Proceedings of the 2005 IEEE
International Conference on Robotics and Automation
Barcelona, Spain, April 2005

A Simulation/Experimental Study of the Noisy Behavior of the Time Domain Passivity Controller for Haptic Interfaces

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***Abstract*— A noisy behavior of the time domain passivity controller during the period of low velocity is analyzed. Main reasons of the noisy behavior are investigated through a simulation with a one-DOF haptic interface model. It is shown that the PO/PC is ineffective in dissipating the produced energy when the sign of the velocity, which is numerically calculated from the measured position, is suddenly changed, and when this velocity is zero. These cases happen during the period of low velocity due to the limited resolution of the position sensor. New methods, ignoring the produced energy from the velocity sign change, and holding the control force while the velocity is zero, are proposed for removing the noisy behavior. The feasibility of the developed methods is proved with both a simulation and a real experiment.**

***Index Terms*— Noisy behavior, haptic interface, passivity controller, passivity observer, time-domain passivity.**

I. Introduction

A haptic interface is a kinesthetic link between a human operator and a virtual environment (VE). One of the most significant problems in haptic interface design is to create a control system which simultaneously is stable (i.e. does not exhibit vibration or divergent behavior) 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. These include quantization [4], interactions between the discrete time system and the continuous time device/human operator [5], and delays due to numerical integration schemes [12].

Initial efforts to solve this problem introduced the "virtual coupling" between the virtual environment and the haptic device [1], [4], [17]. 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 non-linear 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 [2] and Neimeyer and Slotine [13] have used passivity ideas in the related area of stable control of force-feedback teleoperation with time delay. Colgate and Schenkel [5] 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. Several other passivity based approaches were also proposed for stable haptic interaction [3], [10], [11].

A different passivity based approach has been proposed by Hannaford and Ryu [6], 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. Recently, the PO/PC approach has been improved for estimating exact energy output [15], and removing sudden impulsive PC force [16].

In our previous researches [6], [14]–[16], the PO/PC was ineffective in dissipating the produced energy during the period of low velocity (series type PC in impedance causality) or low force (parallel type PC in admittance causality), and it has been open as a future work. Even though there has been an effort to solve the noise problem [8], it was a tuning method of heuristic control parameters depending on a system. In this paper, main reasons of the noisy behavior of the PO/PC are analyzed, and methods to remove the noisy behavior are proposed.

II. Analysis of the Noisy Behavior of the PO/PC

In this Section, the main reasons of the noisy behavior are investigated through the simulation of a one-DOF haptic interface system (Fig. 1), consists of the Human Operator (HO), the Haptic Interface (HI), the PC, and the VE with impedance causality. In this paper, human and device are assumed to be one-DOF linear time invariant models as used in many other researches [1], [5], [6] for making the problem as simple as possible. The following simulation parameters were used for HO and HI.

$$M_{HO} = 0.1(Kg), B_{HO} = 0.5(Ns/m), K_{HO} = 50(N/m),$$
$$M_{HI} = 0.2(Kg), B_{HI} = 0.0(Ns/m), K_{HI} = 0.0(N/m).$$

Note that the HI and HO have very low damping, and the high stiffness VE consists of a first order, penalty based spring model ($K = 1000N/m$) executed at 1000 Hz. Two separate simulations with 1.0×10^5 Hz, one in Matlab/simulink, and one in a C program using trapezoidal integration were used including sensor quantization effect (minimum resolution is $1.0 \times 10^{-5}(m)$).

Recently, reference energy following PO/PC was proposed [16] for removing sudden impulsive force of the PC with the following time-varying energy threshold instead of fixed zero energy threshold as follows:

$$W(k) = \sum_{j=0}^{k} f(t_{j-1})(x(t_j) - x(t_{j-1})) \geq E_{ref}(t_k), \quad \forall t_k \geq 0, \tag{1}$$

where $W(k)$ is the PO value for the case of impedance causality, which is the net energy input to a one-port network from 0 to t_k, and $E_{ref}(t_k)$ is the time-varying reference energy threshold which can be designed using VE model information or conjugate pair of input/output signal. In this paper, this PO/PC approach was used at 1000 Hz. Please refer to [6], [14]–[16] for more detail about time domain passivity control approach.

