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An Analog Input Shaper for Stability Enhancement of Haptic Interfaces and Its Application to Energy-Bounding Algorithm

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Abstract: An analog input shaper is proposed for a haptic control system to improve stability when interacting with virtual environments. High frequency inputs to a haptic device, which usually occur in collision with virtual objects with high stiffness, can induce limit cycle oscillations and instabilities. In order to reduce these high frequency inputs to haptic devices, an analog input shaper is added to the control system. In order to minimize the delay, which is also one of major causes of instabilities, the analog input shaper is implemented with a high-pass filter instead of a low-pass filter. Since the input shaper has its own dynamics, when a haptic pointer leaves a virtual wall, a user may feel slow decrease of impedance. Moreover there may be negative impedance as if the wall is pulling. In order to solve these problems, we add linear half-wave rectifiers which allow fast decrease of impedance and no negative input to a haptic device. The rectifiers can also eliminate the undesirable energy. The input shaper reduces the total energy supplied to a haptic device by preventing high frequency inputs from flowing into a haptic device and by using rectifiers, therefore, it can be regarded as an artificial damping element. Energy-bounding algorithm, which is an energy-based method, can guarantee stable haptic interaction by limiting the input energy. So, it inevitably sacrifices transparency in haptic interaction. The analog input shaper is incorporated into energy-bounding algorithm to increase the impedance range that the algorithm can stably display. A digital filtering scheme, which uses the same structure as in an analog input shaper, is also tested. Through experiments, we show that the analog input shaper can enhance the stability and thus increase the impedance range which can be stably displayed by a haptic device.

Keywords: Analog input shaper, haptic control, stability enhancement, artificial damping, virtual wall

1. INTRODUCTION

The human-computer interaction can be more immersive through haptic interfaces by giving users the touch sensation in response to their movements. Haptic interfaces function as input devices just like computer mice and also as output devices which reflect force. Ideally, when a haptic device contacts with a virtual wall, it should transparently display the wall's impedance while when it is in free motion a user should not feel any impedance. But in practice, transparency and stability, which mainly decide the performance of a haptic device, can be deteriorated due to several factors.

Colgate and Brown [1994] and Colgate and Schenkel [1997] suggested a performance measure, called Z-width, which meant the dynamic range of impedance that a haptic device could display while maintaining passivity. They also discussed factors affecting Z-width, such as sample-and-hold, inherent interface dynamics, encoder quantization and velocity filtering and then pointed out that the inherent damping of a haptic device was a major factor that decided the Z-width. Through experiments they showed that a physical damper applied to a haptic device played significant role in increasing the Z-width. However, the physical damper had an adverse effect, that is, since the resisting force caused by the damper always existed, a user felt resistance even when a haptic device was in free motion. Consequently, the transparency of haptic interaction was weakened while the passively displayed impedance was enlarged. Mehling et al. [2005] added a frequency-dependent analog damping circuit parallel with a motor to increase the impedance range of haptic interaction. The analog damping circuit was to dissipate unwanted energy when high frequency inputs existed, since the high frequency input could cause instabilities, in other words, it could reduce the impedance range. The frequency-dependent damping circuit added damping effects only when high frequency inputs existed, therefore when a haptic device was in free motion there was no added damping. But due to capacitance in the circuit, system inertia slightly increased when low frequency inputs entered. Weir et al. [2007] proposed another analog damping method to increase Z-width. They implemented an analog circuit to estimate the back electromotive force (EMF) which was proportional to velocity of a motor. The estimated velocity was used to determine the magnitude of added damping. In other words, when the velocity was very high, which might mean the haptic device was unstable, large damping was added and when the velocity was low enough, no damping was added. In fact, it did not add physical damping but just reduced the input to a haptic device. When commutation happens, a motor generates high frequency noises. So the damping circuit which used the voltage and current of a motor as inputs for the estimation would be also significantly affected, which resulted in highly noisy velocity estimation. In order to prevent this, they limited the range of rotation angle of a motor in which no commutation happened. Gosline et al. [2006] proposed the tunable eddy current damper which was proportional to velocity in haptic interaction.

