Time Domain Passivity Control With Reference Energy Following

Jee-Hwan Ryu, Carsten Preusche, Blake Hannaford, and Gerd Hirzinger

***Abstract*—A recently proposed method for stabilizing haptic interfaces and teleoperation systems was tested with a PHANToM commercial haptic device. The passivity observer (PO) and passivity controller (PC) stabilization method was applied to stabilize the system but also excited a high-frequency mode in the device. To solve this problem, we propose a method to use a time-varying desired energy threshold instead of fixed zero energy threshold for the PO, and make the actual energy input follow the time-varying energy threshold. With the time-varying energy threshold, we make the PC control action smooth without sudden impulsive behavior by distributing the dissipation. The proposed new PO/PC approach is applied to PHANToM with high stiffness ($K = 5000$ N/m), and stable and smooth contact is guaranteed. Resetting and active environment display problems also can be solved with the reference energy following idea.**

***Index Terms*—Haptic interface, passivity controller (PC), passivity observer (PO), reference energy, time-domain passivity.**

I. Introduction

A HAPTIC interface is a kinesthetic link between a human operator and a virtual environment. One of the most significant problems in haptic interface design is to create a control system which simultaneously is stable and gives high fidelity under any operating conditions and for any virtual environment parameters. There are several mechanisms by which a virtual environment or other part of the system might exhibit active behavior which is a necessary condition for instability in this application. These include quantization [2], interactions between the discrete time system and the continuous time device/human operator [3], and delays due to numerical integration schemes [6].

Initial efforts to solve this problem introduced the "virtual coupling" between the virtual environment and the haptic device [2], [13]. The virtual coupling parameters can be set empirically, but several previous research projects have sought out a theoretical design procedure using control theory. However, interesting virtual environments are always nonlinear and the dynamic properties of a human operator are always involved. These factors make it difficult to analyze haptic systems in terms of system models with known parameters and linear control theory. Anderson and Spong [1] and Neimeyer and Slotine [7] have used passivity ideas in the related area of stable control of force-feedback teleoperation with time delay. Colgate and Schenkel [3] have used it to derive fixed parameter virtual couplings (i.e., haptic interface controllers). The major problem with using passivity for design of haptic interaction systems is that it is over conservative. In many cases, performance can be poor if a fixed damping value is used to guarantee passivity under all operating conditions.

Recently, a different passivity based approach has been proposed by Hannaford and Ryu [4] that measures active system behavior and injects variable damping whenever net energy is produced by the virtual environment. They proposed a passivity observer (PO) and a passivity controller (PC) to insure stable contact under a wide variety of operating conditions.

In our previous research [4], we fixed the threshold of the PO/PC at zero. However, sometimes this fixed zero threshold can produce sudden big impulsive changes in control force, since accumulated active energy input must be dissipated at the end of contact within a short time. Moreover, the big impulsive force might excite an internal mode of a system. In this brief, we introduce a way to make the PC output smoother. We introduce a time-varying reference energy behavior with or without the model information. By making the actual energy input follow the reference energy behavior, we can make the PC action smooth. We can solve the resetting problem [4], [5] and active environment display problem as well.

II. Review of the Time Domain Passivity Control

In this section, we briefly review time-domain passivity control. First, we define the sign convention for all forces and velocities so that their product is positive when power enters the system port. The following widely known definition of passivity is used.

Definition 1: The one-port network N with initial energy storage $E(0) = 0$ is *passive* if and only if

$$\int_0^t f(\tau)\dot{x}(\tau)d\tau \geq 0, \quad \forall t \geq 0 \tag{1}$$

for forces (f) and velocities $(\dot{x})$. Equation (1) states that the energy supplied to a passive network must be positive for all time [11], [12].

The conjugate variables that define power flow in such a system are discrete-time values, and the analysis is confined to systems having a sampling rate substantially faster than the dynamics of the system. We assumed that there is no change in force and velocity during one sample time. Thus, we can

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easily "instrument" one or more blocks in the system with the following PO for a one-port network to check the passivity (1)

$$E_{\text{obsv}}(k) = \Delta T \sum_{j=0}^{k} f(t_j)\dot{x}(t_j) \tag{2}$$

where ΔT is the sampling period. If $E_{\text{obsv}}(k) \geq 0$ for every k, this means the system dissipates energy. If there is an instance when $E_{\text{obsv}}(k) < 0$, this means the system generates energy and the amount of generated energy is $-E_{\text{obsv}}(k)$.