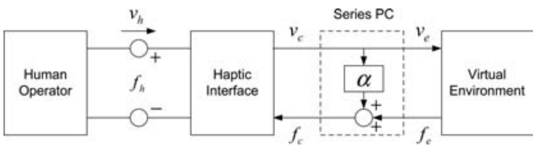

Fig. 1. Haptic interface system with series type PC for simulation

The HI was pushed to make a contact with the high stiffness VE at Position ≥ 0. The contact seemed stable (Fig. 2a) on the position response, but the PC input was chattering (Fig. 2d) and the PO value kept falling down to more negative value (Fig. 2c) during the period of low velocity. As a result, operator felt small and continuous vibration. Note that we bounded the PC force to escape the sudden big force change. There are two undesirable behaviors of the velocity which make the PO/PC ineffective due to the limited resolution of the position sensor.

A. Sudden Sign Change of the Velocity

When the sign of the numerically calculated velocity ($v(k) = \frac{x(t_k)-x(t_{k-1})}{\Delta T}$) is suddenly changed from positive (or negative) at step k to negative (or positive) at step $k+1$, the energy difference between the PO value and the reference energy is increased even with the PC force.

This undesirable behavior can be explained with position versus force response of a VE which composed of a linear spring. It has shown a staircase shape due to the limited resolution of the position sensor and the ZOH. The dotted line indicates the behavior of the ideal linear spring. The solid line shows the case when the VE is pressed and released. The measured position versus force response with PC is magnified when the sign of the velocity is changed in one sample time (Fig. 3). Assume that the measured position was increased from $x(k-1)$ to $x(k)$ at step k, and back to the initial value at step $k+1$. If both the PO and the reference energy had the same value ($E(k-1)$)

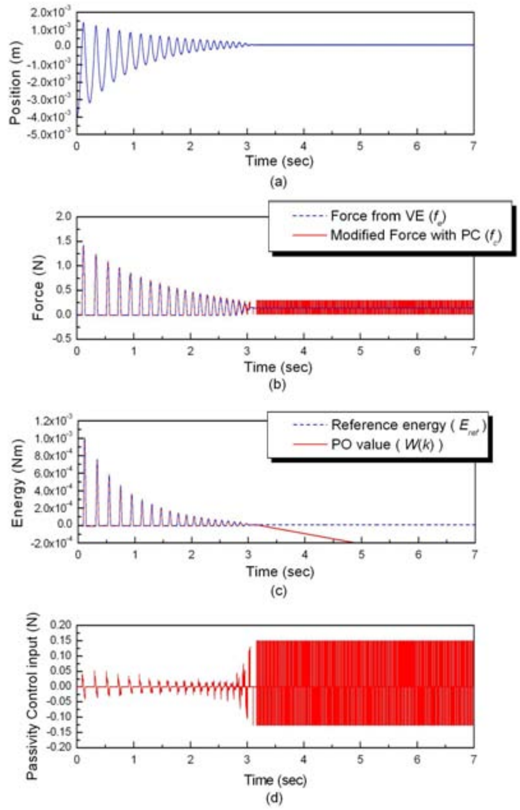

Fig. 2. Contact response with the energy following PO/PC [16] for the high stiffness VE ($K = 1000N/m$). PC was noisy during the period of low velocity

at step $k-1$, each values at step k would be as follows:

$$\begin{aligned} W(k) &= E(k-1) + f_e(k-1)(x(k) - x(k-1)), \\ E_{ref}(k) &= E(k-1) + f_e(k-1)(x(k) - x(k-1)) \\ &\quad + \frac{1}{2}(f_e(k) - f_e(k-1))(x(k) - x(k-1)), \end{aligned}$$

where the amount of increment is the area below each curve. Since the PO value was less than the reference energy, the PC was activated to make the PO value follows the reference energy based on the current positive velocity. As a result, the force output was increased from $f_e(k)$ to $f_c(k)$. However, the energy difference between the PO value and the reference energy was increased at step $k+1$ since the sign of the velocity was suddenly changed.

$$\begin{aligned} W(k+1) &= E(k-1) \\ &\quad + (f_e(k-1) - f_c(k))(x(k) - x(k-1)), \\ E_{ref}(k+1) &= E_{ref}(k) \\ &\quad + f_e(k-1)(x(k+1) - x(k)) \\ &\quad + \frac{1}{2}(f_e(k) - f_e(k-1))(x(k+1) - x(k)) \\ &= E(k-1). \end{aligned}$$

With this velocity change, certain amount of energy $((f_c(k) - f_e(k-1))(x(k) - x(k-1)))$ was produced while the reference energy became zero. If the same situation happens several times, the energy difference

