Increasing the Impedance Range of a Haptic Display by Adding Electrical Damping
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Increasing the Impedance Range of a Haptic Display by Adding Electrical Damping

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Abstract

This work examines electrical damping as a means for improving haptic display performance. Specifically, electrical damping, like its mechanical counterpart, can significantly reduce the occurrences of limit cycle oscillations at high impedance boundaries in virtual environments. Furthermore, electrical damping has a number of advantages including its simplicity of design and the ease at which it can be made frequency dependent so that it does not adversely affect a device's low impedance range. This work examines the theoretical behavior and practical application of frequency dependent electrical damping as it applies to haptic displays. Data is presented illustrating a significant increase in the range of virtual wall behaviors that a one degree-of-freedom device is capable of displaying when electrical damping is added.

1. Introduction

Haptic display devices have a limited range of virtual environments, objects, and surfaces that they are capable of rendering effectively. For common impedance causality haptic displays, which output a force in response to a user's motion, these device limitations can be described in terms of an impedance range. Impedances, or dynamic relationships between velocities and forces, are quite varied in the physical world; yet, only a limited range of impedances can be exhibited with a given haptic display. For example, devices are limited in the low impedance range by their inherent friction, mass, and other physical characteristics. This means that a user's motion while interacting with a haptic device will never feel completely unhindered because some minimum mass, minimum damping, or other small resistive force will always be felt. On the other hand, haptic displays can be limited in the high impedance range by sampled data effects, time delay, sensor quantization, or noise [1]. This means that a user's motion while interacting with a haptic device will never feel as completely constrained as it would when interacting with a stiff surface. In fact, it is well known that haptic devices often lose stability and begin to oscillate when attempting to represent high impedances.

A goal in haptic display design is to maximize impedance range so that a wider range of virtual environments can be modeled stably and effectively for the user. This paper focuses on the potential for expanding the high impedance range of haptic displays. Past work towards this goal can, for the most part, be classified under one of two headings. The first of these is the use of psychophysical means to understand how people interpret the feel of surfaces and impacts. Novel modeling techniques can then be used, with these results in mind, to make a user think that a virtual surface has a higher impedance than the device is otherwise capable of rendering. In fact, it has been shown that *perceived* stiffness or wall hardness can be affected by means other than strictly increasing the stiffness and damping of a virtual surface model [2], [3]. In contrast to developing novel techniques to work within a given device's limits, another method for improving the haptic display of virtual environments is to *physically* expand the range of impedances that a device is capable of displaying without exhibiting unstable limit cycle behavior. This is especially interesting because improvements made to a device itself will increase the effectiveness of both traditional virtual environment models and the more complex models that employ perceptual techniques.

To improve upon the limiting characteristics of the zero-order hold, both Ellis, et al. [4] and Gillespie and Cutkosky [5] developed better methods for approximating the behavior of continuous systems. Hannaford and Ryu [6] took another approach to increasing impedance range, developing a method for both measuring and dissipating excess energy that could cause instabilities. Hasser [7] investigated the limit cycle behavior of a haptic knob and its relation to the sample time and position quantization of the display device. Colgate and Brown [8] also investigated how the discrete characteristics of a system such as encoder resolution and sample time can affect the ability of a haptic display to render stable virtual walls. In addition to this they found that, far beyond any other changes that were made to their system, the addition of physical damping to the haptic display provided the greatest increase in device impedance range.

Adding physical mechanical damping is not without problems, however. Using a viscous mechanical damper connected to the output shaft of a direct drive haptic display as Colgate and Brown [8] did, improves performance at a virtual wall boundary, but at the cost of performance outside the wall. Away from the wall, the user still feels the physical damping as he tries to move about freely. This adversely impacts the range of low impedances that the device is capable of displaying. To get around this problem, negative virtual damping can be used so that the device assists the user's motion outside the wall, canceling out any effects of the mechanical damper [9], [10]. This technique, in theory, makes the device more transparent while still preserving the damping at the virtual wall boundary. In practice, however, viscous mechanical dampers can be highly nonlinear and temperature dependent. Thus, negative virtual damping cannot be added based only on a simple model of the damper. Forces must be measured in real-time and compensated for accordingly as in Brown's work [9]. This necessitates a more complex device design that might not be desired. Therefore, it is desirable to look for an alternative means of increasing the physical damping of a haptic display.

