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Perception Centered Transparency Evaluation of Wave-variable based Bilateral Teleoperation

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***Abstract*—Wave-variable transformation is a means to maintain stability of haptic teleoperation in the presence of communication time delays. Its drawback is that it affects haptic perception of remote properties and thereby degrades transparency. This paper studies the effect of wave-variable transformation on human haptic perception. Based on a framework of haptic perception developed in previous work, we systematically investigated how the wave variable affects human perception of damping, mass and stiffness properties of an arbitrary linear environment. Both the original wave-variable approach and the generalized wave-variable approach are investigated. Results show how both approaches change human perception of all three mechanical properties of the environment, and how these changes vary with both excitation frequency and time delay. The generalized wave-variable approach on the whole outperforms the original in terms of rendering mass and stiffness, but not always for rendering damping. Results also show that human perception of the dynamics rendered by both approaches is similar to that of the original environment only when time delays are small. As the time delay increases, evaluating the mechanical properties can become very difficult for a human operator if the interaction with the environment is not static.**

***Index Terms*—Teleoperation, Transparency, Wave variable, Haptic perception, Mechanical properties**

I. INTRODUCTION

Bilateral teleoperation enables a human operator to operate on a remote or hazardous site without the need for physical presence, while rendering the force feedback to let the operator sense mechanical properties – damping, mass and stiffness – of the remote environment. The fidelity of the force feedback can significantly affect the performance of the human operator [1]. Transparency is a measure of the feedback fidelity. This concept is used by researchers and engineers to design, improve and optimize the performance of teleoperation systems. The other important issue is stability. When the transmission of signals between the local and remote sites is delayed, the stability of the teleoperation system can be severely affected. Effective methods, e.g., scattering/wave-variable based approaches [2], [3], [4], are proposed to deal with this problem. These methods can restore stability margin, however, at the cost of transparency.

Maximizing the full potential of the teleoperation system requires rendering the proper perception of mechanical properties of the environment. To this end, the effect of the wave-variable transformation on transparency should be understood and mitigated. Up to now, research on this topic is mainly limited to the static perception of stiffness or an approximation of the free-space inertia [5], [6], [7].

In this study, we use recent advances in understanding of human perception of haptics [8], to systematically investigate the effect of the wave-variable transformation on human haptic perception, for cases where delays are present in the transmission channel. Using this approach the perception of all three mechanical properties of an arbitrary linear environment can be studied over the full range of potential manual excitation.

The contributions of this paper are summarized as follows:

1) A non-parametric perception-centered transparency evaluation method.

   The foundation of our proposed method is laid by the frequency-domain framework discussed in [8]. This framework offers a systematic understanding of how the human perception of mechanical properties (mass, stiffness and damping) of an arbitrary linear environment changes by a teleoperation system, or haptic interface.

2) Perception-centered transparency evaluation of two typical wave-variable based approaches.

   The original wave-variable approach [3] and the generalized wave-variable approach [4] are evaluated in terms of their transparency and their induced changes in the perception of a mass-spring-damper environment. The bandwidth of human arm neuromuscular system [9] is considered as the frequency range of the evaluation.

The paper is organized as follows. We first discuss the transparency evaluation method. In Section III we review the two wave variable based approaches. The perception-based transparency evaluation of these two approaches is conducted in Section IV. A short discussion of our study is given in Section V. Our work is then concluded in Section VI.

II. PERCEPTION-CENTERED TRANSPARENCY EVALUATION

In this section, our framework [8] is extended to describe the perception of dynamical properties in teleoperation. We first briefly describe the principle of this framework, then propose the perception-based transparency evaluation approach.

A. Expressing human perception in the frequency domain

Humans use the patterns between the excitation movement of their manipulator and the force feedback they receive to estimate the mechanical properties of a dynamic system [8],

[10]. More specifically, stiffness is usually estimated on the basis of how much force is perceived with a *displacement* (spring force), mass is related to the effort to *change the movement direction* (inertia force), and damping is identified from the force resisting the *movement velocity* (viscous force). Changes in the observed relations (in other words, changes in the three force components) lead humans to perceive the mechanical properties in a different way. Thus, a changed perception of mechanical properties is not necessarily caused by an actual change in the properties of the dynamic system [8]. Delays in the transmission channel, motor dynamics, filtering and so forth, can all result in a change in perception of mass, spring and damper properties [8], [10], [11], [12].