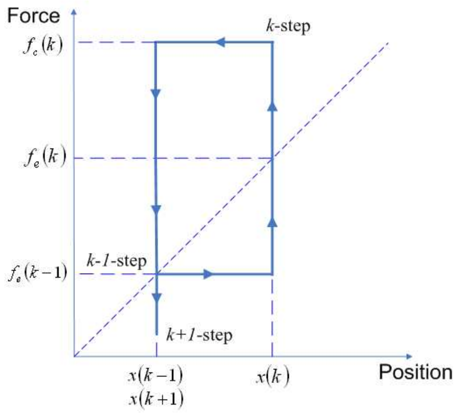

Fig. 3. Position vs. force response when the velocity sign is changed in one sample time

become bigger, and the magnitude of the PC input will be increased.

B. Zero Values of the Velocity

Even though the sudden sign change of the velocity increased the energy difference between the PO value and the reference energy, the PC is supposed to make up for the energy difference for the rest of the cases. However, the PC could not give any effect for compensating the energy difference during the period of low velocity since the numerically calculated velocity were zero for the most of the time due to the resolution of the position sensor.

Assume that the velocity at step k was positive, and zero at step $k+1$ (Fig. 4). The PO values at step k and $k+1$ would be

$$\begin{aligned} W(k) &= E(k-1) + f_e(k-1)(x(k) - x(k-1)), \\ W(k+1) &= E(k-1) + f_e(k-1)(x(k) - x(k-1)) \\ &\quad + f_c(k)(x(k+1) - x(k)) \\ &= E(k-1) + f_e(k-1)(x(k) - x(k-1)). \end{aligned}$$

Even though the PC was activated at step k to make the PO follow the reference energy, the PC could not give any effect to the PO value at step $k+1$ since there was no position difference ($x_k = x_{k+1}$).

III. Methods for Removing the Noisy Behavior

The first idea we could apply for solving this noisy behavior is estimating the velocity. A starting point of the velocity/displacement estimation was in [9]. Relatively nonconservative velocity filter in [7] was used for the same simulation of Fig. 2. However, the results were much worse (Fig. 5). The estimation error from the delay of the filter made the PO value, based on the filtered velocity, greater than the reference energy. Therefore the PC was not activated even though the system was vibrating.

A. Ignoring the Produced Energy from the Velocity Sign Change

Although the measured position remained constant, the actual position might vary when quantization effect was

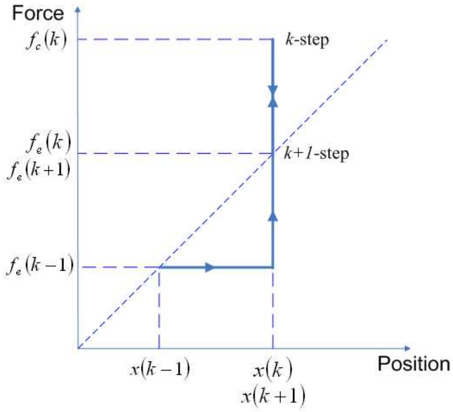

Fig. 4. Position vs. force response when the velocity become zero after the PC action

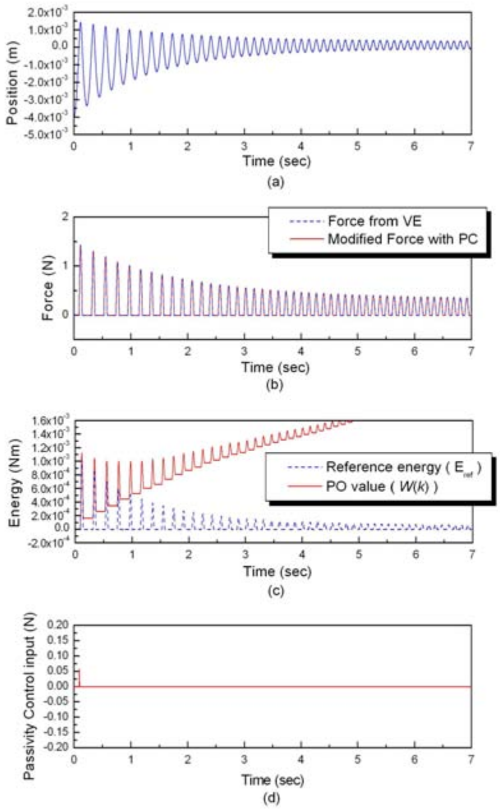

Fig. 5. Contact response with the energy following PO/PC, based on filtered velocity, for the high stiffness VE ($K = 1000N/m$). The PO value was greater than the reference energy value even though the contact was unstable.

