The effect of static virtual couplings on realistic performance of haptic systems

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Abstract

The performance of haptic system depends on two properties, i.e. stability and transparency. Improving system stability unfortunately suffers transparency. A virtual coupling network, an artificial coupling between haptic devices and virtual environment, is used to guarantee system stability. However, the use of static virtual couplings could deteriorate the transparency performance. In this paper, we study the effect of a static virtual coupling on realistic performance of a haptic system. Realistic performance boundaries are then proposed as ones in which haptic systems would display realistic interaction between users and environment. These boundaries could be derived from an arbitrary virtual environment model. Finally, the effect of a static virtual coupling on transparency of a haptic system is illustrated by using realistic performance boundaries verified by experimental results.

1. Introduction

The field of virtual reality (VR) enhances communications between human and computers. The VR interface, e.g. visual, audio and etc, promotes natural feeling of human as if he or she interacts with real environment. A haptic interface is an interface that provides force feedback to human. The main objective of haptic interfaces is to provide realistic feeling to users while maintaining stability. Colgate and his colleagues [1] proposed a linear two-port network named *virtual coupling* in order to guarantee system stability. Such component is used to couple simulation of a virtual environment and a haptic device. The passivity concept developed by Colgate and Schenkel [2] was applied to determine parameters of haptic devices. These parameters are necessary for achieving system stability. Hannaford and Adams [3][4][5][6] also implemented a virtual coupling in their system. When each end of this coupling is connected with passive environment and human, necessary and sufficient conditions of the virtual coupling to guarantee the system stability, could be determined. They also modeled passive virtual environment. However, while enhancing the system stability, such a virtual coupling affects the realism of haptic simulation due to coupling impedance. The virtual coupling behaves like a mechanical coupling element connecting between a haptic device and virtual environment simulation.

A high performance haptic interface should allow users to feel like he or she interacts with real environment while, in fact, interacting with virtual environment. Hence, the transparency defined as a quality of force and velocity transformation of haptic systems, is a very crucial property, in the required performance. Colgate and Brown [7] used a dynamic range of achievable impedance so called "Z-Width" to measure the performance of force reflecting interfaces. Furthermore, Lawrence [8] proposed a concept of "Ideal-Equivalent" which considers the limitation of human sensation. By knowing this limitation, an impedance objective, a range of realistic interaction impedance sufficiently convincing users, could be determined. Yokokohji and his colleagues [9] proposed a concept of visual/haptic interfaces called "What You can See Is What You can Feel (WYSIWYF)". This concept benefits from using correct visual/haptic registration in enhance realism.

The concept of transparency was mainly discussed in two types of motion: free motion and constraint motion. However, in actual simulation, the impedance during interacting processes usually varies considerably from these two cases above. Therefore we propose a new method in performance measuring called "realistic performance boundaries". These boundaries depend on simulation impedance. A haptic system satisfies realistic interaction if the displayed impedance is in these boundaries. We have found that the unrealistic characteristics of haptic simulation depends on several factors. One of them is the virtual coupling. Our preliminary study is to analyze the effect of a static virtual coupling, a virtual coupling whose parameters are not functions of time, on realistic performance of a haptic system (High bandwidth force display: HBFD built by Moreyra [10]) by using realistic performance boundaries. Our study aims at understanding fundamental relationships between stability and transparency such that we can optimize these two properties in our future work. The experimental results which were used to define these boundaries are also included herein.

2. Stability concept and haptic system modeling

2.1 Stability concept

Haptic interface is generally comprised of three components which are human operator, haptic device and virtual environment simulation as shown in Fig 1.

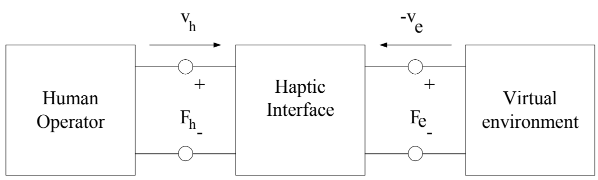


Fig.1 Two-port network of a haptic interface.

These three components could be written in form of a linear two-port mapping as

$$\begin{bmatrix} F_1 \\ -v_2 \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ F_2 \end{bmatrix}. \qquad (1)$$

We assume that the human operator and the virtual environment are passive. Hence, the stability criteria can be derived by using Llewellyn's stability criteria [3] which provides both necessary and sufficient conditions for an absolute stability, i.e.

$$\mathrm{Re}(p_{11}) \geq 0,\ \mathrm{Re}(p_{22}) \geq 0, \text{and} \qquad (2)$$

$$2\,\mathrm{Re}(p_{11})\,\mathrm{Re}(p_{22}) \geq \mathrm{Re}(p_{12}p_{21}) + |p_{12}p_{21}|. \qquad (3)$$

In the next subsection, the system model is formulated using a two-port network and the stability criteria is considered, based on $eq^{\underline{n}}$ (2) and $eq^{\underline{n}}$ (3).

