Framework for a Two-step Evaluation of Haptic Displays

Fu, Wei; Van Paassen, Marinus M.; Mulder, Max

DOI
10.1016/j.ifacol.2019.12.119

Publication date
2019

Document Version
Final published version

Published in
IFAC-PapersOnline

Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 52-19 (2019) 97–102

Framework for a Two-step Evaluation of Haptic Displays

Wei Fu, [1] **Marinus M. (René) van Paassen, and Max Mulder**

Control and Simulation, Faculty of Aerospace Engineering, TU Delft, 2629 HS, Delft, The Netherlands

Abstract: Haptic displays can greatly facilitate manual control tasks. Their capacity of allowing the operator to perceive the desired dynamics is an important design parameter. However, attempts to evaluate haptic displays on the basis of what dynamics humans actually perceive are scarce. This paper proposes a two-step framework which incorporates the characteristics of human haptic perception into the evaluation of haptic displays. The first step is to evaluate the haptic display based on a recently developed model of the threshold for changes in the perception of system dynamics. It allows us to know the frequency spectrum in which a haptic device alters the operator's perception of the system dynamics. The second step is then to understand how the perceived dynamic distortions affect the operator's characterization of the system dynamics. Findings from recent psychophysical studies allow us to relate the changes in perception caused by the haptic device to changes in the perceived mechanical properties of the system. A numerical example illustrates how haptic displays can be evaluated using the proposed framework.

Keywords: Display Design, Human - Computer Interaction, Virtual and Augmented Reality

1. INTRODUCTION

Haptic interfaces can facilitate manual control by establishing bilateral transmission of information between human operators and machines (Abbink and Mulder (2009); Smisek et al. (2017)). In most cases, a haptic interface is a control manipulator through which the human operator can sense the force feedback while performing a control task. It allows the operator to directly *feel* the dynamics of the environment in which the task is performed, or the dynamics of the system which is being controlled, such as a vehicle or a slave robot (see Cavusoglu et al. (1999); Hou et al. (2016); Reintsema et al. (2007); Wildenbeest et al. (2014); Yokokohji and Yoshikawa (1994)).

The feedback fidelity is crucial for a successful application of haptic interfaces. Ideally, the dynamics as portrayed by a haptic device should appear to be the same as the dynamics that one intends to communicate. Inevitable distortions of the haptic display, such as those caused by limitations from the control systems and actuators, and transmission time delays in tele-operation, can distort this communication, however. Poor fidelity may lead the operator to perceive the system dynamics differently, deteriorating the interface effectiveness.

Clearly, there is a need to assess and evaluate the quality of the haptic communication. A perfect transparency would mean that the displayed dynamics are exactly the same as the desired dynamics, and this is indeed considered to be the benchmark for most evaluations reported in literature (Hashtrudi-Zaad and Salcudean (1996); Kim et al. (2013); Yokokohji and Yoshikawa (1994)). The difference between the desired and the rendered dynamics is often used as an indication of the performance of a haptic device (e.g., Chang and Kim (2012)).

Most studies, however, do not consider the human element in their evaluations. This is caused by the fact that our understanding of the limitations of human haptic perception is rather limited. We claim that an evaluation should always be centered around what the human operator *perceives* from the haptic device. Some changes in the displayed dynamics caused by the haptic interface design may not be perceived at all by the operator, because of for instance a threshold in perceivable changes. Working towards a perfect transparency can place excessive, and because small changes are no longer perceived even unnecessary, demands on the haptic device. In addition, some crucial elements regarding *how* the dynamic changes which *are* perceived can affect the operator in characterizing the system's response are usually overlooked. This hampers a further optimization of the haptic display considerably.

In this paper we explain how recent advances in understanding human haptic perception (see Fu et al. (2018, 2019a,b)) allow us to integrate perception characteristics into the design and evaluation of haptic displays. Starting from the perspective that what the operator *perceives* is what matters most, we consider the two following questions to be crucial:

1. At what point, or, *when* does a haptic device start to alter the human perception of the system dynamics?
2. When perception changes, *how* does the haptic device affect the operator's characterization of the system dynamics?