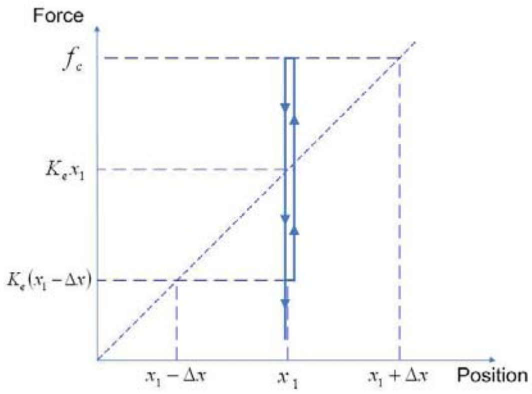

Fig. 6. Actual position vs. force response when the sign of the velocity is suddenly changed in one sample time

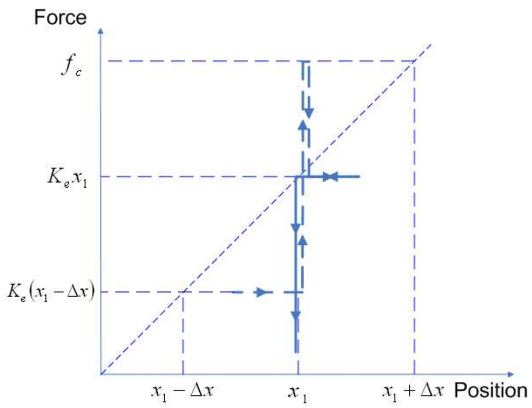

Fig. 7. Actual position vs. force response when the sign of the velocity is changed during low velocity

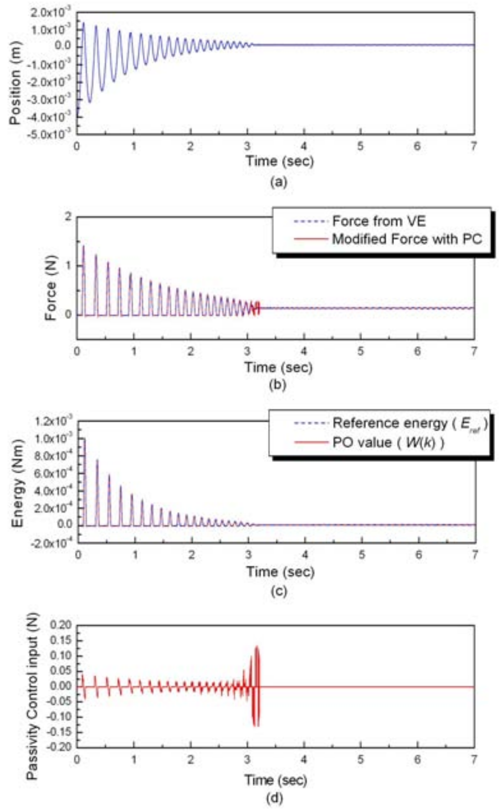

Fig. 8. Contact response with the proposed energy ignoring method from sign change

considered as follows:

$$\begin{array}{llll} If & x_1-\Delta x \le x(t_k) < x_1 & then & x(k)=x_1-\Delta x, \\ elseif & x_1 \le x(t_k) < x_1+\Delta x & then & x(k)=x_1, \end{array}$$

where Δx is the minimum resolution of the position sensor. If the actual position behavior is considered for the calculation of the PO, the more accurate and nonconservative PO value can be obtained for escaping the unnecessary PC operation. The actual position versus force response is redrawn when the sign of the velocity is suddenly changed in one sample time (Fig. 6).

Since we confined the analysis to systems that have fast enough sampling rate compared to the system mode, the position sensor usually can catch the instance when the actual position hit the digitized line, especially during the period of low velocity. If the position sensor missed the exact instance, certain amount of energy is produced by the area of rectangle like Fig. 6. However the width of the rectangle was significantly reduced, compared to Fig. 3.