The aforementioned correlations can be characterized by the frequency response function (FRF) of the dynamic system. Changes in the FRF indicate how the perception of mechanical properties changes at each excitation frequency. Consider a human operator interacting with an arbitrary linear environment. We define the FRF of the environment as $H_{env}(\omega)$, a complex-valued function with a real and imaginary part:

$$H_{env}(\omega) = \frac{F(\omega)}{X(\omega)} = \Re H_{env}(\omega) + \Im H_{env}(\omega) \cdot j, \qquad (1)$$

where F and X denote the Fourier transforms of the force and position which the human operator uses to interact with the environment (for example, X_{env} and F_{env} in Fig. 2).

The real part $\Re H_{env}$ reflects the coupled correlations that humans use to estimate the stiffness and mass. Depending on the frequency of excitation, this variable determines the spring or inertia force that humans use for the estimation. When the human operator excites the environment at frequencies where $\Re H_{env}$ is positive, $\Re H_{env}$ generates the spring force; $\Re H_{env}$ generates an inertia force when the environment is excited at frequencies where $\Re H_{env}$ is negative. As a result, a change in the positive $\Re H_{env}$ causes a change in the perception of stiffness, and a change in the negative $\Re H_{env}$ causes a change in the perception of mass.

The imaginary part $\Im H_{env}$ determines the velocity-dependent force that is used by humans to estimate the damping. A change in $\Im H_{env}$ *only* changes the human perception of the environment damping.

To better illustrate this, consider a mass-spring-damper system as an example. The position-to-force dynamics of this system ($H_{env}(\omega)$) are shown as the blue curve in Fig. 1. The real projection of the system dynamics, $\Re H_{env}$, changes from positive to negative at the frequency ω_c, referred here to as the ‘changeover frequency’. For mass-spring-damper systems, this frequency corresponds to the undamped eigen-frequency ($\omega_c = \sqrt{k/m}$)[1].

Each point of the curve represents the frequency response of the system at a particular frequency. Changes in the perceived spring force will be caused by changes in the real projection of the points for frequencies below ω_c, e.g., a point at ω_1 in Fig. 1. A larger real projection $\Re H_{env}(\omega_1)$ moves this point to the right, generating a larger spring force in response to the excitation movement at this frequency. This causes the human operator to perceive an increase in stiffness. A smaller real projection moves the frequency response leftwards, causing a lower stiffness perception.

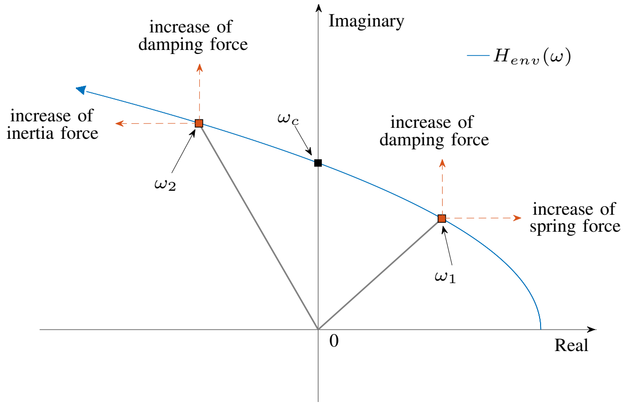

Fig. 1. Nyquist plot of a typical mass-spring-damper system (the dynamics from position input to force output): $H_{env}(\omega)$. The arrow of the curve (the blue arrow) indicates the increase of frequency.

Changes in the perceived inertia force are associated with frequencies above ω_c, e.g., a point marked at ω_2. An increase in the amount of the negative real projection moves the point to the left. This causes an increase in the inertia force and leads humans to perceive the environment as having a higher mass. When the point is moved to the right, the inertia force decreases, and the perceived mass will be smaller.

The change in the perception of damping can be estimated from how the curve changes vertically. An increase in the imaginary projection moves the frequency response at the corresponding frequency upwards (illustrated by the two points marked at ω_1 and ω_2 in Fig. 1). This causes a stronger damping force and results in a higher level of perceived damping.

Hence, the changes in $\Re H_{env}$ and $\Im H_{env}$ at every frequency within the bandwidth of the potential manual excitation indicate how the perception is altered. A similar idea is also suggested in [12], which employs an “effective impedance” to express the net level of mechanical properties that lead to the same frequency response at each frequency. In the following subsection, we propose a perception-based transparency evaluation approach on this basis.