Recently, other research has allowed this constant force and velocity assumption to be relaxed [10], and a more accurate PO was proposed for the case of impedance causality [9]

$$\sum_{j=0}^{k} f(t_{j-1})\left(x(t_j) - x(t_{j-1})\right) + f(t_j)\left(x(t_j) - x(t_{j-1})\right). \tag{3}$$

The first term of (3) means the net energy input to a one-port network from 0 to t_k, and the last term of (3) is the estimation of the one-step ahead energy input, which is the input energy from t_{k-1} to t_k based on the assumption that the velocity during one sample $[t_{k-1} \leq t \leq t_k]$ will be constant. Even though this was the same assumption as the previous PO, (3) improves on previous work because the error caused by this assumption was not integrated.

Consider a one-port system which may be active. Depending on operating conditions and the specifics of the one-port element's dynamics, the PO may or may not be negative at a particular time. However, if it is negative at any time, we know that the one-port may then be contributing to instability. Moreover, we know the exact amount of energy generated and we can design a time-varying element to dissipate only the required amount of energy. We call this element a PC. The PC takes the form of a dissipative element in a series or parallel configuration depending on the input causality [4].

Please see [4], [8], [9] for more detail about time domain passivity control approach.

III. Implementation of the PO/PC With a PHANToM

To measure the performance of the recent PO/PC [9], on a popular haptic device, we implemented the method with a PHANToM (Fig. 1) haptic interface and a high stiffness ($K = 5000$ N/m) virtual environment which runs on RT-Linux with 2-kHz sampling rate.

PHANToM was pushed to make a contact with about 0.28 m/s. Without the PC, the contact was unstable (Fig. 2). However, even after applying the PC, the contact was not perfectly stable (Fig. 3). During the transient state, the system started to vibrate (around 1 s) and stabilized in about 0.5 s.

To find the reason for transient unstable behavior, the experimental data in Fig. 3 was analyzed. Fig. 4 shows the velocity profile of the PHANToM at the first contact. During the contact ($t = 0.59 \sim 0.63$), an internal mode of the PHANToM with about 200 Hz was found. If we model the PHANToM from the gripper to the actuator, this could be modeled as a flexible system (Fig. 5) composed of a series of springs and masses corresponding to cable and the mechanical structure of the PHANToM. This internal mode can be excited by the sudden impulsive PC output (Fig. 6). At the end of each contact, the PC is activated by changing the control force suddenly to satisfy the time-domain passivity condition. This broad-band input can excite the internal mode of the PHANToM. Therefore, we need to

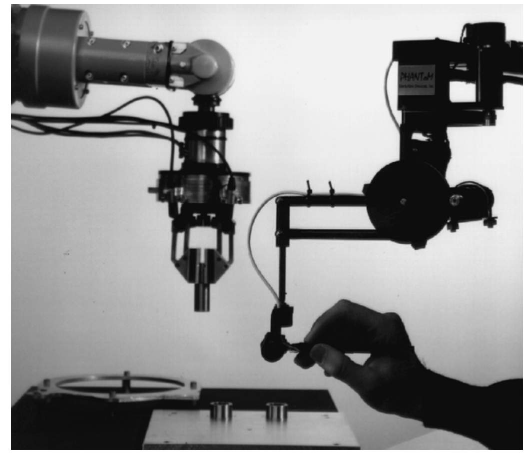

Fig. 1. Phantom haptic interface (right) which is used in this brief as an experimental test bed.