In this study we present a two-step evaluation framework which addresses these two questions. The first step is based

[1] E-mail: w.fu-1@tudelft.nl

2405-8963 © 2019, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2019.12.119

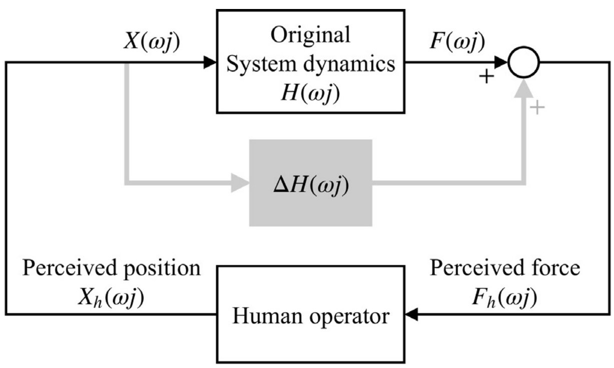

Fig. 1. Haptic interaction between a human operator and an arbitrary system.

on the frequency-domain model of the just-noticeable difference (JND) in system dynamics (see Fu et al. (2018, 2019b)). It allows us to know the frequency bandwidth within which a haptic device can render the desired dynamics with "perceptual transparency". In other words, up to what frequency are changes in the dynamics *not perceived*? The second step, which is based primarily on the findings from our recent psychophysical study reported in Fu et al. (2019a), allows us to understand *how* the changes in dynamics which *are* perceived, are characterized by the human operator as changes in the mechanical characteristics of the system.

In the next section we will discuss the theoretical foundations of the evaluation framework. In Section 3 we propose the framework, and use a numerical example to illustrate how the two steps of the evaluation can be performed. Section 4 summarizes the contributions of this paper.

2. CHARACTERISTICS OF HAPTIC PERCEPTION

The evaluation framework defines two steps, which respectively examine when and how a haptic device affects the operator's haptic perception of system dynamics. The theoretical bases of these two steps are explained here.

2.1 Preliminaries

To make the problem more tractable, restrictions must be placed to the scope of this paper. Firstly, this paper is restricted to *linear* systems, as the majority of relevant studies concern. Such a restriction allows for the development of powerful analytic tools. Due to the fact that many nonlinear systems at/around the equilibrium conditions possess strong linearity, this study covers a broad class of systems. Secondly, this study only concerns the *continuous* haptic interaction with *soft* objects. Although these restrictions exclude the cases of hard environments (such as stiff walls), and the effect of transient responses (such as the moment of contact), the framework proposed in this paper applies to a great number of applications, such as de Stigter et al. (2007); Hosman et al. (1990); Lam et al. (2008); Mulder et al. (2011); Smisek et al. (2017); Van Baelen et al. (2018); Venrooij et al. (2017).

Consider that the human operator is directly interacting with an arbitrary system, as shown in Fig. 1. Define $H(\omega j)$ as the frequency response function (FRF) of the system dynamics that describe how the system generates force $F(\omega j)$ in response to the displacement $X(\omega j)$:

$$H(\omega j) = \frac{F(\omega j)}{X(\omega j)} \tag{1}$$

In addition, the FRF is a complex-valued function which can be divided into two parts:

$$H(\omega j) = \Re H(\omega j) + \Im H(\omega j) \cdot j \tag{2}$$

Here, $\Re H(\omega j)$ and $\Im H(\omega j)$ denote the real and imaginary parts of the system dynamics, respectively. As will be seen later, the evaluation of system dynamics on the complex plane is the foundation of the framework.

Due to the effect of the haptic interface, the dynamics rendered to the human operator may be different from $H(\omega j)$. Here we define the dynamic change as $\Delta H(\omega j)$ (see Fig. 1). It can also be expressed with the real and imaginary parts:

$$\Delta H(\omega j) = \Re \Delta H(\omega j) + \Im \Delta H(\omega j) \cdot j \tag{3}$$

The dynamics the human operator perceives are affected by $\Delta H(\omega j)$. The two key questions mentioned earlier now become clear. The first question becomes *when* $\Delta H(\omega j)$ leads the human operator to perceive the system dynamics to be different from $H(\omega j)$. And the second question becomes *how* the change caused by $\Delta H(\omega j)$ in the system's response is characterized by the human operator.