B. Transparency evaluation method

Fig. 2 illustrates the general structure of a teleoperation system. We use the “Teleoperator” to include all the elements (master/slave devices, transmission time delays and wave-variable transformations) between the human operator and the environment. The objective of this paper is to investigate the effect of the teleoperator on the haptic perception of the environment, i.e., how the human perception of the rendered dynamics is different from that of the environment. We de-

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[1] In the following we assume the environments as those whose FRFs can cross the imaginary axis only once. This is to provide a concise introduction to how the perception can be estimated in the frequency domain. In practice, the environment can be arbitrarily chosen.

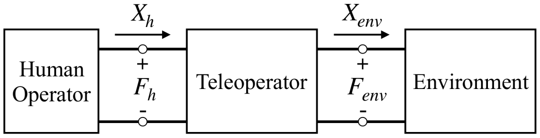

Fig. 2. The general structure of a teleoperation system shown with a network representation. Subscripts "h" and "env" refer to "human" and "environment", respectively.

fine the rendered dynamics as the open-loop dynamics from position X_h to force F_h:

$$H_{to}(\omega) = \frac{F_h(\omega)}{X_h(\omega)}, \tag{2}$$

and use $\Delta H(\omega)$ to denote the difference between the rendered and original environment dynamics:

$$\begin{aligned} \Delta H(\omega) &= H_{to}(\omega) - H_{env}(\omega) \\ &= \Re\Delta H(\omega) + \Im\Delta H(\omega) \cdot j \end{aligned} \tag{3}$$

The imaginary part of this difference $\Im\Delta H(\omega)$ directly shows how the perception of damping changes: a positive value indicates an increase in the perceived damping, a negative value indicates a decrease. The real part of this difference $\Re\Delta H(\omega)$ indicates the changes in the perception of stiffness and mass. By defining ω_c as the changeover frequency of the original environment, changes in the perception of mechanical properties can be evaluated through the following two variables[2]:

$$E_{sm}(\omega) = \begin{cases} \dfrac{\Re\Delta H(\omega)}{|H_{env}(\omega)|}, & \text{when } \omega_{min} \leq \omega \leq \omega_c \\ \dfrac{-\Re\Delta H(\omega)}{|H_{env}(\omega)|}, & \text{when } \omega_c \leq \omega \leq \omega_{max} \end{cases} \tag{4}$$

$$E_d(\omega) = \frac{\Im\Delta H(\omega)}{|H_{env}(\omega)|}, \text{ where } \omega_{min} \leq \omega \leq \omega_{max}$$

where ω_{min} and ω_{max} denote the higher and lower ends of the considered frequency range of manual excitation. Here the errors are normalized to the frequency response magnitude of the original environment. Doing this would allow us to know how the perception of the rendered dynamics is different from that of the original one on a relative scale.

In order to have a general comparison of different systems, the "transparency index" [13] can be employed. This index is calculated by integrating the normalized magnitude of $\Delta H(\omega)$ in Eq. (3) over the frequency range of the considered excitation:

$$T_{idx} = \sum_{i=0}^{N} W(\omega_i) \cdot \left| \frac{\Delta H(\omega_i)}{H_{env}(\omega_i)} \right| \tag{5}$$

Here ω_i can be chosen as N evenly or normally spaced points within the frequency range [ω_{min}, ω_{max}]. $W(\omega_i)$ denotes the weight for each individual frequency point. The lower T_{idx}, the higher the transparency.

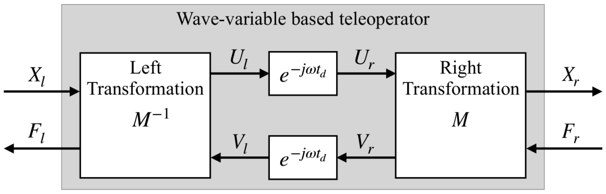

Fig. 3. The wave-variable based teleoperator.