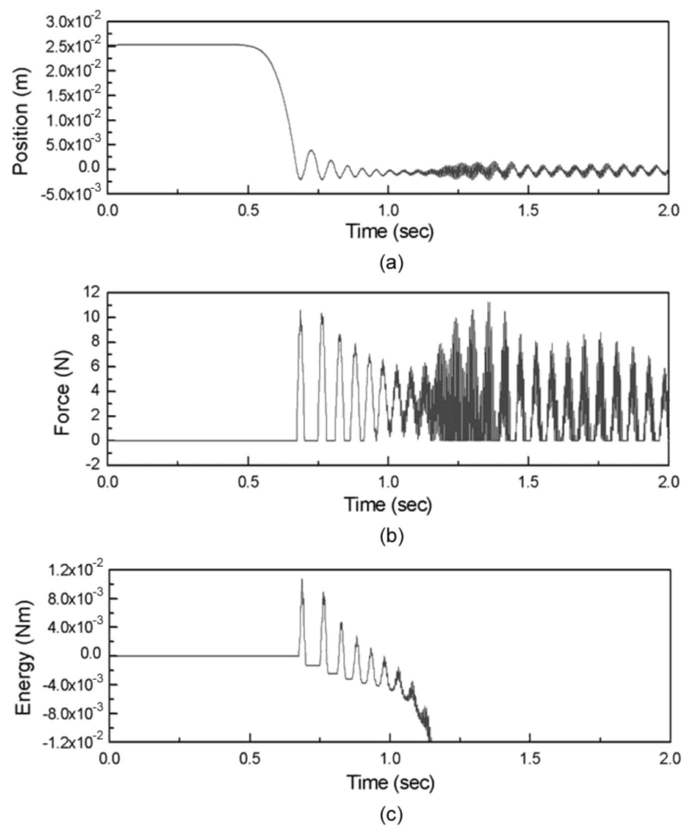

Fig. 2. Experimental results. Contact response without the PO/PC for high stiffness VE ($K = 5000$ N/m).

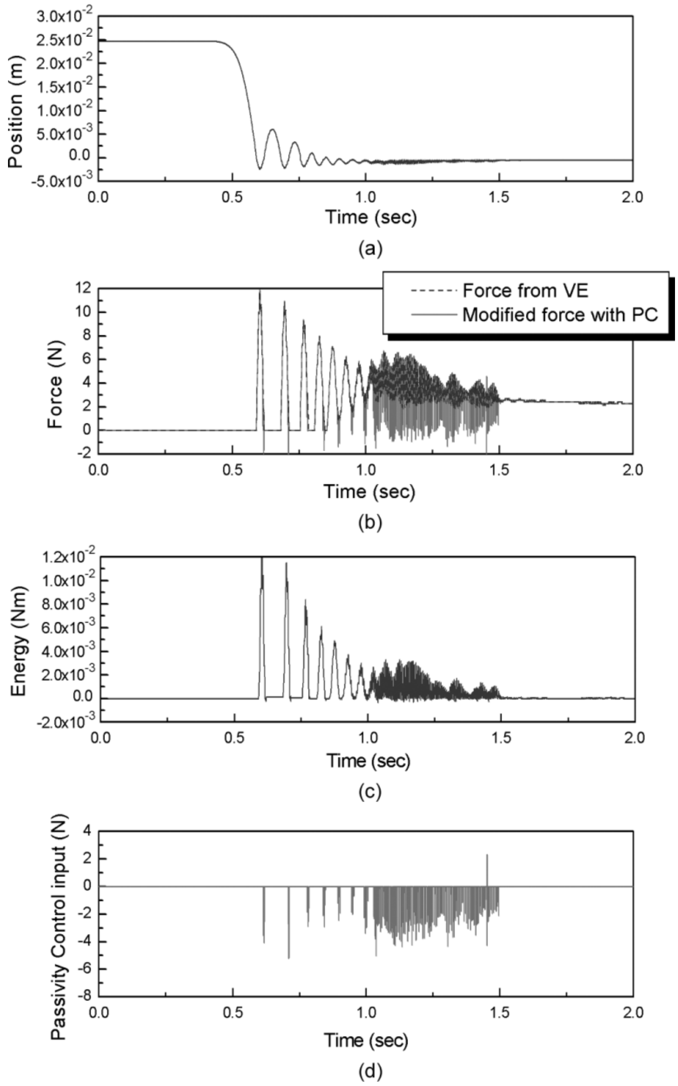

Fig. 3. Experimental results. Contact response with the PO/PC for high stiffness VE ($K = 5000$ N/m). Although contact is now stable, transient behavior is poor.