2.2 Haptic system modeling and stability criteria

In this paper, we consider an impedance display haptic interface with virtual coupling as shown in Fig.2. This haptic system receives motion of a haptic device and computes forces required for such a motion.

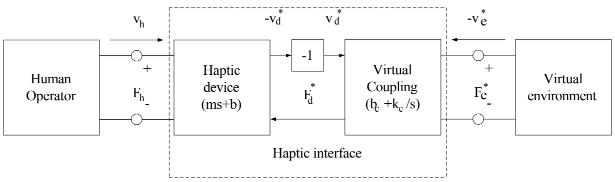


Fig.2 Two-port network of an impedance display haptic interface with a virtual coupling.

A two-port mapping of this device, based on Hannaford [3] is mathematically depicted in a matrix form:

$$\begin{bmatrix} F_h \\ -v_e^* \end{bmatrix} = \begin{bmatrix} Z_d(z) & ZOH(z) \\ -1 & \dfrac{1}{Z_c(z)} \end{bmatrix} \begin{bmatrix} v_h \\ F_e^* \end{bmatrix}, \qquad (4)$$

where F_h, v_h, F_e and v_e are human force, human velocity, virtual environment force and virtual environment velocity respectively. The parameters with "*" are in discrete forms. As seen in Fig.2, the device impedance, $Z_d(z)$ discretized by the Tustin's method is

$$Z_d(z) = (ms + b)\,|_{s \to (2/T)(z-1/z+1)}, \qquad (5)$$

where m and b are mass and coefficient of viscosity of the haptic device in Fig.2. The virtual coupling impedance $Z_c(z)$ in discretized format is

$$Z_c(z) = (b_c + \frac{k_c}{s})\,|_{s \to (z-1)/Tz}, \qquad (6)$$

where b_c and k_c are coefficient of viscosity and stiffness of the virtual coupling. The virtual environment discretized by Tustin's method is formulated as

$$Z_e(z) = (m_e s + b_e + \frac{k_e}{s})\,|_{s \to (2/T)(z-1/z+1)}, \qquad (7)$$

where m_e, b_e and k_e are mass, coefficient of viscosity and stiffness of the virtual environment respectively. The zero-order hold operator is considered as a low pass filter:

$$ZOH(z) = \frac{1}{2}\frac{(z+1)}{z}. \qquad (8)$$

By using the Llewellyn's stability criteria mentioned in $eq^{\underline{n}}$ (2) and $eq^{\underline{n}}$ (3) with the two-port mapping model in $eq^{\underline{n}}$ (4), necessary and sufficient conditions for an absolute stability of the impedance display are

$$\mathrm{Re}(Z_d(z)) \geq 0,\ \mathrm{Re}(1/Z_c(z)) \geq 0, \text{ and} \qquad (9)$$

$$\mathrm{Re}(1/Z_c(z)) \geq \frac{1-\cos(\angle ZOH(z))}{2\,\mathrm{Re}(Z_d(z))}\,|ZOH(z)|. \qquad (10)$$

In the next subsection, we will discuss stability analysis of our testbed. The experiment on this testbed aims at further understanding such conditions in $eq^{\underline{n}}$ (9) and (10).

2.3 High bandwidth force display (HBFD): stability analysis

The high bandwidth force display is a two-degrees of freedom cartesian haptic device built at the University of Washington Seattle as shown in Fig.3.

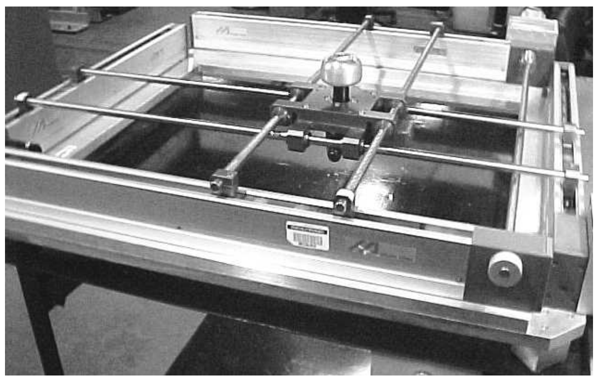


Fig.3 High bandwidth force display (HBFD)

This device can produce a high force output of 100 N (peak at 400 N). A fast update rate of 1000 Hz causes this device suitable for haptic simulation. The details of this system can be found in [10].

By following the analysis processes in [4], determining a mathematical model of the high bandwidth force display, we can plot the right-hand side of equation $eq^{\underline{n}}$ (10) versus frequency to form a theoretical lower bound for $\mathrm{Re}(1/Z_{cI}(z))$. It is plotted as a solid-line in Fig.4.