Hannaford and Ryu [2002] proposed time-domain passivity control which was an energy-based method for stable haptic interaction. They discussed a passivity observer (PO) and a passivity controller (PC) to ensure stable contact under a wide variety of operating conditions. PO measured energy flows of the haptic system in real-time and PC was an adaptive dissipative element which absorbed the net energy output measured by PO at each sample time. In their work, sampling rate of the system should be significantly faster than the dynamics of a haptic device, human operator, and virtual environment. Kim [2007] and Kim and Ryu [2004] proposed the energy-bounding algorithm (EBA), which was also an energy-based method, for stable haptic interaction control. EBA can guarantee the stable haptic interaction by limiting the energy generated by a sample-and-hold operator within the energy which can be exhausted by the damping elements in a haptic device and by making the virtual environment passive. Also the algorithm can guarantee stable haptic interaction regardless of sampling rate.

In this paper, an analog input shaper (AIS) is proposed in order to increase the impedance of virtual walls which can be stably displayed by a haptic device. AIS can be regarded as a frequency-dependent artificial damping element which reduces high frequency inputs to a haptic

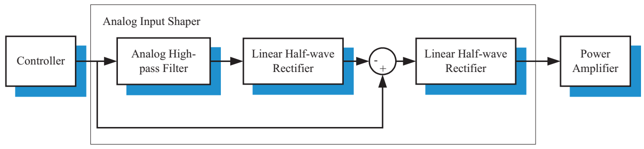


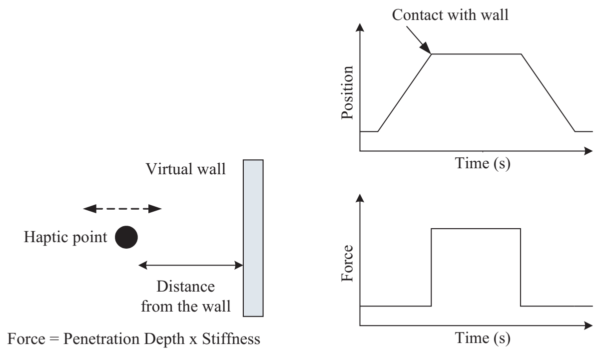
Fig. 1. Configuration of an analog input shaper

device. AIS is placed between a controller and a power amplifier, in other words, at the signal stage but not at the power stage, assuming that the amplifier operates so fast as to be regarded as being transparent to other system components, such as a haptic device, human operator, and a controller. The advantage of placing the input shaper at the signal stage is that the input shaper can be made more flexible, which means that we can use many analog signal processing schemes and also by varying the resistance and capacitance of a filter an adaptive input shaper is possible. Moreover, AIS at the signal stage causes no increase of system inertia at low frequency motion, which previously existed in the analog damping scheme due to the added parallel capacitance (see Mehling et al. [2005]). In order to minimize the delay, which is thought as one of major causes of instability in haptic control, AIS is implemented with a high-pass filter instead of a low-pass filter. Since AIS has its own dynamics, a user may feel slow decrease of impedance when a haptic pointer leaves the virtual wall and sometimes there may be negative impedance as if the wall is pulling. In order to get rid of these adverse behaviors, linear half-wave rectifiers are added in the circuit. The rectifiers are also to reduce the undesirable energy flowing into a haptic device.

This paper is organized as the following. In section 2, AIS is discussed in detail and in section 3, EBA is briefly explained . Experimental results are presented in section 4 and we discuss conclusions and future work in section 5.

2. ANALOG INPUT SHAPER

Fig. 1 shows the configuration of AIS. Basically, AIS is an analog electrical circuit composed of a high-pass filter, linear half-wave rectifiers, and adders. The high-pass filter extracts high frequency signals from inputs and the rectifiers are for the fast decrease of signal and non-negative input to a haptic device when a haptic point



(a) A virtual wall and a haptic point

(b) Position and output force

Fig. 2. Position of a haptic point and output force when the wall stiffness is assumed very high