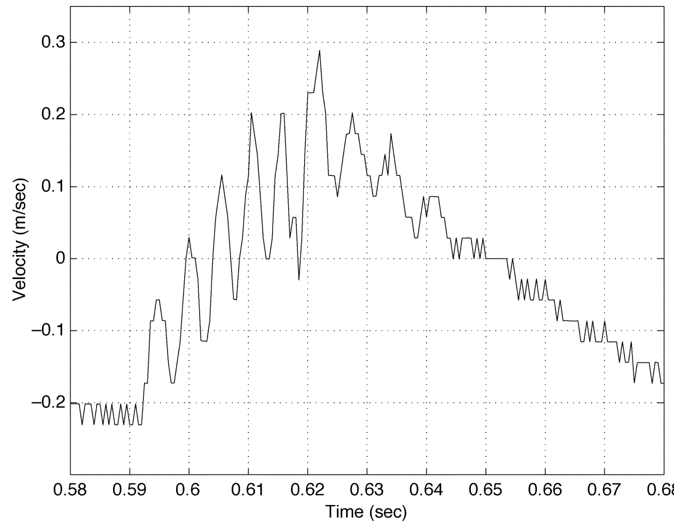

Fig. 4. Experimental results. Velocity behavior during the contact, 200 Hz internal mode.

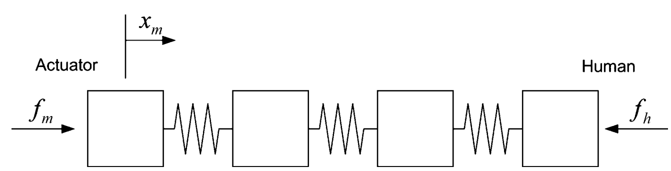

Fig. 5. From human to actuator, PHANToM can be modeled as a flexible system having internal modes.

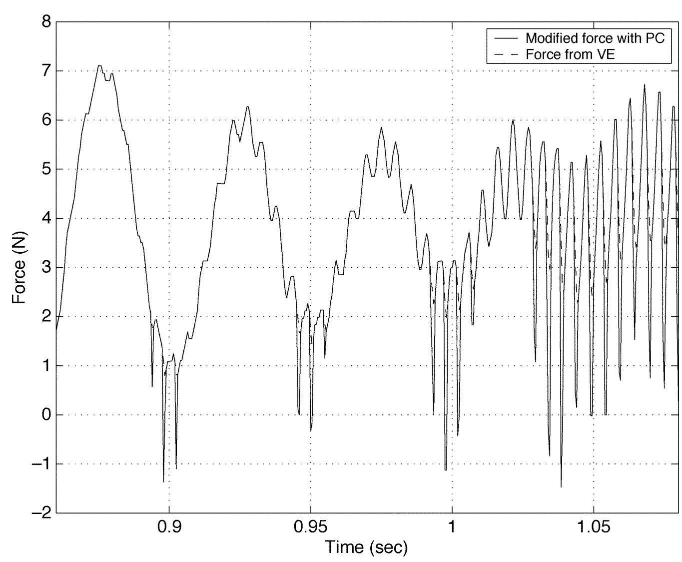

Fig. 6. Experimental results. Impulsive PC control action makes the internal mode vibrate.

make the PC output smooth to prevent magnifying the internal mode of the haptic device or other part of the system.

IV. Time Domain Passivity Control With Reference Energy Following

In this section, a method to make the PC output smooth is proposed. First, the operation of the current PO/PC with simulation of a simple virtual wall is illustrated with impedance causality (velocity in, force out). The wall consists of a first-order penalty-based spring-damper model executed at 1 kHz. Active behavior of this system can be easily created by setting the damping parameter b to a negative value. The wall generates forces only when $x(t) > 0$. In our simulation, the wall is probed by a point following a sinusoidal velocity trajectory ($\dot{x}(t) = sin(\pi t)$(m/s)). With negative damping ($K =$ 710 N/m, $B =$ -50 Ns/m, dashed line of Fig. 7), the PO value returns after each "bounce" to a more negative value, indicating the active behavior of the virtual wall. The solid line of Fig. 7 shows the way to make the active system (dashed line) passive with the current PO/PC. The PO keep monitoring the energy behavior, and the PC is not activated unless the PO value cross the zero line at the end of contact. Once the PO hits the zero line, the PC is activated and makes the energy input stay zero until the PO value goes up. In this case, sometimes we need big PC output at the end of contact since we only know whether the system is passive or active at the end of contact, and the accumulated active amount of energy flow out at the end for a short time.

