilde{D} + wI)^{-1}\widetilde{C} \end{bmatrix}$$
$$\mathfrak{D} = (\widetilde{D} - wI)(\widetilde{D} + wI)^{-1}.$$

Theorem 2: The network system is stable and $\|S(s)\|_\infty \leq \gamma$ if and only if there exists a $P = P^T > 0$ such that

$$\begin{bmatrix} \mathfrak{A}^T P + P\mathfrak{A} & P\mathfrak{B} & \mathfrak{C}^T \\ \mathfrak{B}^T P & -\gamma^2 I & \mathfrak{D}^T \\ \mathfrak{C} & \mathfrak{D} & -I \end{bmatrix} \prec 0. \quad (23)$$

If the condition in Theorem 2 holds, then the human-machine system is stable for

$$\Delta(s) = \begin{bmatrix} S_{human}(s) & 0 \\ 0 & S_{pend}(s) \end{bmatrix}, \quad (24)$$

where $\|S_{human}(s)\|_\infty \leq \gamma^{-1}$ and $\|S_{pend}(s)\|_\infty \leq \gamma^{-1}$.

Note that the scattering matrix S (22) will not vary unless we modify the parameters of the controllers or the machine. Therefore, we can guarantee that the network system is stable when the inequality (23) holds. However, we cannot guarantee the stability of the overall human-machine interaction system in Fig. 5, unless (23) and $\|\Delta(s)\|_\infty \leq \gamma^{-1}$ also hold.

Most controllers, equally the washout controller and the PD controller are digitally implemented in such systems in discrete-time. Then, to check our formulated scattering transfer function in state space realization with respect to discrete-time controllers, we apply the bilinear transformation in the LFT form to map the discrete-time domain to a continous time domain by using the bilinear transform $z = \frac{\sigma + s}{\sigma - s}$ to map the z-domain to the s-domain, where $\sigma = \frac{2}{T}$ and T is sampling time. For example, the bilinear transformation between the s-domain and the z-domain in the linear fractional transformation form is given by

$$z^{-1}I = F_u(N, s^{-1}I), \tag{25}$$

where $N = \begin{bmatrix} -\sigma I & \sqrt{2\alpha} I \\ \sqrt{2\sigma} I & -I \end{bmatrix}$.

For the continuous-time scattering transfer function $S(s) = H + G(sI - E)^{-1}F$, it can be represented by

$$S(s) = F_u(M_c, s^{-1}I), \tag{26}$$

where $M_c = \begin{bmatrix} E & F \\ G & H \end{bmatrix}$ is a coefficient matrix of a state space realization of $S(s)$. Hence, when a discrete-time transfer function $S(z) = \mathfrak{D}_d + \mathfrak{C}_d(zI - \mathfrak{A}_d)^{-1}\mathfrak{B}_d$ is given, the corresponding continuous-time system is obtained from

$$F_u(M_d, z^{-1}I) = F_u(M_c, s^{-1}I), \tag{27}$$

where $M_d = \begin{bmatrix} \mathfrak{A}_d & \mathfrak{B}_d \\ \mathfrak{C}_d & \mathfrak{D}_d \end{bmatrix}$.
Hence, M_c is given by the star product of M_d and N as

$$M_c = \begin{bmatrix} (\mathfrak{A}_d + I)^{-1}(\sigma\mathfrak{A}_d - \sigma I) & \sqrt{2\sigma}(\mathfrak{A}_d + I)^{-1}\mathfrak{B}_d \\ \sqrt{2\sigma}\mathfrak{C}_d(\mathfrak{A}_d + I)^{-1} & \mathfrak{D}_d - \mathfrak{C}_d(\mathfrak{A}_d + I)^{-1}\mathfrak{B}_d \end{bmatrix}. \tag{28}$$

VII. Experimental Results

In this section, we explore the proposed approaches, time domain passivity and scattering representations to describe the human-machine system in the experiment. First, we show the stability to demonstrate the passivity in the experiment. Since the feedback forces are not acquireable to the human, we assumed the weighting factor α is equal to one. The objective of the human is to stabilize the inverted pendulum in its upper equilibrium position by moving the cart with the mouse. The length from the joint to the center of gravity of the pendulum l is 0.5 m, the mass of the pendulum m is 0.056 kg, the mass of the cart M is 0.235kg, and the sampling time is 20 ms.