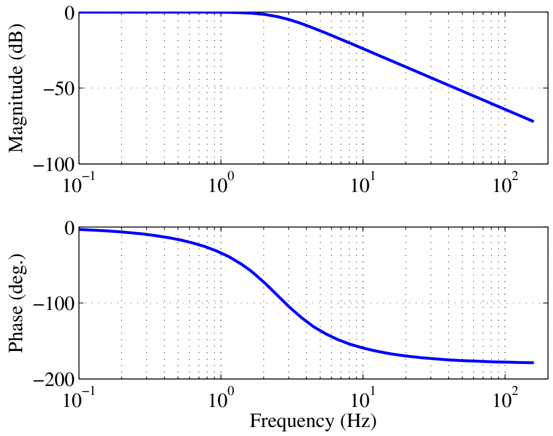


Fig. 3. Bode plot of $G_{lpf}(s)$

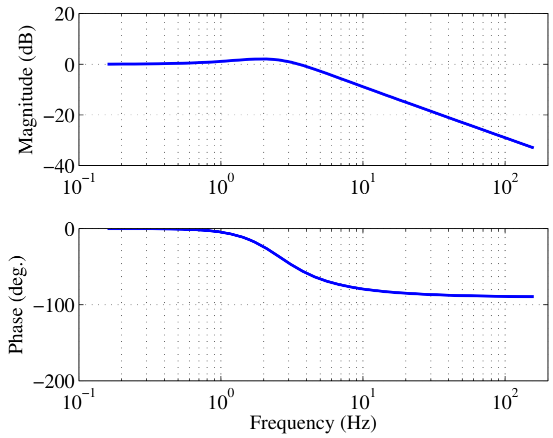
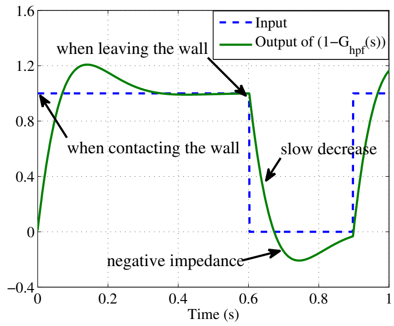


Fig. 4. Bode plot of $1 - G_{hpf}(s)$

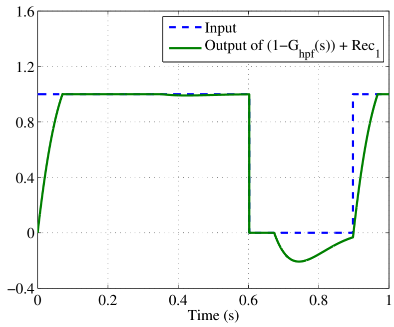
leaves the virtual wall. AIS can be regarded as a frequency-dependent analog damping in haptic interactions which has effects only on the high-frequency inputs. Therefore, when the input contains no high frequency components, typically when in free motion, AIS does not add any damping which deteriorates the performance. As can be seen in the figure, AIS is located between the system controller and the power amplifier, so there is no need to deal with power electronic components. In order to apply the rectifiers, a high-pass filter, but not a low-pass filter, is required. Moreover, using the high-pass filter induces less delay than using the low-pass filter. We will discuss about this below.

2.1 Delay (high-pass filter vs. low-pass filter)

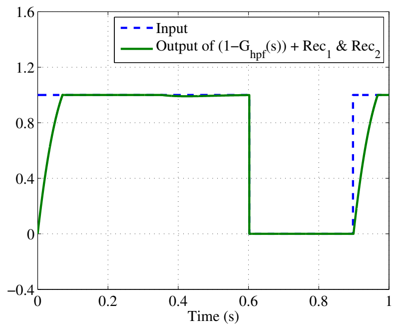
In order to reduce the high frequency components included in the inputs, usually a low-pass filter is used. But a low-pass filter brings considerable delays, which can cause instabilities in haptic interfaces. So, it can be said that the balancing between the reduction of high frequency inputs and the delay is crucial. Another way to reduce the high frequency components is to use a high-pass filter. By subtracting the output of the high-pass filter from the input, we can reduce high frequency components and this imposes much less delays than a low-pass filter.



(a) When no rectifier is used



(b) When the first rectifier is used



(c) When both rectifiers are used

Fig. 5. Functions of two linear half-wave rectifiers

Let $G_{lpf}(s)$ be the transfer function of a low-pass filter and $G_{hpf}(s)$ be the transfer function of a high-pass filter. Both are second order butterworth filters and have 2.5 Hz cutoff frequency. Fig. 3 and Fig. 4 show the frequency response of $G_{lpf}(s)$ and $1 - G_{hpf}(s)$, respectively. The operation range of haptic interaction is mainly decided by motion of a human hand and typically less than a few Hz. As can be seen in the figures, within the operation range, the delay in Fig. 4 is less than half of that in Fig. 3. Thus using a high-pass filter $(1 - G_{hpf}(s))$ will cause less instabilities than using a low-pass filter $(G_{lpf}(s))$ when considering delays. Note that the magnitude attenuation in Fig. 3 is larger than in Fig. 4, but it is thought that the attenuation when using a high-pass filter is still large enough to reduce the high frequency components.