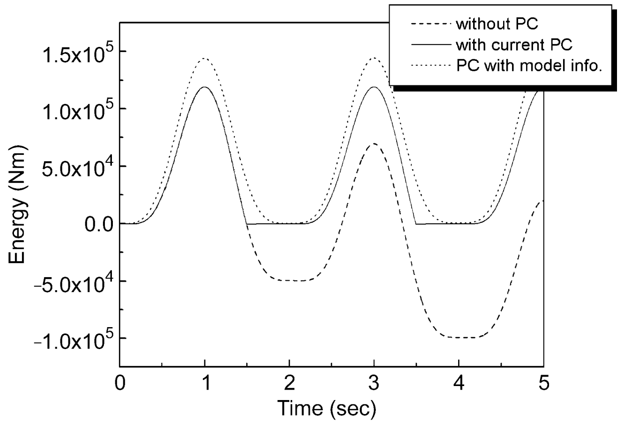

Fig. 7. Simulated two different ways to make the active behavior passive.

However, if we can shift up the actual active energy behavior by distributing the required amount of damping throughout the whole contact, the energy change will be smoother, and big impulsive force is not required. To that end, it is required to introduce time-varying reference energy threshold, which is passive, instead of fixed zero energy threshold for the PO, and make the actual energy follow the reference energy. The dotted line in Fig. 7 shows the energy behavior when the negative damping, which was the main source of the active energy, is removed ($K = 710$ N/m, $B = 0$ Ns/m) to make the system marginally passive. This behavior can be the reference energy which the actual energy input want to follow.

A. Reference Energy Based on Model Information

There could be many possible ways to design the reference energy behavior. One possible way is to use a model of the virtual environment. With such a system model, it is possible to design a passive reference energy behavior by calculating the stored energy and the dissipated energy of the system. For a continuous and energy lossless one-port network system, the net energy input to the system [the left term of (4)] should be equal to the stored energy (S) plus dissipated energy (D) of the system

$$\int_0^t f(\tau)\dot{x}(\tau)d\tau = S(t) + D(t), \quad \forall t \geq 0. \tag{4}$$

Thus, the stored energy plus dissipated energy [right term of the (4)] could be the reference energy behavior.

With the reference energy behavior, the PC algorithm for one-port network with impedance causality (Fig. 8) is similar to an earlier work [9], except the right term of the equation is replaced with reference energy $(S(k)+D(k))$ instead of 0, and one step ahead energy prediction is removed.

1) $x_1(k) = x_2(k)$ is the input;
2) $\Delta x(k) = x_1(k) - x_1(k-1)$;
3) $f_2(k)$ is the output of the one-port network;
4) $E_{\mathrm{obsv}}(k) = \sum_{j=0}^{k} f_1(j-1)\Delta x(j)$ is the actual energy input at step k;
5) $S(k)$ and $D(k)$ is the amount of stored energy and the dissipated energy of the virtual environment (VE) at step k, respectively;

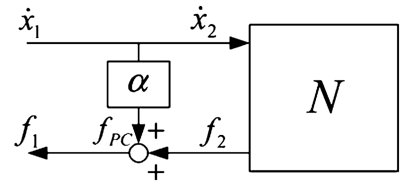

Fig. 8. One-port network with PC.

6) the PC control force to make the actual input energy follow the reference energy is calculated

$$f_{PC}(k) = \begin{cases} \frac{-(E_{\mathrm{obsv}}(k)-S(k)-D(k))}{\Delta x(k)} & \text{if } W(k) < 0 \\ 0 & \text{if } W(k) \geq 0 \end{cases} \tag{5}$$

where $W(k) = E_{\mathrm{obsv}}(k) - S(k) - D(k)$;
7) $f_1(k) = f_2(k) + f_{PC}(k)$ is the output.

The proposed energy following method was implemented with the same system as mentioned in Section III. Since the model information of the VE ($K = 5000$ N/m) is given, the energy storage of the VE can be exactly calculated ($S(k) = (1/2)\dot{K}\dot{x}(k)^2$, $D(k) = 0$). The PC is designed based on the (5). The contact was stable [Fig. 9(a), (b)] and the internal mode was not excited since the PC output was significantly reduced [Fig. 9(d)] compared to the previous results (Fig. 3).