2.2 JND model

Although the system presented to the operator is different from $H(\omega j)$, it is not necessarily perceived differently due to the limitation of human sensory system. The change in the system dynamics must exceed a certain level to become noticeable. The threshold for causing a different perception is usually referred to as just-noticeable difference (JND).

Knowledge about the JND in the system dynamics is necessary to answer the first question. Through previous studies, we have found that the JNDs in the two parts, i.e., the minimum changes in $\Re H(\omega j)$ and $\Im H(\omega j)$ that are likely to alter human perception of the system, can be expressed as a function of the system's FRF (see Fu et al. (2018, 2019b)):

$$\left|\frac{\Delta_{jnd}\Re H(\omega j)}{H(\omega j)}\right| \approx \left|\frac{\Delta_{jnd}\Im H(\omega j)}{H(\omega j)}\right| = c\,, \tag{4}$$

where the constant c is approximately 10% for the general impedance range used in typical manual control tasks (see Fu et al. (2018, 2019b)).

This model defines a threshold region in which a distortion of the system dynamics does not alter the perception of the operator. To better illustrate this, Fig. 2 shows an example which considers the dynamics of an arbitrary system at a single frequency. In the complex plane, the FRF at a single frequency is represented by a vector (the black line). The real and imaginary parts define the projections on the two axes, respectively. A change in the system dynamics will result in a different vector which has at least one different projection, as shown by the red and blue vectors.

Any change in the system dynamics, independent of its direction, can always be expressed as changes in the real and imaginary parts (see Eq. (3)). Thus, perceiving a

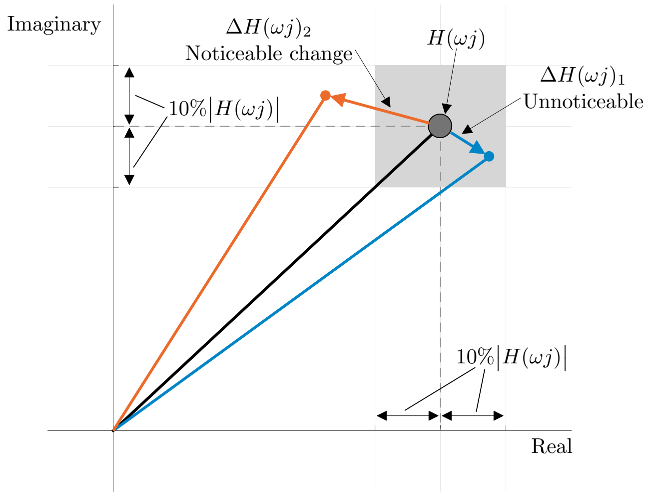

Fig. 2. An illustration of the threshold for altered perception of the system dynamics. Dynamic changes within the threshold are not perceptible (e.g., the blue vector), whereas those exceeding the threshold alter the perception of the system (e.g., the red vector).

change in dynamics of a system is, in fact, discerning changes in the two parts. This means that a dynamic change will alter the human perception of the system when the threshold for perceiving changes in either of the two parts is exceeded. In other words, JNDs in these two parts represent the JND in the system dynamics. Eq. (4) defines the corresponding two JNDs – the intervals for imperceptible changes in the projections on the two axes of the complex plane. As a result, there exists a square region within which humans perceive different systems as the same. One can imagine that when the haptic interaction occurs at this particular frequency, for example using a sinusoidal manipulator movement, ΔH will only lead the human operator to have a different perception if it exceeds the threshold region.

To evaluate the quality of a haptic display, comparisons between the JND thresholds and the changes caused by the haptic device in the system dynamics can be carried out at frequencies where the interaction takes place. It allows us to know whether or not the haptic device alters the operator's perception of a system, and when this occurs.

2.3 Change in perceived characteristics of the system

Studies suggest that humans characterize the behavior of a system according to the correlation between the movement and force perceived during the interaction (Fu et al. (2019a); Nisky et al. (2008)). Usually, humans are inclined to compare the system behavior to that of mechanical systems, particularly when one needs to assess the mechanical properties (i.e., mass, damping, and stiffness) (see Fu et al. (2019a)). In general, the force against a displacement (spring force) is usually perceived as the behavior of a spring; the force resisting the movement velocity (viscous damping force) is considered to be the effect of damping; and the effort to change the movement direction (inertia force) is related to inertia.