The PD controller implemented is designed to make the trajectory of the cart position track to the human command. For the design of the washout controller, we applied the SSARX method to identify the closed-loop inverted pendulum system. See for details [8], [9].

In the first experiment, the human successfully balanced the inverted pendulum in a 5 second period in an upright position using the full-order washout controller to suppress the vibrations as shown in Fig. 6. The calculated energy defined by (18) remains almost positive in this experiment.

In the second experiment, the human was not able to balance the inverted pendulum in an upright position due to the impact of the environment and the vibrations from the human without applying the full-order washout controller as shown in Fig. 7. The calculated energy remains negative values which obviously shows the overall human-machine interaction is unstable.

In the third experiment, we implemented the reduced-order washout controller with the wave impedance $w = 5$ as shown in Fig. 8. The overall results shows better performance

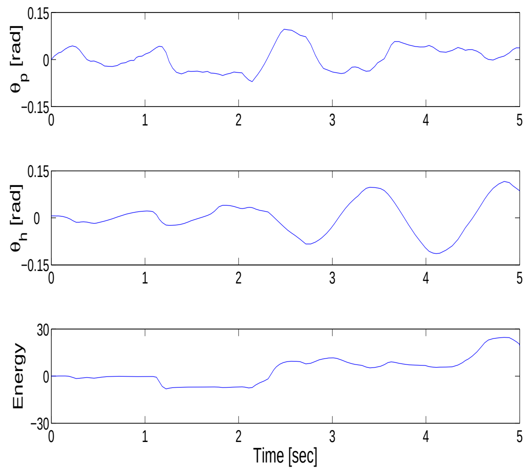

Fig. 6. Time responses for the stabilized inverted pendulum system with support of the full-order washout controller.

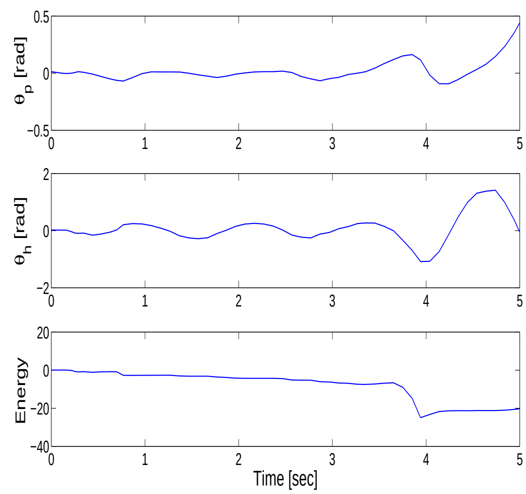

Fig. 7. Time responses of the unstable case whereas the inverted pendulum system is supported by without the washout controller.

compared to Fig. 6 with less motion from the pendulum and the human loads. Moreover, the energy also remains positive and lower than the results from the full-order washout controller.

The maximum singular values of $S(jw)$, shown in Fig. 9, also show the superior performance using the reduced-order washout controller.

We can determine the appropriate wave impedance to reduce the scattering norm from Fig. 10 which is related to the performance of the human-machine closed-loop system.

VIII. Conclusions

We have investigated the extended notion of a human-machine interaction system in a two-port network framework by comparing its passivity, impedance and scattering

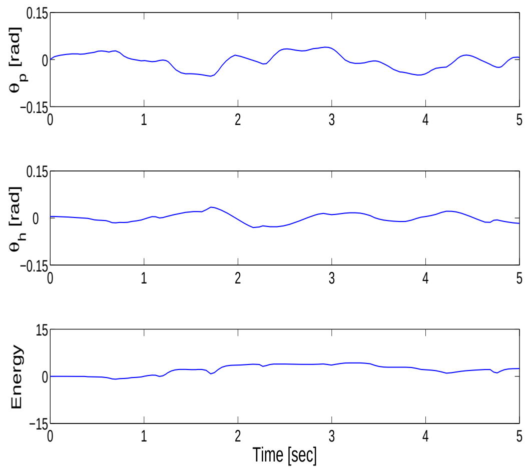

Fig. 8. Time responses for the stabilized inverted pendulum system with suport of the reduced-order washout controller with the wave impedance for $w = 5$.