2. Electrical Damping

2.1. Theoretical Behavior

One such alternative for increased damping is to introduce damping on the electrical side rather than the mechanical side of the system's drive motor. Using a one degree-of-freedom device modeling a virtual wall as an example, it is seen that this can be accomplished by inserting an electrical resistance in parallel with the motor (Fig. 1b). After analyzing the constitutive relations of such a system it is seen that the equivalent mechanical damping that this electrical system adds is

$$B_{eq} = \frac{K_t^2}{\left(R_1 + R_m\right)}. \tag{1}$$

where K_t is the motor's torque constant, R_m is the motor's internal resistance, and R_1 is the added parallel resistance.

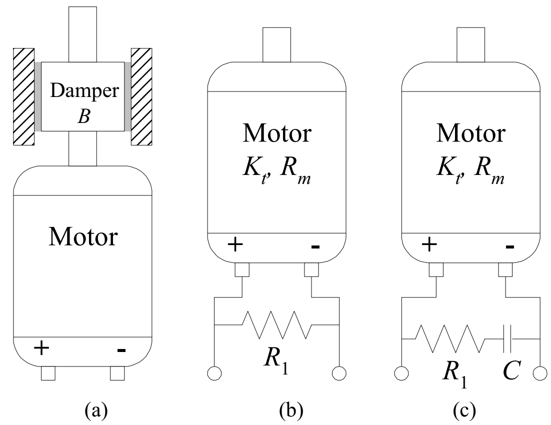

Figure 1: A mechanically damped system (a) and two electrically damped systems; one without (b) and one with frequency dependence (c).

With only an added resistor the electrical system acts just as a mechanical damper, dissipating energy throughout the device's range of motion. An improvement can be made, however, by adding a capacitor in series with the added parallel resistance (Fig. 1c). This makes the electrical damping frequency dependent. The values of resistance and capacitance can be chosen to give the system a cutoff frequency around the normal bandwidth of human hand motion (a relatively small 2 Hz [11] to 4.5 Hz [12]). Thus, away from any constraints, when movement is governed almost entirely by inputs from the human user, the system acts as if there is no extra damping. When a high frequency event occurs, as in impacting a virtual wall, the electrical damping can serve to prevent the energy growth that leads to limit cycle oscillations and other instabilities. This method of providing real physical damping, therefore, eliminates the need for unwieldy mechanical dampers while also simplifying the control structure and device design by doing away with the need for negative virtual damping.

To further understand the behavior of an electrically damped system, a one degree-of-freedom device with electrical damping can be modeled (as in Fig. 2) and the following system transfer function can be analyzed. This model omits friction and structural compliance for simplicity.

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$$\tau(s)=K_t n\left[\frac{R_1 Cs+1}{LCs^2+(R_1+R_m)Cs+1}\right]I(s) - \left[\frac{K_t^2 n^2 Cs}{LCs^2+(R_1+R_m)Cs+1}+n^2(B+Js)\right]v(s) \quad (2a)$$

$$\tau(s) = A(s)I(s) - Z(s)v(s) \quad (2b)$$

where:

$\tau(s)$ = motor torque
K_t = motor's torque constant
n = transmission ratio
L = motor's inductance
R_m = motor's internal resistance
B = inherent mechanical damping of system
J = mechanical inertia of system
R_1 = added parallel resistance
C = added parallel capacitance
$I(s)$ = current from amplifier
$v(s)$ = angular velocity of motor output shaft

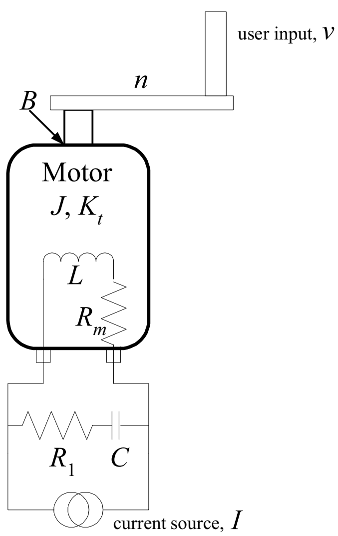
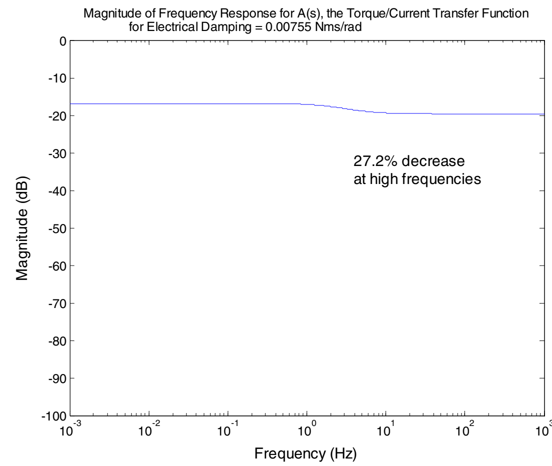