Not only sudden sign change but also slow sign change could gives undesirable effect to the PO value. However this effect is ignorable if the sampling rate is fast enough. Fig. 7 shows different two paths of the actual position vs. force response when it was compressed (dashed line) and released (solid line). Note that one sample time after the actual position crossed x_1, the output force was decreased to $K_e x_1$ and stayed until the position became less than x_1. This behavior produced two rectangles. The area of upper one is the dissipated energy with the PC, and the lower one is the produced energy due to the velocity sign change. If the PO value and the reference energy were same at the begining of this graph, f_c would be same as $K_e(x_1+\Delta x)$. Please see [16]. Therefore the dissipated and produced energy would be summed to almost zero as long as the actual position is not suddenly changed.

We assume that the inherent dissipative elements in HI and HO are enough to dissipate the produced energy for the above two cases, if there is. As a result, it can be ignorable that the negative effect of the PO value from the above two sign changes.

Fig. 8 shows the result of the simulation which ignores the change of the PO value during the sign change. Noisy behavior and the PC control force were significantly reduced. However, during the transient time (near $t = 3(sec)$), some levels of noisy behavior remained (Fig. 8b,d). This was because the zero value of the velocity could not contribute to modify the PO value.

B. Holding the PC Force During Zero Velocity

Since we found that the actual velocity was nonzero even though the numerically calculated velocity was zero, The

PC force was held during the zero velocity for using the actual velocity information. In Fig. 9, the PC force was held during the measured position was constant. Even though the measured position was constant, the actual position was gradually increased from x_1 to $x_1 + \Delta x$. Therfore, the PC force could contribute to compensate the energy difference. Moreover, once the measured position became greater than or equal to $x_1 + \Delta x$, the compensated energy was automatically updated considering the actual position displacement without any PO modification.

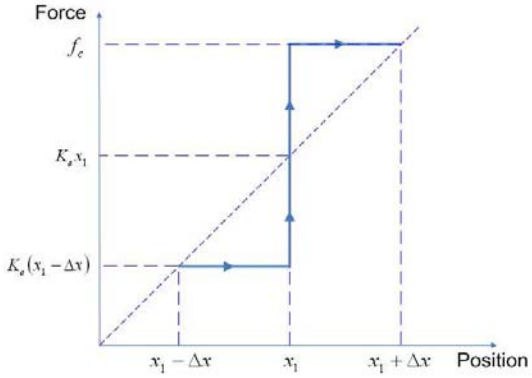

Fig. 9. Actual position vs. force response when the PC force is held while the velocity is zero

The proposed holding and ignoring algorithm were implemented to the same simulation as Fig. 8. The noisy behavior during the transient state was removed (Fig. 10b), and the nonnecessary PC force was also significantly reduced (Fig. 10d).

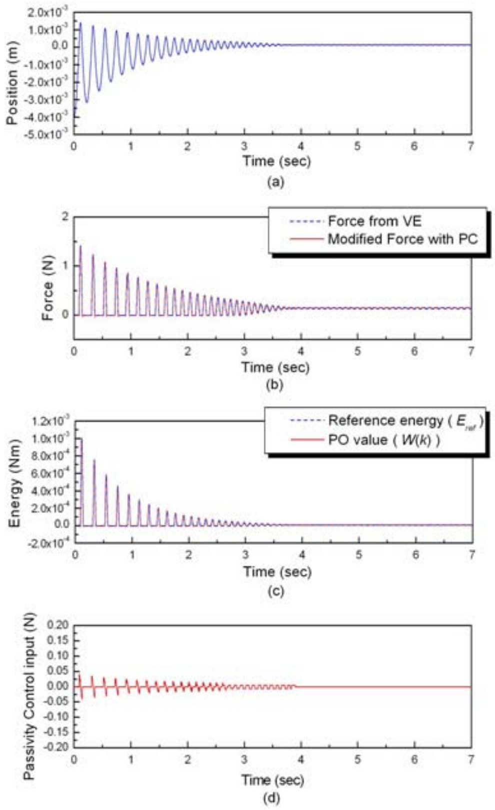

Fig. 10. Contact response with the PC force holding and the energy ignoring method as well

IV. Experimental Results

The similar experiment with the simulation in Section II and III was done with a PHANToM haptic device. We made a contact with a VE ($K = 1000N/m$) at Position > 0 by applying the previous PO/PC in [16]. The device was pushed to make a contact and operator kept pushing the VE to maintain the contact. Without the proposed methods, the similar result with the simulation (Fig. 2) was obtained. The position response seemed stable (Fig. 11a), but the modified force was vibrating (Fig. 11b), and operator felt small and continuous vibration during the period of low velocity (See Fig. 11).