B. Reference Energy Without Model Information

In some cases, such as highly nonlinear VE, it is difficult to use model information for calculating reference energy behavior. Also sometimes we want to design haptic interface without exact knowledge of the VE. In these cases, a hypothetical reference energy behavior is required, which simulates the continuous time energy behavior of the VE and stay passive as long as VE is mean to simulate passive objects. The numerical integration of the power flow (the product of displacement and the resulting force output for impedance causality) into the VE

$$E_{\mathrm{ref}}(t_k) = \sum_{j=0}^{k} f\left(x(t_j), x(t_{j-1}), \ldots, x(t_0)\right)\left(x(t_j) - x(t_{j-1})\right) \tag{6}$$

can be used as a reference energy behavior. Where $f(x(t_j), x(t_{j-1}), \ldots, x(t_0))$ is the computed force output of VE for the input position displacement $(x(t_j) - x(t_{j-1}))$. This numerical integration (6) approximately follows the continuous time ideal energy behavior of the VE, and stays positive if the VE is composed of physically passive elements (such as mass, spring and damper) even if they are time-varying. Even if it goes negative, we assume that the VE is intentionally active. For example, if we grab a cup and move it down from a high shelf in a virtual world, then this behavior is active that we want to display.

By using the integrated energy (6) as the reference energy behavior, the same experiment as in Section IV-A is executed. The contact was also stable. However, the reference energy behavior was distorted as though small amount of damping is added even though the VE was only composed of a spring since the reference energy behavior (6) is greater than the ideal energy input (4). Therefore, the PC output increased little bit [Fig. 10(d)]

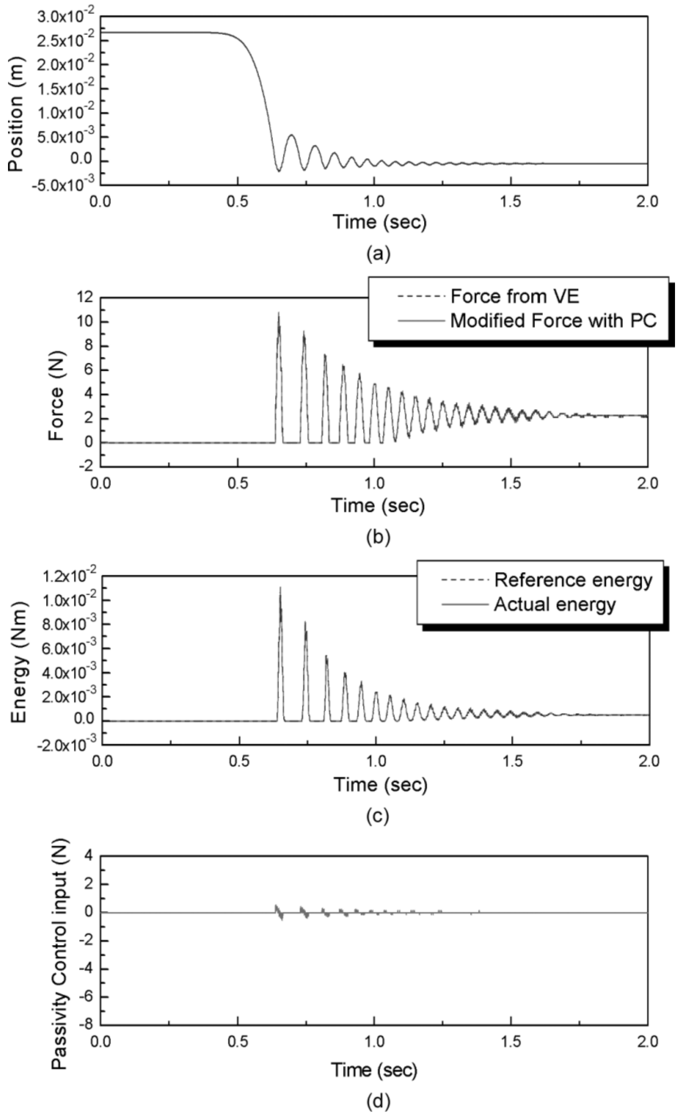

Fig. 9. Experimental results. Contact response with the PO/PC with reference energy based on model for high stiffness VE ($K = 5000$ N/m).