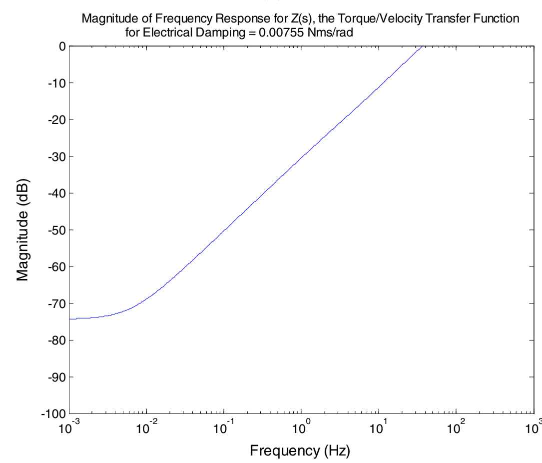
Figure 2: Model used for analyzing the theoretical behavior of a one degree-of-freedom haptic display with electrical damping

Here, it is seen that the torque, τ, is responsive to two inputs: the current from the amplifier, I, and the angular velocity of the motor shaft, v.

The system characteristics of the device used in testing (described in Section 3) can be substituted into (2a) and the resulting frequency responses can be plotted to obtain a more complete picture of haptic display performance. First, velocity is assumed to be zero and the resulting plot of the magnitude of A(s), Fig. 3a, shows the frequency response of torque to a current input (specific parameter values are given in Section 3). It is desirable to have this plot constant, or as close as possible, because any shift in this effective "torque constant" corresponds to a change in the ability of a commanded current to output a desired torque. While the goal of electrical damping is to dissipate unwanted energy at high frequencies, the ability to control the haptic display with current commands of reasonable magnitude, at all frequencies, must be maintained.



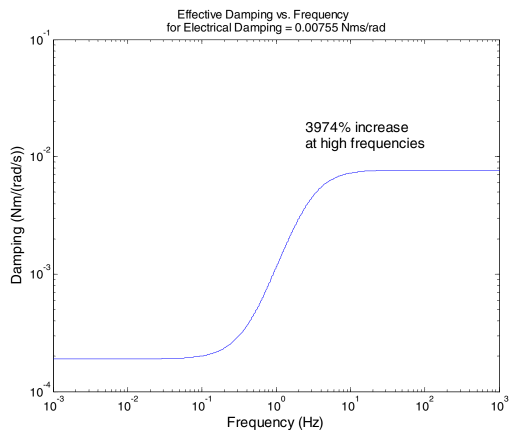
(a)



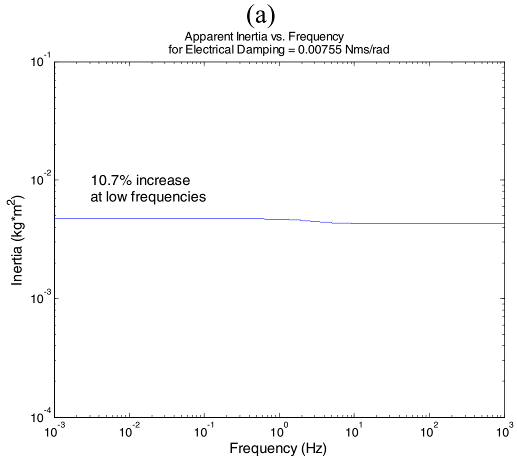
(b)

Figure 3: Magnitude portions of the Bode plots for the transfer functions A(s) (a) and Z(s) (b) for a system with 0.00755 Nm/(s/rad) of electrical damping

If current rather than velocity is assumed zero, the magnitude of Z(s), the transfer function from velocity input to torque output can be plotted (Fig. 3b). This magnitude can be further broken down into its real and imaginary components (see Fig. 4). Re{Z(s)} corresponds to the effective damping of the system while Im{Z(s)}/ω represents the apparent inertia felt at the device output. From these plots it is clear that significant additional damping is added to the system at high frequencies, and only high frequencies. Also, motions at low frequencies experience only a slight increase in system inertia due to the added parallel capacitance. Thus, electrical damping can aid in stabilizing high frequency events like an impact with a virtual wall, while not hindering a user's unconstrained motion away from the boundary.