III. WAVE-VARIABLE BASED APPROACHES

Fig. 3 illustrates a schematic of a wave-variable based teleoperator. For simplicity we omit the dynamics of the master and slave devices, thereby we assume that $X_l = X_h$, $F_l = F_h$; $X_r = X_{env}$, $F_r = F_{env}$. As can be seen, instead of the physical variables (movement and force), the wave-variables U and V are transmitted between the local and remote sites. For simplicity, we assume a constant but otherwise arbitrary time delay t_d in both forward and backward transmission channels. In this paper, we use matrix M to represent the transformation from the position and force signals to the wave variables:

$$\begin{aligned} \begin{bmatrix} U_l \\ V_l \end{bmatrix} &= M \begin{bmatrix} X_h \\ F_h \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} X_h \\ F_h \end{bmatrix} \\ \begin{bmatrix} U_r \\ V_r \end{bmatrix} &= M \begin{bmatrix} X_{env} \\ F_{env} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} X_{env} \\ F_{env} \end{bmatrix} \end{aligned} \tag{6}$$

By considering the shaded area in Fig. 3 as a linear two-port network, the rendered dynamics can be expressed with the elements of M, as:

$$\begin{aligned} H_{to} &= \frac{F_h}{X_h} \\ &= \frac{G_{n1} + G_{n2}H_{env}}{G_{d1} + G_{d2}H_{env}}, \\ \text{where } G_{n1} &= \omega^2 m_{11}m_{21}(e^{-2j\omega t_d} - 1) \\ G_{n2} &= j\omega(m_{11}m_{22}e^{-2j\omega t_d} - m_{12}m_{21}) \\ G_{d1} &= j\omega(m_{11}m_{22} - m_{12}m_{21}e^{-2j\omega t_d}) \\ G_{d2} &= m_{12}m_{22}(1 - e^{-2j\omega t_d}) \end{aligned} \tag{7}$$

In this section, we review two typical wave-variable based approaches and derive their transformation matrices.

A. The original wave-variable approach

The original wave-variable approach was proposed in [3]. The transformation from physical variables to wave variables can be expressed as:

$$\begin{aligned} U(\omega) &= \frac{1}{\sqrt{2b}}(F(\omega) + b \cdot j\omega X(\omega)) \\ V(\omega) &= \frac{1}{\sqrt{2b}}(F(\omega) - b \cdot j\omega X(\omega)) \end{aligned} \tag{8}$$

Here, b denotes the wave impedance which is a tunable constant. The transformation matrix can be expressed as:

$$M = \begin{bmatrix} \dfrac{b \cdot j\omega}{\sqrt{2b}} & \dfrac{1}{\sqrt{2b}} \\ \dfrac{-b \cdot j\omega}{\sqrt{2b}} & \dfrac{1}{\sqrt{2b}} \end{bmatrix} \tag{9}$$

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[2] As $\Re H_{env}(\omega)|_{\omega > \omega_c}$ is negative, the sign of the difference has to be reverted to show the change in the size.

B. Generalized wave-variable approach

The original wave-variable approach creates passivity in the delayed transmission channel independently of the two terminations (the human operator and the environment) of the teleoperator. However, this approach may be too conservative since these two subsystems' dissipative properties, which are able to compensate for the shortage of passivity of the transmission channel, are often neglected.

Taking advantage of the potential input-feedforward-output-feedback passive (IF-OFP) properties of the environment and the human operator can improve teleoperator transparency. Based on this principle, the generalized wave-variable approach was proposed in [4], [14]. This approach guarantees the L_2 stability of the overall teleoperation system (including human operator, the teleoperator and the environment) while being less conservative. It uses the following transformation:

$$M = R_\theta \cdot B \,, \text{ where:}$$

$$R_\theta = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \,, \; B = \begin{bmatrix} b_{11} \cdot j\omega & 0 \\ 0 & b_{22} \end{bmatrix} \tag{10}$$

Here, R_θ and B can be considered as a rotation matrix and a scaling matrix, respectively. The rotation angle θ can be chosen from a range $[\theta_l, \theta_r]$. The two ends of this range, θ_l and θ_r, are the solutions of the following two conditions [14]:

$$\begin{gathered} \cot(2\theta_i) = \frac{\epsilon_{B_i} - \delta_{B_i}}{2\eta_{B_i}} \\ 2\eta_{B_i} \sin(\theta_i)\cos(\theta_i) - \delta_{B_i} \cos^2(\theta_i) - \epsilon_{B_i} \sin^2(\theta_i) \geq 0, \end{gathered} \tag{11}$$

where the subscript $i \in \{l, r\}$. The variables ϵ_{B_i}, δ_{B_i} and η_{B_i} are elements of the matrix P_{B_i}:

$$\begin{gathered} P_{B_i} = B^{-T} P_i B^{-1} = \begin{bmatrix} -\delta_{B_i} I & \eta_{B_i} I \\ \eta_{B_i} I & -\epsilon_{B_i} I \end{bmatrix} , \\ \text{where } P_i = \begin{bmatrix} -\delta_i I & \frac{1}{2} I \\ \frac{1}{2} I & -\epsilon_i I \end{bmatrix} \end{gathered} \tag{12}$$