By applying the proposed methods, the noisy behavior was signicantly removed, and operator felt smooth force as shown in Fig. 12.

V. Conclusion and Future Works

Methods to remove the noisy behavior of the PO/PC are proposed through the deep analysis of the simulation and experiment. There were two main reasons of the noisy behavior. One of them was the sign change of the numerically calcuated velocity. This was because we can not help estimating the future velocity for calculating the current PO/PC. The other one was the zero value of the velocity after the PC action. Since the calculated velocity was zero for the most of the time during the period of low velocity even though the actual velocity was not, the PO became conservative and generated the nonnecessary PC force. The method for solving the first problem was ignoring the difference of the PO value from the velocity sign change based on the assumption that the actual energy difference is significantly small and can be dissipatable with the inherent damping of HO and HI. The other method for solving the second problem was holding the PC force during zero velocity since the actual velocity is not zero. The feasibility of the proposed methods was proved through the simulation and the experiment, and the PO/PC approach became more practical with the proposed methods.

In some case, the produced energy from the velocity sign change may not be ignorable. If the sampling rate is not fast enough compared to the system mode, the position sensor can not catch the exact instance when the actual position crosses the digitized line. As a result, the width of the rectangle in Fig. 6 will be increased, and the amount of the produced energy may become greater than the allowable energy. Therefore, it is better to turn off the PC when the velocity sign change is repeated. To find the exact condition when the PO/PC is not effective anymore, we are studying the limitation of the PO/PC approach as a further work.

ACKNOWLEDGMENT

This work was supported in part by a grant from BK21 School of Information Technology of KAIST, and in part by a grant from ITRC-IRRC of KAIST.

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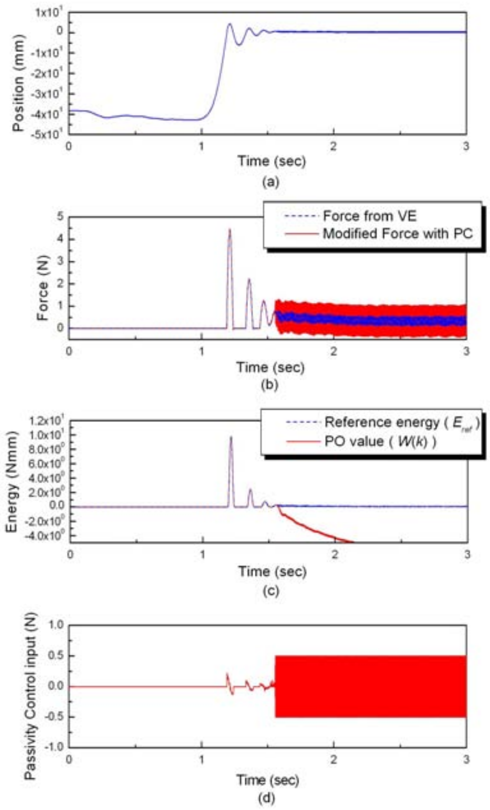

Fig. 11. Experimental result with the PO/PC without the proposed methods

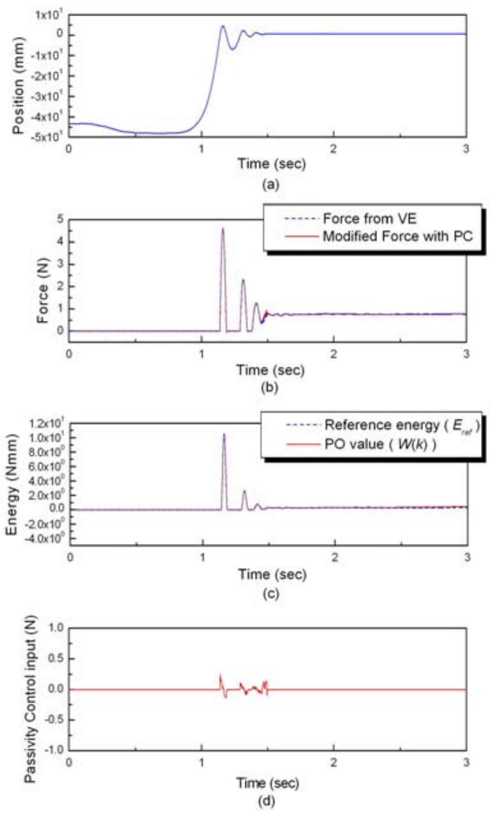

Fig. 12. Experimental result with the PO/PC with the proposed methods