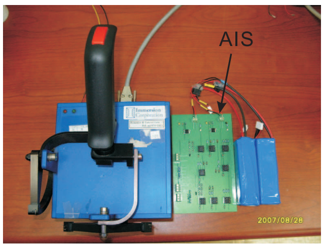
2.2 Half-wave rectifiers

As seen in Fig. 1, two linear half-wave rectifiers are incorporated into AIS. The low-pass filter $(1 - G_{hpf}(s))$, however, has its own dynamics which makes slow decrease of impedance or negative impedance when a haptic point leaves a virtual wall. Fig. 5 illustrates the functions of the rectifiers. In the simulation, the input is assumed as rectangular pulses which is the case when interacting with a virtual wall with very high stiffness (see Fig. 2).

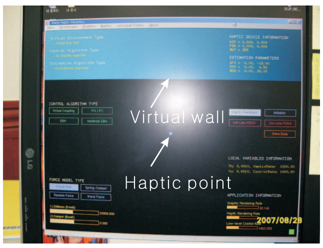
Fig. 5(a) shows the input and output of the filter $(1 - G_{hpf}(s))$ when no rectifier is used. It shows the typical response of a low-pass filter with rectangular inputs. Also slow decrease of impedance and negative impedance when a haptic point leaves the wall can be easily observed. The slow decrease of impedance when a haptic interaction point leaves a virtual wall deteriorates the transparency but also stability in haptic interaction by supplying the undesirable input to a haptic device, in other words, increasing the total energy. Fig. 5(b) shows the output when the first rectifier, which is next to the high-pass filter, is used. Fast decrease of output and the removal of the overshoot can be seen easily. The fast decrease of output can improve the transparency of haptic interaction, but it surely delivers the high frequency input to a haptic device, which may deteriorate the stability. But notice that it happens only when a haptic point leaves the virtual wall. The removal of overshoot may also improve the transparency but it also causes high frequency inputs. Fig. 5(c) shows the output when both rectifiers are used. As seen in the figure, negative impedance display is avoided. But here again, an adverse effect of the rectifiers arises, that is, in order to apply AIS in haptic interaction, an actuator should exert force in only one direction, but not both direction.

3. ENERGY-BOUNDING ALGORITHM

Kim [2007] and Kim and Ryu [2004] proposed Energy-bounding algorithm (EBA), which can guarantee stable haptic interaction by limiting the energy generated by a sample-and-hold operator within the energy which can be exhausted by the damping elements in a haptic device and by making the virtual environment passive. Also the algorithm can guarantee stable haptic interaction regardless of sampling rate. Although EBA can guarantee stability, it sacrifices performance. For example, EBA can realize the stable haptic interaction with a virtual wall of very high stiffness, but the displayed stiffness can be much lower than the actual stiffness. EBA has a parameter, called c_1, which can be set by a user. This parameter represents the estimated damping of a haptic device and a human user. In order to display higher impedance, c_1 should be set as large as possible. But if c_1 is set larger than the actual damping, it may cause instability. An artificial damping added will help this situation, in other words, AIS will increase the impedance which can be displayed by EBA and we show this by virtual wall experiments.



(a) AIS and the haptic device (Impulse engine)



(b) Virtual environments

Fig. 6. Experimental setup: AIS, haptic device (Impulse engine) and virtual wall environments

4. VIRTUAL WALL EXPERIMENTS

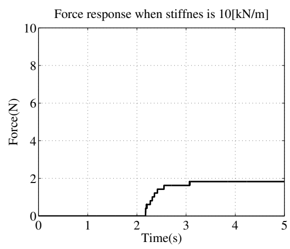
Impulse Engine 2000 (Immersion Corp.) is used as the haptic device. As shown in Fig. 6(a), it is a 2-DOF force feedback device and each axis can be controlled independently. Its maximum force output is 8.9 N/axis. The virtual environment used in the experiments is shown in Fig. 6(b). It has a virtual wall of which stiffness and damping parameters can be set by a user (In this work, the damping parameter is set to zero). Haptic control rate is 1 kHz and the graphic rendering rate is around 33 Hz. Output force is determined by multiplying the penetration depth and the virtual wall stiffness. Force output and displayed impedance are recorded when a user interacts with the virtual wall with the haptic device.