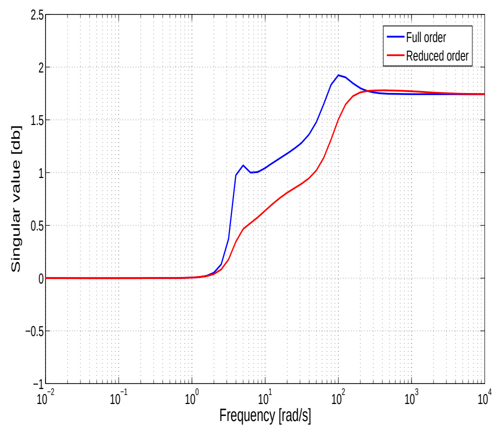

Fig. 9. Maximum singular values for the full-order washout controller, and the reduced-order washout controller.

representation with the washout control. We have adopted an inverted pendulum controlled by a human's manipulation of a mouse as an acceptable model of a human-machine interaction system and successfully compared energy passivity by identifying flows and efforts at each port. By formulating the state space realization of the impedance and the scattering transfer function from our PD controller and washout controller, we were able to achieve better performance. In the experiment, our energy analysis approach revealed better stabilization with the use of the reduced-order washout controller with the appropriate wave impedance than with just the full-order washout controller. The use of the reduced-order washout controller is also superior to the full-order washout controller in our analysis of the scattering representation.

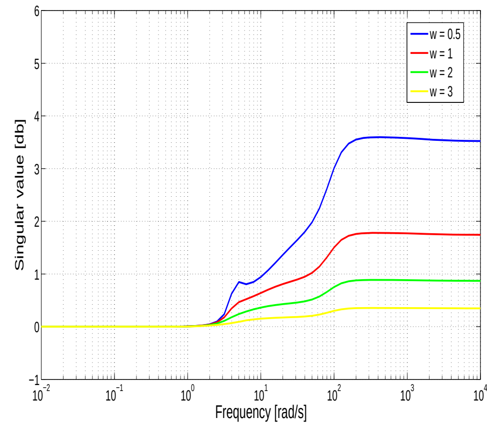

Fig. 10. Singular values and wave impedances

REFERENCES

[1] Md. M. Rahman, R. Ikeura, and K. Mizutani, "Investigation of the Impedance Characteristic of Human Arm for Development of Robots to Cooperate with Humans," *JSME International Journal*, Series C, Vol. 45, No. 2, pp. 510-518, 2002.

[2] J. E. Colgate and N. Hogan, "Robust control of dynamically interacting systems," *Int. J. Control*, Vol. 48, No. 1, pp. 65-88, 1988.

[3] J. E. Colgate, "Power and impedance scaling in bilateral manipulation," In *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 3, pp. 2292-2297, 1991.

[4] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, Vol. 42, Issue 12, pp. 2035-2057, December 2006.

[5] J. H. Ryu, D. S. Kwon, and B. Hannaford, "Stability Guaranteed Control: Time Domain Passivity Approach," In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vol. 3, pp. 2115-2121, 2002.

[6] T. Matiakis, S. Hirche, and M. Buss, "The Scattering Transformation for Networked Control Systems," In *Proceedings of the IEEE Conference on Control Applications*, pp. 705-710, 2005.

[7] T. Matiakis, S. Hirche, and M. Buss, "Control of Networked Systems using the Scattering Transformation," *IEEE Transactions on Control Systems Technology*, Vol. 17, Issue 1, pp. 60-67, 2009.

[8] T. Takimoto, S. Yamamoto, and H. Oku, "Washout Control for Manual Operations," *IEEE Transactions on Control Systems Technology*, Vol. 16, Issue 6, pp. 1169-1176, 2008.

[9] T. Takimoto and S. Yamamoto, "Reduced-order Washout Controllers Stabilizing Uncertain Equilibrium Points," In *Proceedings of the American Control Conference*, pp. 5390-5393, 2007.

[10] T. Takimoto and S. Yamamoto, "An active control method for oscillatory motions in human behavior," In *Proceedings of the SICE Annual Conference*, pp. 3195-3198, 2005.