Here $P_i, i \in \{l, r\}$ is the QSR-dissipativity matrix of the left or right termination (the human operator or the environment). Under the assumption that the left termination (the human operator) is OFP and the right termination (the environment) is IFP, P_i becomes:

$$P_l = \begin{bmatrix} 0 & \frac{1}{2} I \\ \frac{1}{2} I & -\epsilon_l I \end{bmatrix} \,, \; P_r = \begin{bmatrix} -\delta_r I & \frac{1}{2} I \\ \frac{1}{2} I & 0 \end{bmatrix} \tag{13}$$

Here ϵ_l and δ_r are respectively the lower bounds of the velocity-dependent damping properties of the human operator and the environment.

IV. TRANSPARENCY EVALUATION OF WAVE-VARIABLE BASED APPROACHES

In this section, we evaluate the transparency of the aforementioned two wave-variable based approaches. We assume one degree-of-freedom, and choose a mass-spring-damper system as the virtual environment for the evaluation:

$$H_{env}(\omega) = \frac{F_{env}(\omega)}{X_{env}(\omega)} = 1.8 \cdot (j\omega)^2 + 20 \cdot (j\omega) + 200 \tag{14}$$

TABLE I
TRANSPARENCY INDEXES OF THE THREE APPROACHES

Time delay	Transparency index T_{idx}	
	Original wave variable	Generalized wave variable
25 ms	5.94	3.08
100 ms	26.3	11.8
600 ms	56.5	26.2

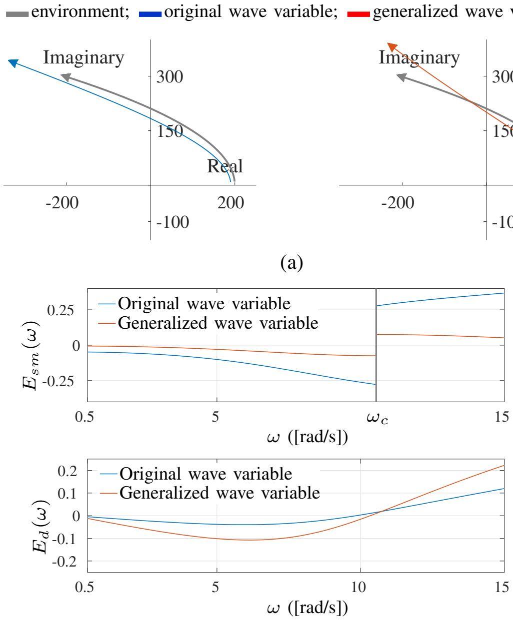
The changeover frequency of the system is $\omega_c = \sqrt{k/m}$ = 10.5 [rad/s]. This indicates that the perception of stiffness rendered by the two approaches should be evaluated below 10.5 [rad/s] while the perception of mass should be evaluated above this frequency.

The transparency evaluation will be conducted with three constant round-trip time delays ($2t_d$): 25 ms, 100 ms and 600 ms. A wave impedance b = 50 is chosen for the original wave-variable approach (Eq. (9)). For the B matrix of the generalized wave-variable approach, we set $b_{11} = \sqrt{b}$ and $b_{22} = 1/\sqrt{b}$. According to Eq. (14), the environment is IFP with δ_r = 20. On the left side, we assume the human operator's arm is OFP with ϵ_l = 5. These settings result in a rotation angle interval with $\theta_l = 0.1°$ and $\theta_r = 55.9°$. In our evaluation, we choose a rotation angle: $\theta = 10°$.

Substituting the above settings into Eqs. (9) and (10), the rendered dynamics H_{to} of the two wave-variable based approaches can be calculated using Eq. (7). In this paper, we consider the scenario of manual control tasks performed by humans. So the frequency range we will consider for the evaluation is 0.5 - 15 [rad/s]. The upper end of this range is around the (open-loop) natural frequency of human arm neuromuscular system identified through manual control tasks [9]. A non-zero small value (0.5) is set as the lower end in order to avoid singularity that may occur in the calculation.