4.1 Without AIS

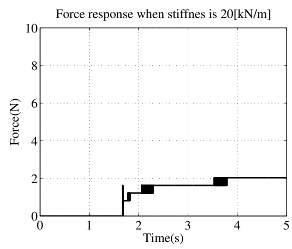
Fig. 7 shows the experimental results when the stiffness of wall is varying. Stiffness of the virtual wall is varied from 10 kN/m to 40 kN/m (damping is set to zero). With the results, it can be said that the wall stiffness which can be stably displayed by the haptic device is between 20 kN/m and 30 kN/m when AIS is not applied. The stair-like increments which can be noticed in Fig. 7(a) and Fig. 7(b) are due to the encoder resolution of the haptic device and the wall stiffness. Although the magnitude of the stair-like increments and the small oscillations in Fig. 7(b) are small, they can be sensed by a user's hand. When the interaction is unstable, the frequency of oscillation is around 100 Hz.

4.2 With AIS

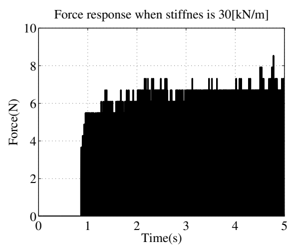
Fig. 8 shows the experimental results when AIS is added. Stiffness is varied up to 70 kN/m. As can be seen in the



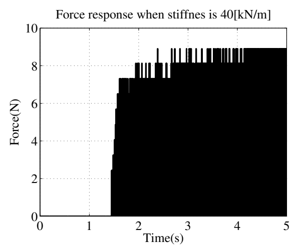
(a) $K = 10$ kN/m



(b) $K = 20$ kN/m

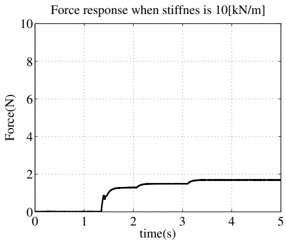


(c) $K = 30$ kN/m

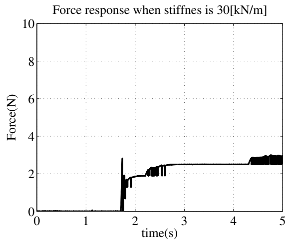


(d) $K = 40$ kN/m

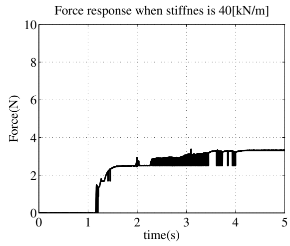
Fig. 7. Force outputs when virtual wall stiffness is varying (without AIS)



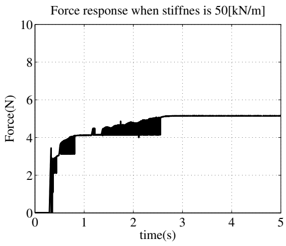
(a) $K = 10$ kN/m



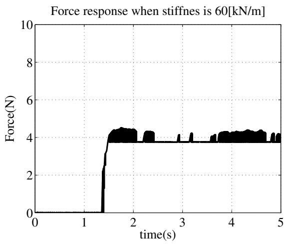
(b) $K = 30$ kN/m



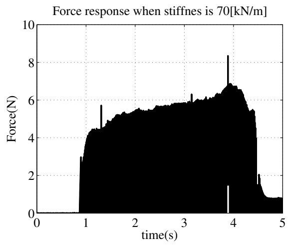
(c) $K = 40$ kN/m



(d) $K = 50$ kN/m

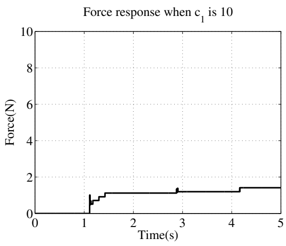


(e) $K = 60$ kN/m

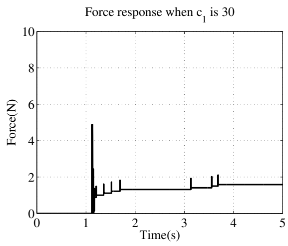


(f) $K = 70$ kN/m

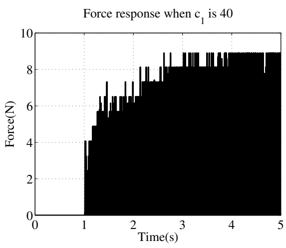
Fig. 8. Force outputs when virtual wall stiffness is varying (with AIS)