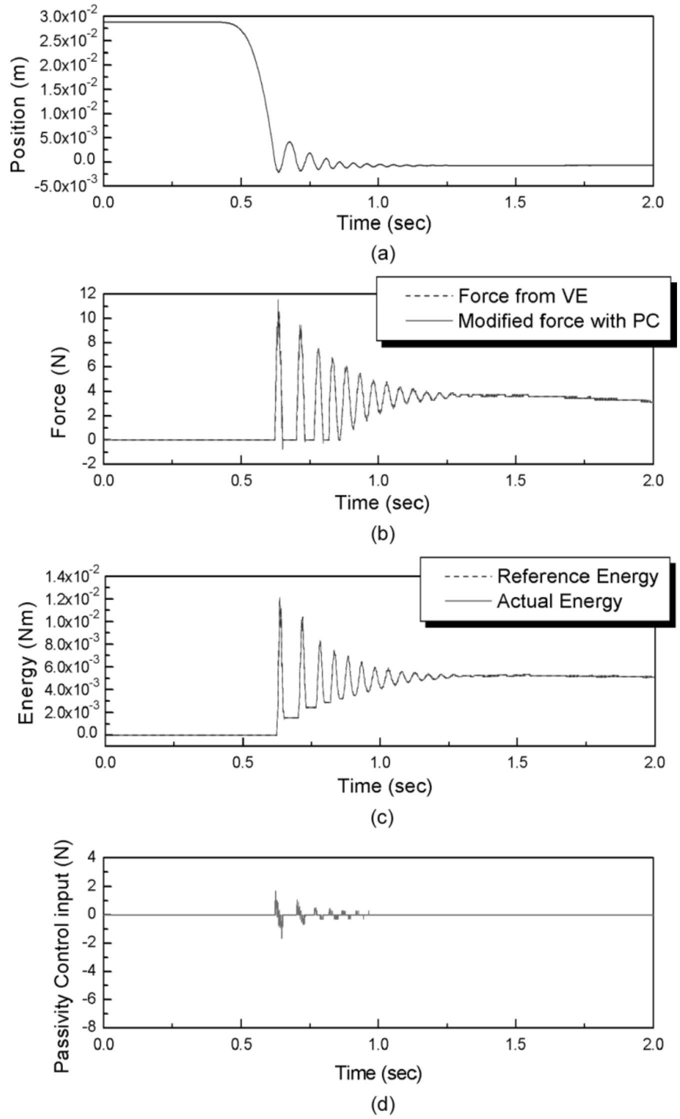

Fig. 10. Experimental results. Contact response with the PO/PC with reference energy without model for high stiffness VE ($K = 5000$ N/m).

compared to the case where VE model information was used (Fig. 9).

C. Resetting Problem

A problem of our previous PO/PC which was described in our previous papers [4], [5] is accumulated energy dissipation. Consider an environment which is very dissipative in location X and active in location Y. If the user spends a lot of time interacting at X, the PO may build up a large positive value. Then, if the user moves over and interacts with location Y, the PC will not operate until a corresponding amount of active behavior is observed.

If we introduce the reference energy behavior, this problem can be solved. This idea is tested for the same experimental system. In Fig. 11, the PO starts with certain positive value [Fig. 11(c)] due to the previous interaction with a highly damped environment. Then, the user interacted with high stiffness environment. The PC was not activated until the PO crossed zero. Thus, the interaction temporarily was unstable [Fig. 11(a), (b)]

However, if we apply the proposed reference energy following method, the PC was activated in small amounts even though the PO never crossed zero (Fig. 12), and stable contact was achieved.

V. Conclusion and Future Works

In this brief, a modified time domain passivity control approach is proposed by replacing the fixed zero energy threshold with time-varying reference energy behavior. Two reference energy behaviors, with or without system model information, are introduced, and in experiment, actual energy input followed the reference energy behavior. As a result, we can make the PC control output smoother, and prevent the excitation of the internal mode of a system by removing the sudden impulsive force of the PC. With the reference energy following method, we can solve the resetting problem, and display an active environment as well since the reference energy allow the actual energy to go below zero.