In order to have a general comparison of the performances of the two approaches, we first calculate the transparency index using Eq. (5). We consider a simple weighting function $W(\omega_i) = 1$, and the chosen frequency points ω_i are evenly spaced within the considered frequency range, with a sampling period being 0.5 [rad/s]. Results are shown in Table I. As expected, the generalized wave-variable approach outperforms the original approach for all tested time delays. The increase of the transmission time delay significantly deteriorates the performance of both approaches.

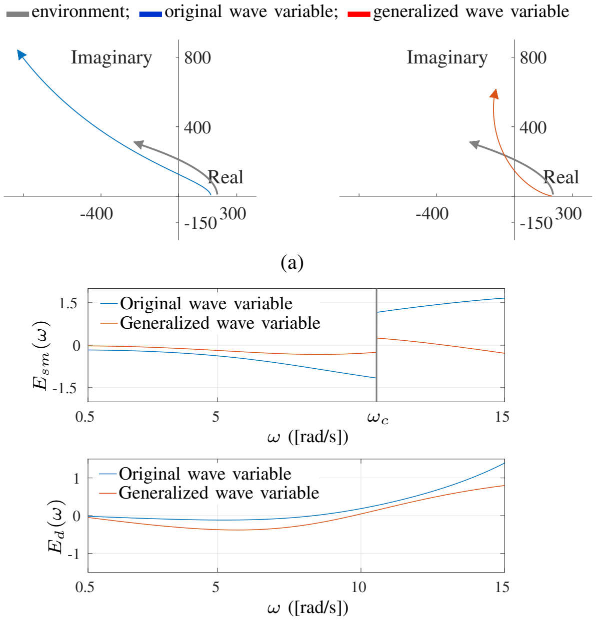
Next, we will interpret the effect of the wave variable transforms using the theory on human interpretation of perceived mechanical properties. Fig. 4a shows the Nyquist plots of the rendered dynamics H_{to} with a round-trip delay of 25 ms for both approaches. The general characteristics of human haptic perception of the environment rendered by the two approaches can be clearly seen. Both approaches are able to render spring-mass-damper behaviors similar to that of the original environment. In order to evaluate the distortion of the perception of the three mechanical properties, we plot E_{ms}



(a)

(b)

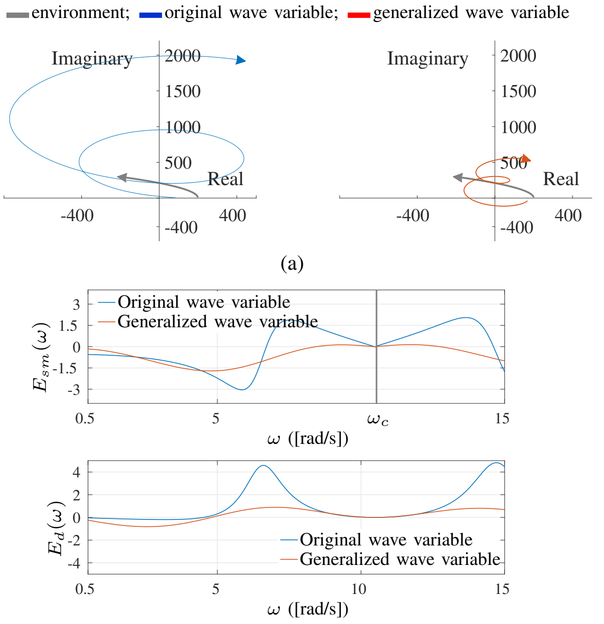
Fig. 4. The perception-centered transparency evaluation of the two wave-variable based approaches when the time delay is 25 ms. (a): Nyquist plots of the original mass-spring-damper environment and the dynamics rendered by the wave-variable approaches. (b): The wave-variable caused changes in perception of the three mechanical properties. Upper: the stiffness and mass; Lower: the damping. In this figure and the following, the arrangements of the sub-figures are the same.



(a)

(b)

Fig. 5. The perception-centered transparency evaluation of the two wave-variable based approaches when the time delay is 100 ms.



(a)

(b)

Fig. 6. The perception-centered transparency evaluation of the two wave-variable based approaches when the time delay is 600 ms.

and E_d in Fig. 4b.