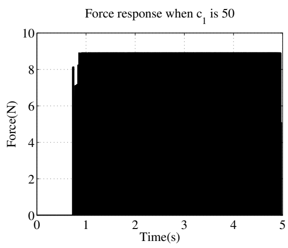
(a) $c_1 = 10$



(b) $c_1 = 30$



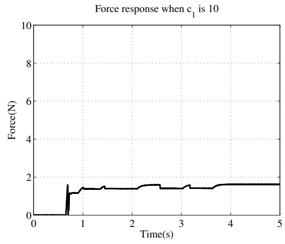
(c) $c_1 = 40$



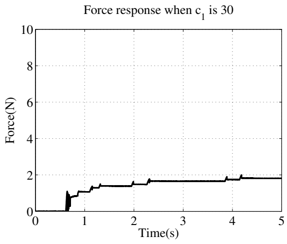
(d) $c_1 = 50$

Fig. 9. Force outputs when using EBA ($K = 100$ kN/m).

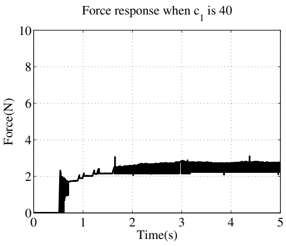
figures, stability is maintained until the stiffness is between 60 kN/m and 70 kN/m, which is much larger than the previous experiments. Notice that the stair-like increment is not evident here and small oscillations, which can be felt by a user, are measured when it is stable. We are still working on the cause of the oscillations, but, until now, it is thought that nonlinearities and high frequency inputs caused by the linear half-wave rectifiers make the oscillations. The frequency of oscillation is around 130 Hz, which can be interpreted that AIS decreases the effective inertia or increases the effective stiffness.



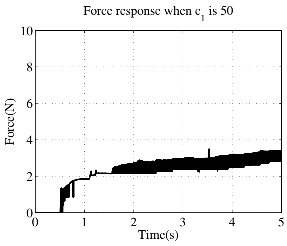
(a) $c_1 = 10$



(b) $c_1 = 30$

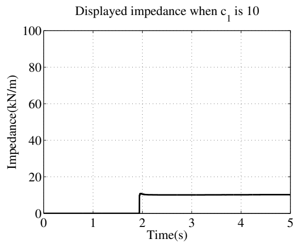


(c) $c_1 = 40$

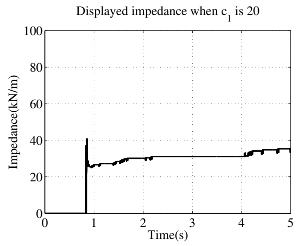


(d) $c_1 = 50$

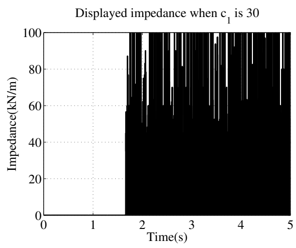
Fig. 10. Force outputs when using AIS and EBA ($K = 100$ kN/m).



