A Simplified Approach to Admittance-type Haptic Device Impedance Evaluation

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ABSTRACT
Evaluating the transparency, or output impedance more generally, of admittance-type haptic devices is challenging due to their inherently non-back-drivable mechanical characteristics. To address this, we describe a new, simplified evaluation approach that eliminates the need for external test fixtures. The simplified approach relies on the easily obtainable closed-loop position control response of the device in combination with a device/system dynamic model. In addition to evaluating output impedance, the approach can be used to evaluate the overall stable rendering range of the device. Finally, the limitations of the approach are discussed.

Keywords: Haptics, Admittance, force control

Index Terms: Performance evaluation, admittance, force control, minimum inertia

1 INTRODUCTION
In general, haptic devices can be categorized as impedance-type or admittance-type devices, based on the device characteristics and the control schemes used. Impedance-type devices are generally back drivable, operated open-loop, can easily render low inertia and low stiffness and generally have less output force. Contrary to this, admittance-type devices are generally non-back drivable, operated closed-loop, used to render high inertia and high stiffness and can generally render high output forces.

In the evaluation of impedance-type and admittance-type haptic devices, transparency, or output impedance more generally, is an important performance characteristic, as it directly measures the ability of the device to render zero forces in the presence of user-imposed device motion [1, 2].

In an impedance type device the transparency is measured by the friction present in the system which can be experimentally obtained through simple (slow) user motion. In addition, it is generally not difficult to determine the output impedance of an impedance-type device, either through modeling of the device’s mechanical dynamics or more directly through experimentation. In this case, the output of the device is driven through prescribed displacements while the interaction forces are measured as a function of frequency.

However, unlike impedance-type devices, experimental assessment of the output impedance of admittance-type devices can be challenging, as these systems are inherently non-back drivable, particularly in the frequency range above the closed-loop bandwidth of the admittance controller where the output impedance of the system is very high. While some researchers have developed alternative methods to assess output impedance [3–6], these methods can be complex to implement, requiring experimental equipment capable of acting as a pure force source1 over a wide frequency range or requiring acceleration measurement of the haptic interface, to name a few. As a consequence, it is difficult to assess and compare the performance of admittance-type devices in general.

2 SIMPLIFIED APPROACH
In this paper we propose a new, simplified approach to evaluate the output impedance of an admittance-type haptic device that eliminates the need for external test fixtures and instead relies on the easily obtainable closed-loop position control response of the device in combination with a device/system dynamic model.

The validity of the approach relies on the non-back drivable characteristics inherent to admittance-type devices. To understand this, we examine a general system dynamic representation of a haptic system, including device and human user dynamic coupling. The system model, represented in both lumped-parameter form (Figure 1) and block-diagram representation (Figure 2) is complex and is not amenable to traditional loop stability analysis commonly used to assess closed-loop control stability due to the coupling of the user applied force.

Figure 1. Lumped-parameter model of admittance-type haptic device, including coupling to human impedance model [6].

However, recognizing that the output impedance of the inner-loop high-gain position controller is very high, we can ignore the effects of the reflected force in the dynamic model (see Figure 2). In this case, the system model reduces to a single feedback loop. As a consequence, classical control theory stability assessment, (e.g., using phase and gain margins), can be used to assess the stability of the system. In this case, the range of virtual admittances that can be stably displayed by the system under consideration can be evaluated by examining the simplified system’s stability margins as the virtual admittance parameters are varied. In addition, the output impedance of the system can be evaluated directly from the system model as shown in Figure 2.

1 A pure torque source is capable of applying a force over a wide frequency range with no magnitude or phase distortion. In addition, a pure torque source has, by definition, zero output impedance. In practice, these requirements are difficult to achieve, particularly when high forces are required.
To ensure that the simplified model provides an accurate evaluation, one must assess both the closed-loop frequency response of the inner position loop, as measured by the position output at the device-user interface, and the parameters of the human impedance model. Typically, sensors mounted on the system for the purpose of closed-loop position control provide the required instrumentation to determine the frequency response of the inner-position loop. In addition, tuning the human impedance model parameters [7], shown in Figure 1, is relatively straightforward, as the high output-impedance of the inner-loop position controller, in combination with the availability of a force sensor embedded in the admittance device, allows for straightforward assessment of the human impedance model parameters—requiring no additional instrumentation. The ability to use the device under consideration to evaluate the human impedance model parameters is helpful as those parameters are strongly influenced by the user-interface of the specific device.

3 EXPERIMENTAL DEMONSTRATION

To demonstrate the approach we examine an admittance-type haptic device previously described in [8] and shown in Figure 3. The system under consideration employs high output impedance piezoelectric actuators and a high gain position controller.

As described in Section 2 we must assess both the closed-loop frequency response of the inner position control loop, and the parameters of the human impedance model.

To evaluate the closed-loop frequency response of the inner position control loop, the system was commanded to move sinusoidally over a range of frequencies. In this case, the very stiff actuator and drive train resulted in a nearly flat frequency response, with little or no phase or magnitude distortion within the range of frequency tested as shown in Figure 4. In this case, the first flexible mode of the system, estimated to be approximately 50 Hz, is not visible.