(a)



(b)

Figure 4: Theoretical effective damping (a) and apparent inertia (b) obtained from Z(s) for a system with 0.00755 Nm/(s/rad) of electrical damping

2.2. Design Considerations

Integration of electrical damping into a haptic display device involves a number of tradeoffs. From (1) it can be seen that the amount of electrical damping introduced into a given system is maximized when R_1, the added parallel resistance, is minimized. Thus,

$$\max_{R_1} B_{eq} = \frac{K_t^2}{R_m}. \tag{3}$$

This suggests that to get the greatest benefit from an electrically damped system, a motor with a large torque constant relative to its internal resistance should be chosen. But, as R_1 is decreased, the drop in effective torque constant at high frequencies (seen in Fig. 3a) increases. This requires an increase in command current to output high frequency torques. Additionally, as R_1 is decreased the capacitance in the system must be increased to keep the cutoff for the frequency dependent electrical damping (seen in Fig. 4a) constant. Aside from the practical issue of getting larger capacitors, the added capacitance is the only characteristic of the electrically damped system that has an adverse affect on the device's behavior when modeling low impedances. Thus, it is desirable to keep the added capacitance small to minimize any perceived increase in inertia for the user.

Many of the factors affecting the performance of a haptic display with frequency dependent electrical damping have been considered, but an optimal design for such a device has yet to be developed. Rather, work has focused on experiments designed to determine the practicality of such a system in an effort to understand how this theory might be applied to the design of future haptic display devices.

3. Experimental Setup

To test the practical application of electrical damping, a one degree-of-freedom haptic display has been designed and built. The device consists of a DC brushed motor (K_t = 0.1441 Nm/A, R_m = 0.75 Ω) attached to an optical encoder with a resolution of 120,000 counts per revolution. Also attached to the motor shaft is a crank handle, 0.15 meters in length, and all of these components are mounted inside an aluminum frame. The motor is driven by a PWM amplifier and 200 μH series inductor.

To add electrical damping to the system, arrays of readily available 2200 μF bipolar capacitors and various power resistors are combined to give one of two circuits. The first has an equivalent capacitance of 0.022 F in series with an equivalent resistance of 2 Ω and the second has an equivalent capacitance of 0.044 F in series with an equivalent resistance of 0.625 Ω. Either one of these circuits can be placed in parallel with the motor to create a system with frequency dependent electrical damping. They add 0.00755 Nms/rad and 0.0151 Nms/rad of electrical damping respectively and both circuits have a cutoff frequency of approximately 2.6 Hz.

The virtual environment implemented by the control system is a common virtual wall model consisting of a virtual spring and damper in mechanical parallel coupled with a unilateral constraint operator. The virtual spring stiffness, K, and the virtual damping coefficient, B, are set in software and can be changed to vary the type of virtual wall being displayed. In effect, the wall model is a version of proportional-derivative (PD) control. For use in this feedback loop, position is obtained by the system's encoder and a velocity estimate is calculated using backward difference differentiation and a second order low pass software filter with a cutoff frequency of 30 Hz (a value of which has been used in the past and found to illicit more realistic feeling walls than those displayed without a filter [9]).

This implementation lends itself to using Z-width plots to classify the impedance range of the system (as developed in [8]). As a means for determining the stability of a given wall model, the motor is provided with an offset torque to drive the handle into the virtual wall. Once at the wall, the virtual model counteracts the offset torque and brings the handle to rest if the wall model is stable. If unstable limit cycles occur, however, the handle will oscillate with noticeable amplitude at the wall boundary (as measured by the system's encoder) and the given wall model is then classified as being outside the system's range of stable impedances. While haptic display devices are specifically designed for interaction with a human operator, an automated stability test that takes the human out of the loop was used so that variations between user grasps would not affect the experimentally determined stability boundaries.