What mechanical behavior a system exhibits is determined by the FRF (i.e., $H(\omega j)$ in Eq. (1)), in particular, the real and imaginary parts. Firstly, the real part $\Re H(\omega j)$ affects the spring and mass properties humans perceive from the system (Fu et al. (2019a)). Depending on the frequency of excitation, this part generates a spring or inertia force:

$$F_{si}(\omega j) = X(\omega j)\left|\Re H(\omega j)\right| e^{j\angle \Re H(\omega j)},$$
$$\text{where } \angle \Re H(\omega j) = \begin{cases} 0^\circ \text{ , if } \Re H(\omega j) > 0 \\ 180^\circ \text{ , if } \Re H(\omega j) < 0 \end{cases} \tag{5}$$

When the haptic interaction occurs at a frequency where $\Re H$ is positive, the system feels like a mechanical spring. This is because the system generates a spring force which is directly proportional to the displacement (with a ratio of $\Re H$). When $\Re H$ is negative, the system exhibits an inertia-like behavior. It generates a force which is 180-degree out of phase with the displacement, thus directly proportional to the acceleration. Therefore, the sign of $\Re H$ determines which of these two mechanical behaviors the system exhibits, and the magnitude of $\Re H$ determines the amount of the corresponding force that an operator perceives.

Secondly, a positive imaginary part $\Im H$ generates a force which has a 90-degree phase shift from the displacement:

$$F_d(\omega j) = X(\omega j)\left|\Im H(\omega j)\right| e^{j\angle \Im H(\omega j)},$$
$$\text{where } \angle \Im H(\omega j) = 90^\circ \tag{6}$$

Such a phase shift makes this force proportional to (and resist) the movement velocity. The magnitude, $|\Im H|$, determines the amount of this force. One can imagine that this part affects the damping property humans perceive from the system. Please note that a negative imaginary part makes the system unstable, and how humans characterize this is beyond the scope of this study.

The effect of $\Delta H(\omega j)$ on the perception of mechanical properties can be understood by means of changes in the two parts of the system dynamics. Fig. 3 shows an example which considers the dynamics of an arbitraty system as a single frequency. As can be seen, a change in the real part, $\Delta\Re H$, alters the perception of stiffness (see Fig. 3a) or mass (see Fig. 3b). And a change in the imaginary part, $\Delta\Im H$, leads to a different perception of the damping property.

The effect of a haptic interface on the mechanical characteristics the operator perceives can be understood in this way. The evaluation can be carried out over the frequency range of interest, as shown in the following section.

3. EVALUATION FRAMEWORK

The evaluation framework can be established based on the theoretical foundations given above. In this section we propose the framework using a numerical example. Although for the sake of a straightforward illustration the problem considered here is simple, the evaluation routine suits much more complicated cases in practice.

Consider a manual control task in which a human operator interacts with a virtual environment through a haptic interface, as shown by a modified two-port representation in Fig. 4. In this example, we consider the environment to be a typical mass-spring-damper system:

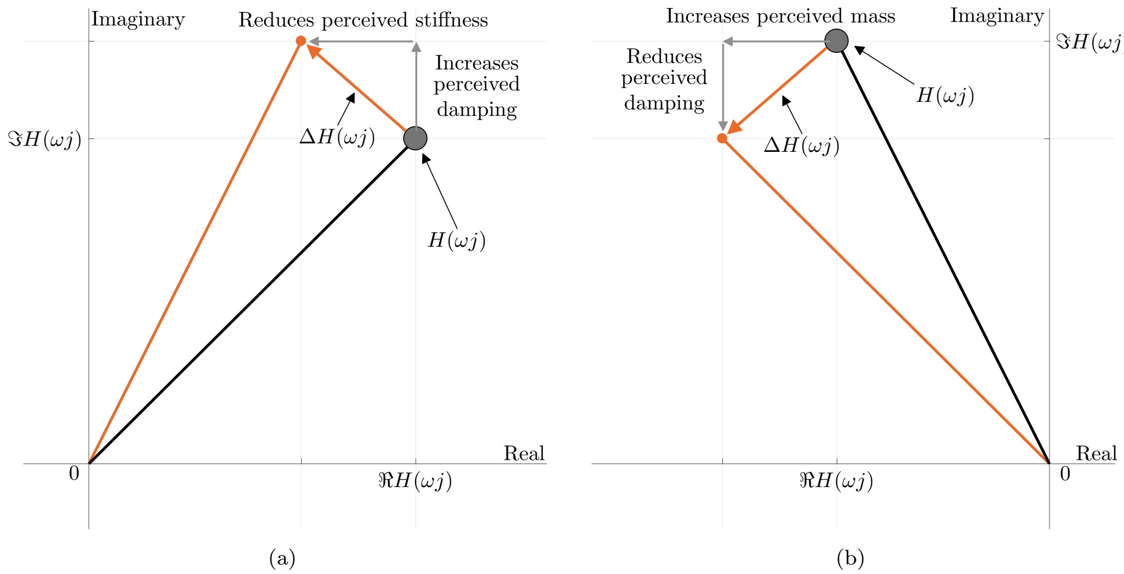

Fig. 3. An illustration of the changes associated with a change in the system dynamics in the mechanical characteristics perceived by humans, (a): when $\Re H(\omega j)$ is positive; (b): when $\Re H(\omega j)$ is negative.

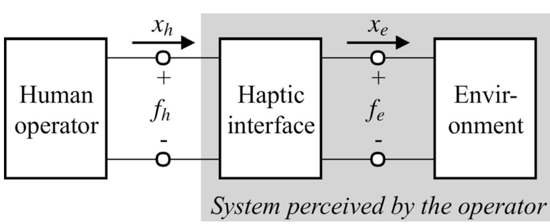

Fig. 4. Two-port representation of the interaction between the operator and the environment through the haptic interface. Here we consider the *flow* to be the position x instead of the commonly used velocity $\dot{x}$. Such a modification is made to keep the expressions consistent with those used by the framework.

$$H_{env}(\omega j) = \frac{F_e(\omega j)}{X_e(\omega j)} = m \cdot (\omega j)^2 + b \cdot (\omega j) + k\,, \tag{7}$$

where m, b, and k denote the mass, damping and stiffness, respectively. For this example, these three parameters are set to: $m = 1.8$ kg, $b = 15$ Ns/m, and $k = 100$ N/m.

In this example, the environment dynamics $H_{env}(\omega j)$ can be considered to be the original system dynamics $H(\omega j)$ shown in Fig. 1. The dynamics perceived by the human operator are those between the perceived movement x_h and force f_h (as can be seen from Fig. 1, the perceived dynamics are the sum of $H(\omega j)$ and $\Delta H(\omega j)$). For simplicity, the effect of the haptic device is considered to be an independent second-order low-pass filter. The dynamics rendered by the haptic interface (those perceived by the operator) are defined as:

$$\begin{aligned} H_{perc}(\omega j) &= \frac{F_h(\omega j)}{X_h(\omega j)} \\ &= H_{env}(\omega j) \cdot \frac{6400}{(\omega j)^2 + 80(\omega j) + 6400} \end{aligned} \tag{8}$$

In addition, the difference in dynamics between the environment and the haptic display can be expressed as:

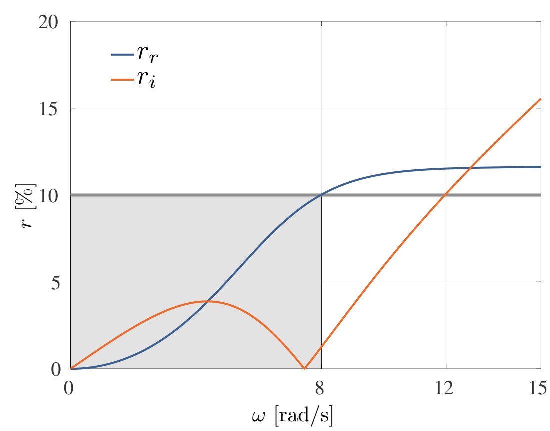

Fig. 5. The dynamic difference caused by the haptic device in the real and imaginary parts. The gray area represents the frequency range within which the haptic display is perceived the same as the environment.

$$\Delta H(\omega j) = H_{perc}(\omega j) - H_{env}(\omega j) \tag{9}$$

The frequency range for the evaluation is set to 0-15 rad/s. The higher end of this range is slightly higher than the bandwidth of the neuromuscular system (van Paassen et al. (2004)). Frequencies beyond this range are of no interest because humans seldom generate voluntary actions beyond the capacity of their neuromuscular system in manual control tasks.