The human impedance model parameters were evaluated by fitting the frequency response of the model to the frequency response of the open loop system obtained by commanding sinusoidal trajectories and measuring the output force with human subjects holding on to the input knob. Figure 5 shows the experimental frequency response (an average of two human subjects) and the fitted model of the human impedance.

Using the experimentally obtained frequency response data, we can evaluate the stability of desired virtual admittances. Of particular interest for admittance type devices is the evaluation of the minimum value of virtual inertia, below which the system cannot operate stably. To estimate this minimum inertia, we examine the stability margins of the simplified system model shown in Figure 2 as a function of various values of virtual inertia, m. In this case the damping and stiffness admittance values are set equal to zero while the delay is a function of the selected system sample rate (in this case 4000 Hz). As seen in Figure 6, the point at which the phase margin crosses zero corresponds to an inertia of 45 grams. This compares well to the experimentally obtained value of 50 grams. When the delay is increased (by reducing the sample rate), the minimum inertia predicted by the simplified model increases. This change closely tracks the experimentally obtained values as shown in Figure 6.

Figure 2. Block diagram representation of admittance-type haptic device.

Figure 4. Experimentally obtained closed-loop frequency response of the inner position control loop. The response of the unloaded system is shown in red while the response of the loaded system (by a human user grasp) is shown in blue. Note that the loaded and unloaded response are essentially identical, verifying the non-back driveable characteristics of this particular system.

Figure 5. Overlaid plot of the experimental frequency response of the human impedance and the fitted model response for two different human subjects.

Figure 3. Admittance-type haptic device used to demonstrate proposed approach.
In this case, the output impedance is dominated by the reflected motor inertia and friction. It must be noted that while the output impedance evaluation may be valid over a wide frequency range, it can only be guaranteed over the more limited frequency range where the closed-loop position loop frequency response of the inner-loop position controller was evaluated (see Figure 4). For example, unmeasured flexible modes in the drive train will have a significant effect on output impedance prediction if not explicitly measured and included in the simplified model.

4 Approach Limitations

While the approach presented offers significant advantages as compared to existing methods, care must be taken when it is applied. In particular, the fundamental assumption made, namely that the system is inherently non-back driveable, must be a reasonable one for the system under consideration.

To understand the range of applicability in regards to device type, we can examine the predicted output impedance of a hypothetical system as a function of output impedance of the open-loop position drive system, consisting of the drive actuator, gear reduction, and driven output (see Figure 1). As the open-loop drive system impedance is reduced, in this case by modifying the gear reduction between the actuator and the driven output, the system’s output impedance response changes. However, as the gear ratio, \( N \), is decreased the closed-loop position control bandwidth of the inner position controller does not generally change – as the maximum achievable bandwidth is commonly limited by factors other than gear reduction, such as unmodeled dynamics such as drive-train compliance. As such, the change in overall system output impedance may not be apparent from experimental evaluation of the inner position control loop. This effect can be seen in Figure 8 where the output impedance, as predicted by the simplified model, is shown alongside the output impedance of the full system, including the effects of the reflected user forces.

In this case, the virtual admittance block was set to render the minimum stable inertia of 50 grams evaluated for the nominal system. As seen in Figure 7, the output impedance at low frequencies closely tracks that of a pure inertia, where \( Z_d(s) = ms^2 \) and \( m \) is equal to the minimum stable inertia of 50 grams. Above the closed-loop bandwidth of the inner-loop position control, the output impedance of the system reverts to that of the open-loop, uncontrolled system, with the subsequent increase in output impedance.

Figure 6. Open-loop transfer function of the simplified system model shown in Figure 2, tuned to the parameters of the experimental system shown in Figure 3. The gain of the transfer function was adjusted by varying the virtual admittance inertia, \( m \), such that the system was on the boundary of stability.

Using the simplified system model, we can examine the system’s output impedance as a function of frequency (see Figure 7). In this case, the output impedance, \( Z_d(s) \), is defined as the transfer function relating the output force, \( F_d(s) \), as measured at the device input, to device input displacement, \( X_d(s) \)

\[
Z_d(s) = F_d(s)/X_d(s)
\]

(1)

Figure 7. Output impedance of example admittance-type haptic device

Figure 8. Deviation in output impedance as the drive axis gear ratio is varied.

The deviation in the predicted output impedance between the simplified and full system is particularly apparent above the closed-loop bandwidth of inner position loop controller where the impedance is dominated by open-loop characteristics of the system, including the effects of the unmodeled reflected user forces. Similarly, the range of predicted stable admittance parameters can be in error if the non-back driveable assumption inherent to the approach is violated.

Finally, it is important to note that the approach described here is essentially linear, in that the effects of backlash, saturation, and
other nonlinear characteristics are incorporated into the method only in the sense that they are present during the experimental characterization of the system. Particularly when the device under investigation has low open-loop output impedance, where the static stiffness of the position control is low, the effects of actuator saturation can be significant and must be accounted for.

5 CONCLUSIONS

A new, simplified evaluation approach to assess the output impedance of admittance-type devices has been presented. The approach eliminates the need for external test fixtures. The simplified approach relies on the easily obtainable closed-loop position control response of the device in combination with a device/system dynamic model. In addition to evaluating output impedance, the approach can be used of evaluate the overall stable rendering range of the device. While the approach presented offers significant advantages as compared to existing methods there are limitations to its application which must be carefully considered.

REFERENCES