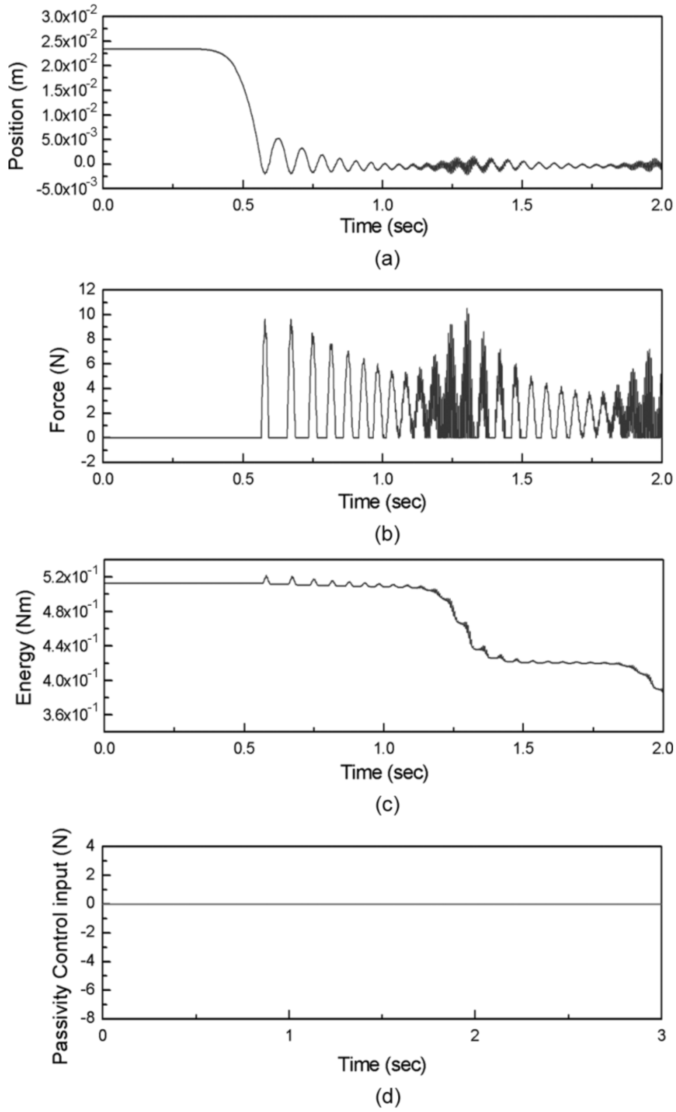

Fig. 11. Experimental results. Contact response with the PO/PC without resetting and reference energy.

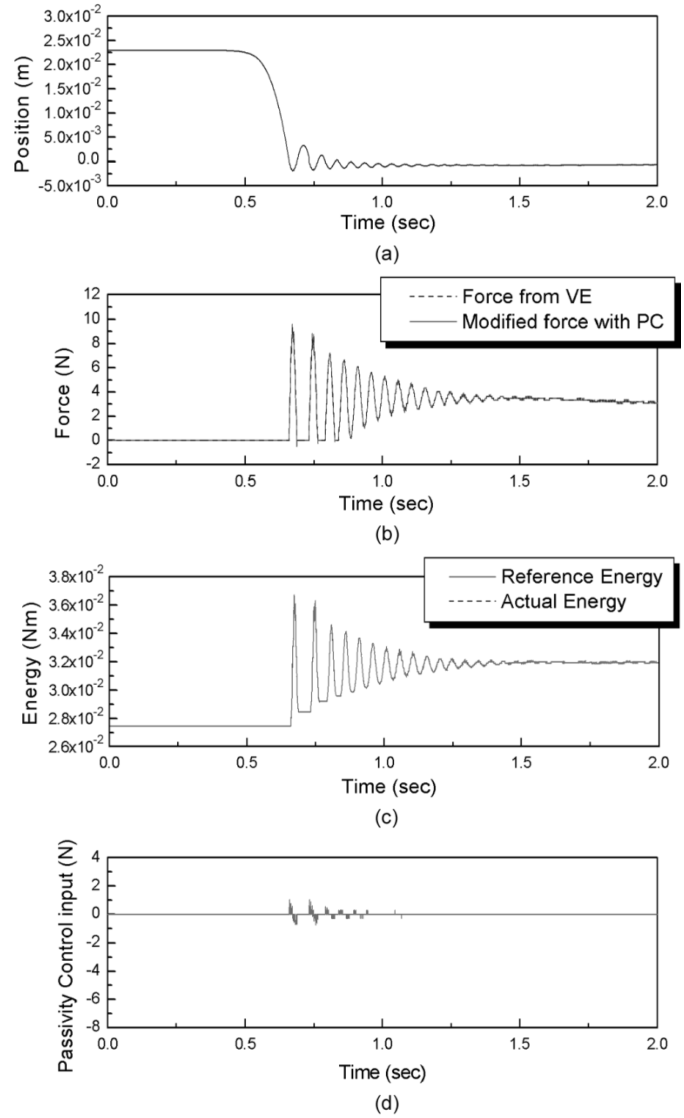

Fig. 12. Experimental results. Contact response with the PO/PC without resetting and with reference energy.

The PO/PC approach was applied to the most common haptic interface PHANToM and stable and smooth haptic interaction is achieved. We believe that this newly proposed PO/PC approach can generally improve the stability and performance of haptic interfaces.

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