4. Experimental Results

4.1. Stability Boundaries and Z-width Plots

Tests were conducted for systems with no electrical damping, electrical damping of 0.00755 Nms/rad, and electrical damping of 0.0151 Nms/rad. Fig. 5 summarizes these tests with a plot of the average stability boundaries for all three cases. A larger area under the curve represents a greater number of virtual walls, or a larger impedance range, that the device can display stably. From this, it is clear that the addition of electrical damping dramatically increases the scope of a haptic display's usefulness. Also, because higher peak values in stiffness and damping tend to correspond to more realistic walls as judged by the user, electrical damping greatly increases the effectiveness with which a device will display virtual walls. Plus or minus one standard deviation for each curve is also plotted in Fig. 5 and this illustrates a larger variance in the highest damping runs, especially near the curve's peak. This reflects the increased effects of nonlinearities including friction, encoder quantization, and amplifier deadband at the higher impedance levels.

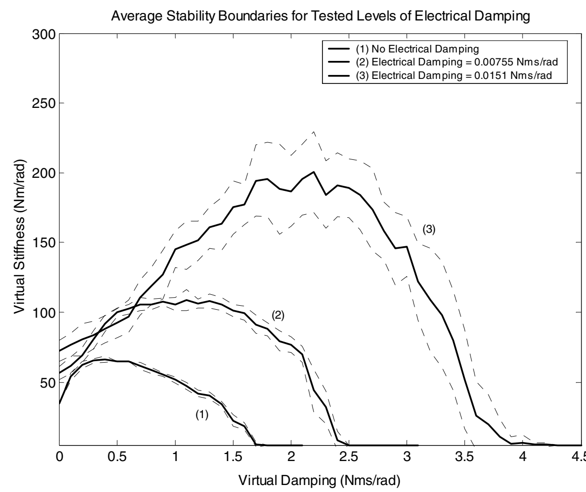


Figure 5. Z-width plot of the average stability boundary for each level of electrical damping. Dashed lines indicate plus or minus one standard deviation.

These variations in stability boundary between trials make it difficult to predict device behavior at any given point. This is a problem beyond the scope of this work. However, it is clear that a boundary does exist and that shifts in this boundary due to the addition or subtraction of electrical damping fall well outside any range of uncertainty or variation in the boundary observed experimentally.

4.2. User Perception of Improvement

An automated stability test has been used to expedite data collection, but this should not suggest that users cannot perceive the improvements made by the addition of electrical damping. In fact, if a wall model is chosen away from the stability boundaries in Fig. 5 (eg. K = 100 Nm/rad and B = 2.5 Nms/rad), the difference between levels of electrical damping are immediately felt upon impacting the virtual wall with a standard four fingered grip on the handle. Plots of handle position versus time clearly show that the added damping eliminates perceptible oscillations [13].

4.3. Effective Torque Constant

One adverse effect of the electrical damping technique is a small reduction in the effective "torque constant" of the system (i.e. the magnitude of A(s)) at high frequencies (seen in Fig. 3a). A series of measurements of A(s) were made by fixing the device handle to a force sensor and driving the system with sinusoidal currents at various frequencies. The experimentally determined magnitude of this transfer function was found to be quite similar to that predicted by the system model of (2) in all cases. This confirms that improved practical performance is achievable through the implementation of frequency dependent electrical damping.

5. Conclusions and Future Work

Both the analysis of a theoretical model and experimental data taken with a one-dof haptic display incorporating a custom-built electric circuit demonstrate that electrical damping can enhance the stability of high impedance virtual environments. Furthermore, the added damping acts on the system at high frequencies only. Thus, high impedance modeling can be improved without any human-perceptible sacrifice in performance.

An important next step is to explore how commutation, either with brushes or with electronics, affects the behavior of the electrical damping circuit proposed here and how the system might need to be changed in order to behave similarly.

The novel design of motor amplifiers might also serve to extend the benefits of electrical damping to systems with commutation. Recent work by Pratt and colleagues [14] suggests that while motor amplifiers govern a constant relationship between a command and output current, it might be possible to vary their behavior in accordance with some other predefined system model. Due to both the high update rate of the current feedback loop (often measuring tens of kHz) and the collocation of the voltage output and current sensing, this type of a discrete approximation of a continuous system might be relatively immune to many of the problems associated with the addition of traditional virtual damping.

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