It can be seen that the perception of the environment stiffness and mass provided by the generalized wave-variable approach has less distortion than that provided by the original approach. Both approaches make the environment to be perceived as having lower stiffness. The distortion of the rendered spring force is the least in the case of static interaction (when ω approaches zero), while it becomes more pronounced as the excitation frequency increases (when the human operator interacts with the environment with faster movements). Both approaches lead the human operator to perceive the environment as having higher mass. However, the changes in the inertia force caused by the two approaches show opposite trends as the frequency increases. The two approaches cause reduction in the perceived damping at lower frequencies while they cause higher damping perceived at higher frequencies. The generalized approach, however, causes more damping distortion.

When a round-trip delay of 100 ms is considered (see Fig. 5), the stiffness and mass perception of the environment is maintained better by the generalized wave-variable approach. The generalized approach is still able to render the static spring force with a high degree of fidelity. This approach causes more distortion of the damping at lower frequencies but less distortion at higher frequencies. The trend of changes in the perception becomes more inconsistent as time delay increases.

This becomes evident when the time delay is very high, 600 ms, see Fig. 6. The spiral shapes of the Nyquist plots are mainly caused by the exponential FRF of the time delay (see Eq. (7)). As a result, the rendered dynamics exhibit dramatically different behaviors even when the excitation frequency only changes slightly, causing severe wave reflections. In this case, evaluating the environment mechanical properties with a non-static excitation movement will become very difficult, if not impossible, for a human operator.

V. DISCUSSION

We studied the two wave variable approaches with specific settings. A different wave impedance b (for the original approach) or different matrices R_θ and B (for the generalized approach) result in different changes in the perception. Investigating the effects of these variables is beyond the scope of this work. Nevertheless, our work provides a method to easily access the information about the perception changes for future research and experiments relevant to this topic.

The difficulty of studying the effect of the wave-variable transformation on human perception is caused by the time delay. Traditional methods [15] usually use a transfer function with a limited order to approximate the rendered dynamics. The open-loop dynamics of a passive environment and well designed master/slave devices are usually governed by a limited number of poles. If no transmission delay, or only very small delays are assumed, this approximation can indeed be accurate enough. However, the infinite number of poles introduced by the exponential transfer function of the time delay will dominate the system behavior as delay increases. Padé approximations can be used to reduce the number of dominant poles, and to make the traditional method still applicable [6], [7]. But their accuracy is limited to a low frequency range. Our evaluation is based on our previous human research [8], which allows us to predict the effect of an arbitrary time delay on human perception without approximation. The essence of this approach is to inspect the polar plot of the lumped dynamics of all subsystems (excluding the human operator) of a teleoperation system. Differences with respect to the original environment can be interpreted in terms of changes in mass-, spring- or damper-relevant forces.

The method we used in this study can be used as a new transparency evaluation method. It can be applied to other architectures of teleoperation systems or haptic interfaces, for the study of human haptic perception of the rendered dynamics, also for the improvement of devices or the selection among candidates with different control solutions. Current transparency evaluation methods include direct evaluation of time-domain measurements of movement and force signals, and frequency-domain approaches such as 'Z-width' [16] and 'error vector magnitude integration' [13]. However, all the existing transparency evaluation methods *only* provide a *numeric* index [13], indicating the general level of transparency, and *lack* the specific information about *perception changes*. Our evaluation approach enables designers to more effectively balance the trade-off between stability and transparency. That is, it allows us to consider the perception of which mechanical property still has room to be compromised (e.g., to improve stability), and that of which must be maintained or improved. Furthermore, combining with recent advances in modeling human haptic threshold [17], [18], our approach allows the evaluation of a haptic interface in terms of perceptual fidelity.

VI. CONCLUSION

We studied the effect of wave-variable based teleoperation systems on human haptic perception of mechanical properties. The original and generalized wave-variable approaches are investigated. Results show that human haptic perception of the dynamics rendered by both approaches is similar to that of the original environment when time delays are small. The generalized approach performs better in terms of rendering the stiffness and mass properties of the environment. But this trend is not consistent in terms of the damping perception, which depends on the excitation frequency. However, the perception is dramatically different from the original environment when time delays are large. Here, with a non-static movement, it becomes very difficult for human operators to accurately assess the mechanical properties of the environment.

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