The first step is to examine whether or not the haptic interface alters the operator's perception of the environment. To this end, the following two ratios are calculated:

$$r_r(\omega) = \left| \frac{\Re \Delta H(\omega j)}{H_{env}(\omega j)} \right|,\ r_i(\omega) = \left| \frac{\Im \Delta H(\omega j)}{H_{env}(\omega j)} \right| \tag{10}$$

According to Eq. (4), the rendered dynamics will be perceived to be the same as the environment dynamics only if both r_r and r_i are below 10%.

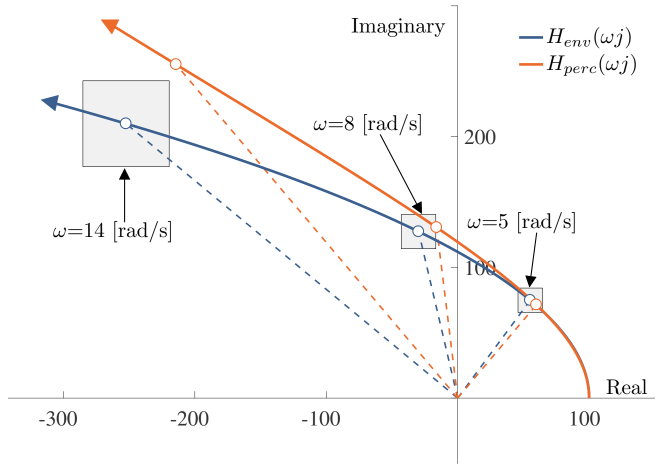

Fig. 6. Nyquist plots of the environment dynamics and those rendered by the haptic interface. The frequency range for the Nyquist plot is 0-15 rad/s. To facilitate the comparison between the two systems, their frequency responses at three different frequencies are also shown.

Fig. 5 shows these two ratios as a function of frequency. As can be seen, the difference in the real and imaginary parts exceed the threshold at 8 and 12 rad/s, respectively. As a result, this haptic device can only display the environment dynamics without altering the operator's perception at frequencies below 8 rad/s. This frequency range can be interpreted as the bandwidth of perceptual transparency for this particular device.

In addition, this also implies that the bandwidth of the haptic interaction must be limited to ensure an unaffected perception of the environment. The rendered dynamics will be perceived to be the same as the environment if the human operator only uses relatively slow movements to interact with the haptic interface. Any movement with substantial energy beyond this frequency range may cause a different perception.

The second step is to assess how the distortion of the environment dynamics is reflected in the mechanical properties perceived by the human operator. Fig. 6 shows the Nyquist plots of the dynamics of the environment and the haptic display. The arrows of the curves indicate an increase in frequency. Each point on a curve corresponds to the frequency response of the system at a particular frequency.

As can be seen, the characteristics of the two curves are similar, indicating that the rendered system exhibits similar mass-spring-damper behaviors. However, the rendered dynamics (red curve) deviate more from the environment dynamics (blue curve) as frequency increases.

The Nyquist plot shows a clear image of the mechanical characteristics of the two systems. Firstly, as can be seen from the real projection, the two systems both exhibit spring behaviors at relatively low frequencies and exhibit inertia behavior at higher frequencies. The environment's changeover frequency at which the sign of the real projection changes is the undamped eigen frequency: $\omega = \sqrt{k/m} = 7.45$ rad/s. As can be seen from Fig. 5, the frequency from which the difference in the real part starts to exceed the threshold is higher than the changeover frequency of the environment. This means that the stiffness of the environment is preserved no matter what movements the human operator uses to interact with the environment, whereas the perceived mass will be different from the mass of the environment for most of the time.