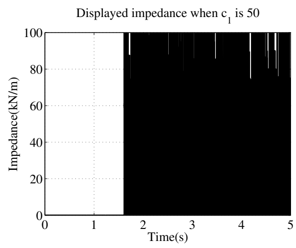
(a) $c_1 = 10$



(b) $c_1 = 20$



(c) $c_1 = 30$

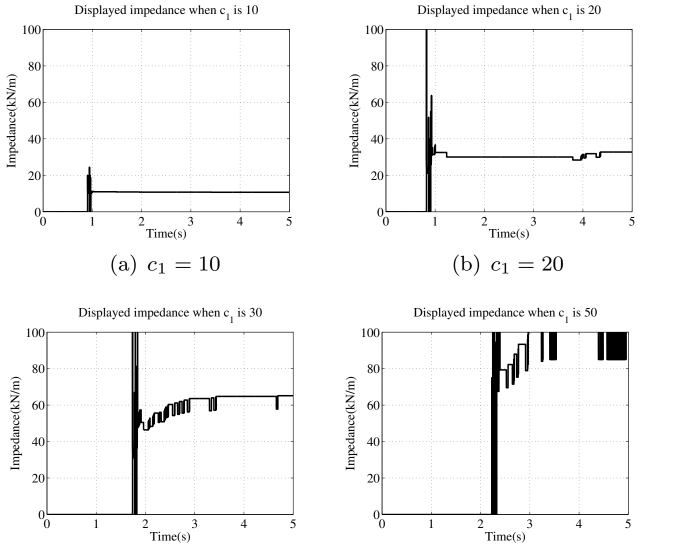


(d) $c_1 = 50$

Fig. 11. Displayed impedance when using EBA ($K = 100$ kN/m).

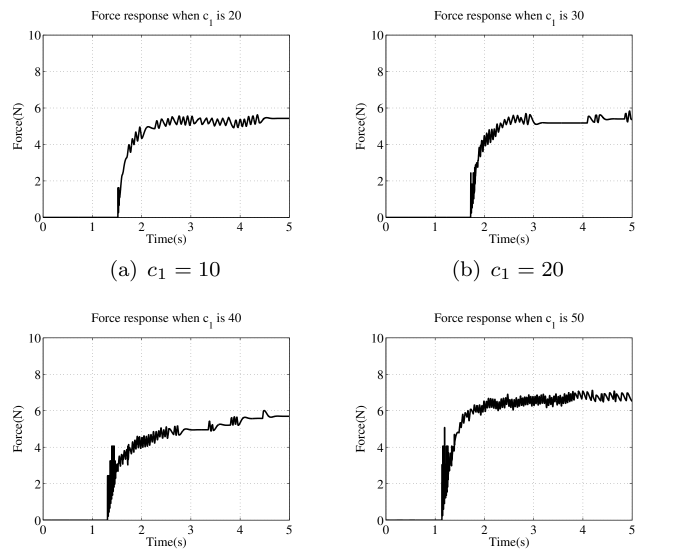
4.3 With EBA

Fig. 9 and Fig. 10 show force responses when only EBA is employed and when both AIS and EBA are employed in the haptic control, respectively. Virtual wall stiffness is set to 100 kN/m and the parameter c_1, which is already discussed, is varied from 10 to 50. As discussed before, although the stiffness is set to 100 kN/m, EBA displays much lower stiffness in order to make the interaction stable. Larger c_1 can make EBA display larger stiffness, but it aggravates stability. With the results, it can be said



(a) $c_1 = 10$ (b) $c_1 = 20$ (c) $c_1 = 30$ (d) $c_1 = 50$

Fig. 12. Displayed impedance when using AIS and EBA ($K = 100$ kN/m).



(a) $c_1 = 10$ (b) $c_1 = 20$ (c) $c_1 = 30$ (d) $c_1 = 50$

Fig. 13. Force output when using digital filtering and EBA ($K = 100$ kN/m).

that AIS can maintain stability for larger c_1 than when only EBA is used. Notice that when AIS is used, there exist small oscillations which are announced before and it is surely one of our future work. Fig. 11 and Fig. 12 show the displayed impedance when only EBA is employed and when both AIS and EBA are employed in the haptic control, respectively. As seen in the figures, when with AIS, the haptic device can display larger impedance since AIS can enhance stability. A digital filtering scheme which has the same structure (Fig. 1) as AIS is also tested. Since digital filters are more flexible and easier to implement than analog ones, they should be more promising if this scheme works. Fig. 13 shows the force output when the digital filtering scheme is incorporated into EBA. When compared with Fig. 9 and Fig. 10, it can be said that digital filtering can also enhance the stability.

5. CONCLUSION

An analog input shaper for haptic control is proposed in this paper. AIS is intended to eliminate the unwanted high frequency inputs which can cause the instabilities. Unlike the previous researches, AIS is placed between the system controller and the power amplifier. For fast decrease and no negative input, when a haptic point leaves the virtual wall, linear half-wave rectifiers are used. Experiments with a 2-DOF haptic device show that AIS can enhance the stability in the haptic interaction, thus increase the stiffness that can be displayed by a haptic device. And by applying AIS to EBA, the impedance range that EBA can display is significantly increased. A digital filtering scheme also shows similar experimental results. Future work includes that analytical ways to find the optimal filter parameters and the causes of the small oscillations occurred when AIS is used will be explored.

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