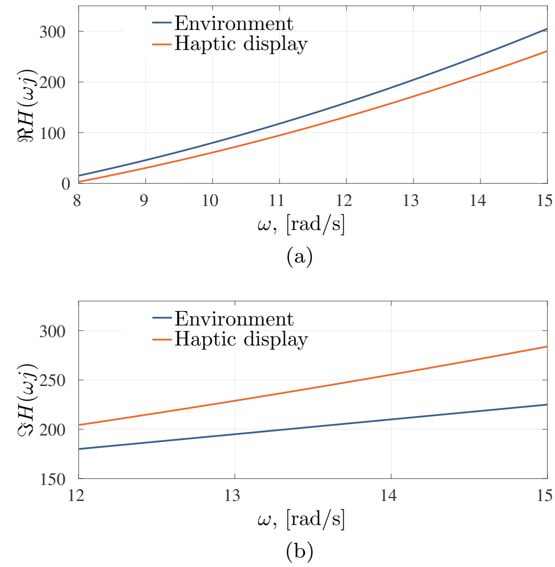

Fig. 7. The real and imaginary parts of the dynamics of the environment and the haptic display, at frequencies where the corresponding distortions exceed the thresholds.

Fig. 7a shows the absolute value of the real projections at frequencies above 8 rad/s for a better understanding of how the perceived mass is affected. As can be seen, the haptic interface will lead the operator to always perceive the environment mass as smaller since the rendered dynamics have a smaller negative projection value.

Secondly, the haptic interface also alters the operator's perception of the environment damping if the interaction occurs at frequencies higher than 12 rad/s, the frequency where the difference in the imaginary part starts to exceed the threshold (see Fig. 5). Fig. 7b shows the imaginary projections of the two systems. As can be seen, the rendered dynamics always have larger projections on the imaginary axis. This indicates that a haptic interaction that occurs at relatively higher frequencies may lead the human operator to perceive the environment as having a higher damping.

4. CONCLUSION

We presented a framework for the evaluation of haptic displays, focused on the operator's haptic perception. Two steps are suggested as pivotal parts of the evaluation, which can provide designers aiming at enhancing the effectiveness of their haptic devices with important insights.

In the first step we investigate with what settings the haptic device starts to change the operator's perception of the desired dynamics. This indicates the allowable bandwidth of the haptic interaction with a particular device if a perceptually transparent haptic display is required. The threshold model used in this step can be considered an alternative to existing criteria for haptic devices, such as the EASA qualification standards (EASA (2012)) for control loading systems in vehicle simulators.

The second step assesses the changes caused by a haptic device in the perception of mechanical properties. This provides insights into how stability and transparency can be more effectively balanced. It allows us to know that the rendering of which mechanical property still has room to be compromised (e.g., to improve stability), and that of which must be maintained or improved.

In this paper, the difference thresholds for the real and imaginary parts are considered to be independent. However, a previous study suggests that there may exist an interaction between the JNDs in the two parts Fu et al. (2017). This will need to be verified in the future.

REFERENCES

Abbink, D.A. and Mulder, M. (2009). Exploring the dimensions of haptic feedback support in manual control. *J. of Computing and Information Science in Engineering*, 9(1), 011006.

Cavusoglu, M.C., Tendick, F., Cohn, M., and Sastry, S.S. (1999). A laparoscopic telesurgical workstation. *IEEE Trans. on Robotics and Automation*, 15(4), 728–739.

Chang, P.H. and Kim, J. (2012). Telepresence index for bilateral teleoperations. *IEEE Trans. on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 42(1), 81–92.

de Stigter, S., Mulder, M., and van Paassen, M.M. (2007). Design and evaluation of a haptic flight director. *J. of Guidance, Control, and Dynamics*, 30(1), 35–46.

EASA (2012). *CS-FSTD(A): Certification Specifications for Aeroplane Flight Simulation.*

Fu, W., Landman, A., van Paassen, M.M., and Mulder, M. (2018). Modeling human difference threshold in perceiving mechanical properties from force. *IEEE Trans. Human-Machine Systems*, 48(4), 359–368.

Fu, W., van Paassen, M.M., Abbink, D.A., and Mulder, M. (2019a). Framework for human haptic perception with delayed force feedback. *IEEE Trans. on Human-Machine Systems*, 49(2), 171–182.

Fu, W., van Paassen, M.M., and Mulder, M. (2019b). Unified human threshold model for perceiving changes in system dynamics from force. *IEEE Trans. Human-Machine Systems*, under review.

Fu, W., van Paassen, M.M., Stroosma, O., and Mulder, M. (2017). Objective inceptor cueing test for control loading systems: Principle and initial design. In *AIAA Modeling and Simulation Technologies Conf.*, AIAA-2017-3669. Denver, USA.

Hashtrudi-Zaad, K. and Salcudean, S.E. (1996). Adaptive transparent impedance reflecting teleoperation. In *IEEE Int. Conf. on Robotics and Automation*, volume 2, 1369–1374. Minneapolis, USA.

Hosman, R.J.A.W., Benard, B., and Fourquet, H. (1990). Active and passive side stick controllers in manual aircraft control. In *1990 IEEE Int. Conf. on Systems, Man and Cybernetics (SMC)*, 527–529. Los Angeles, USA.

Hou, X., Mahony, R., and Schill, F. (2016). Comparative study of haptic interfaces for bilateral teleoperation of VTOL aerial robots. *IEEE Trans. on Systems, Man, and Cybernetics: Systems*, 46(10), 1352–1363.

Kim, J., Chang, P.H., and Park, H. (2013). Two-channel transparency-optimized control architectures in bilateral teleoperation with time delay. *IEEE Trans. on Control Sys. Techn.*, 21(1), 40–51.

Lam, T.M., Mulder, M., and van Paassen, M.M. (2008). Haptic feedback in uninhabited aerial vehicle teleoperation with time delay. *J. of Guidance, Control, and Dynamics*, 31(6), 1728–1739.

Mulder, M., Abbink, D.A., van Paassen, M.M., and Mulder, M. (2011). Design of a haptic gas pedal for active car-following support. *IEEE Trans. on Intelligent Transp. Systems*, 12(1), 268–279.

Nisky, I., Mussa-Ivaldi, F.A., and Karniel, A. (2008). A regression and boundary-crossing-based model for the perception of delayed stiffness. *IEEE Trans. on Haptics*, 1(2), 73–82.

Reintsema, D., Landzettel, K., and Hirzinger, G. (2007). Dlr's advanced telerobotic concepts and experiments for on-orbit servicing. In M. Ferre, M. Buss, R. Aracil, C. Melchiorri, and C. Balaguer (eds.), *Advances in Telerobotics*, 323–345. Springer Berlin Heidelberg, Berlin, Germany.

Smisek, J., Sunil, E., van Paassen, M.M., Abbink, D.A., and Mulder, M. (2017). Neuromuscular-system-based tuning of a haptic shared control interface for UAV teleoperation. *IEEE Trans. on Human-Machine Systems*, 47(4), 449–461.

Van Baelen, D., Ellerbroek, J., van Paassen, M.M., and Mulder, M. (2018). Design of a haptic feedback system for flight envelope protection. In *AIAA Modeling and Simulation Tech. Conf.*, AIAA-2018-0117. Kissimmee, USA.

van Paassen, M.M., van der Vaart, J.C., and Mulder, J.A. (2004). Model of the neuromuscular dynamics of the human pilot's arm. *J. of Aircraft*, 41(6), 1482–1490.

Venrooij, J., Mulder, M., Mulder, M., Abbink, D.A., van Paassen, M.M., van der Helm, F.C.T., and Bülthoff, H.H. (2017). Admittance-adaptive model-based approach to mitigate biodynamic feedthrough. *IEEE Trans on Cybernetics*, 47(12), 4169–4181.

Wildenbeest, J.G.W., Kuiper, R.J., van der Helm, F.C.T., and Abbink, D.A. (2014). Position control for slow dynamic systems: Haptic feedback makes system constraints tangible. In *IEEE Int. Conf. on Systems, Man, and Cybernetics (SMC)*, 3990–3995. San Diego, USA.

Yokokohji, Y. and Yoshikawa, T. (1994). Bilateral control of master-slave manipulators for ideal kinesthetic coupling-formulation and experiment. *IEEE Trans. on Robotics and Automation*, 10(5), 605–620.