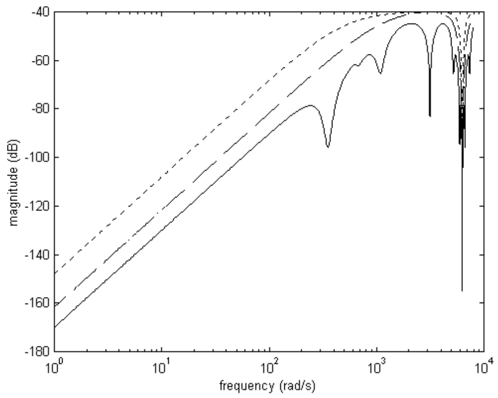


Fig.4 Stability criteria of an impedance haptic display.

The theoretical parameters of virtual coupling are as follow: k_c =110 kN/m and b_c =100 Ns/m, plotted in a long-dash-line in Fig.4. When these parameters are implemented, the system could be easily unstable. This instability results from using the worst case values of virtual coupling for ensuring system stability. In addition, factors such as nonlinear friction, human operator model and etc. are ignored. By fine tuning the virtual coupling parameters, we have found that the suitable parameters are as follow: k_c =50 kN/m and b_c =100 Ns/m. This new virtual coupling is also plotted as a short-dash-line in Fig.3.

3. Transparency Concept

Realistic performance of a haptic interface can be described in term of "Transparency" which indicates the quality of force and velocity transformation between human and virtual environment. The quality of force and velocity transformation is described by human perceived impedance which is an impedance that human perceives while interacting with a haptic system. There are two cases of human perceived impedance i.e. human perceived impedance of a haptic interface with virtual coupling ($Z_{h\_vc}(z)$) and without virtual coupling ($Z_h(z)$). From (4), human perceived impedance of a haptic interface with a virtual coupling ($Z_{h\_vc}(z)$) is derived as

$$Z_{h\_vc}(z) = Z_d(z) + ZOH(z)Z_e(z)(\frac{v_e}{v_h}), \qquad (11)$$

where $\frac{v_e}{v_h}$ can be formulated using (6) and (7) as

$$\frac{v_e}{v_h} = \left(\frac{b_c s + k_c}{m_e s^2 + (b_e + b_c)s + (k_e + k_c)} \right)\Bigg|_{s \to \frac{2(z-1)}{T(z+1)}} . \qquad (12)$$

The human perceived impedance of the haptic interface without virtual coupling ($Z_h(z)$) can be derived from $eq^{\underline{n}}$ (4) by letting $Z_c(z)$ approaches infinity as

$$Z_h(z) = Z_d(z) + ZOH(z)Z_e(z). \qquad (13)$$

The haptic device having a perfect transparency allows the force and velocity perceived by human to be equal to force and velocity of the virtual environment ($F_h = F_e$, $v_h = v_e$). Lawrence [8] proposed a transparency concept called "Ideal-equivalent". This concept is based on limitation of human perception, related to impedance objectives. These impedance objectives are impedance boundaries which adequately convince the users operating in two types of motions, i.e. free motion and constraint motion. The ideal-equivalent concept represents the bound of free and constraint motion, regardless of the realistic performance of the motion which lies between. In fact, types of motion in the real simulation are not restricted in these two cases. For this reason, we propose the realistic performance boundaries, to be thoroughly explained in next subsection.

3.1 Realistic performance boundaries

The realistic performance boundaries represent variation of human perceived impedance ($Z_h(z)$) while stably interacting with the reference environment through a haptic interface without virtual coupling. These boundaries depend on impedance of an adjustable virtual environment. They could be delineated from an experimental data. The parameters of adjustable virtual environment are adjusted by users such that they can perceive this environment to be the same as the reference environment. The adjusted parameters are analyzed using confidence interval theory to find the range of parameters that satisfies this realistic interaction. The upper and lower values of this range are substituted into the human perceived impedance equation (13) and the plot of realistic performance boundaries can be obtained as shown in Fig.5.

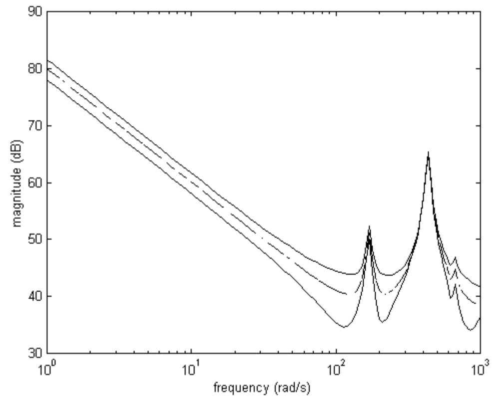


Fig.5 Realistic performance boundaries of a haptic interaction

The dash-line represents the human perceived impedance when interacting with the reference virtual environment. Two solid-lines above and under the dash-line are the upper boundary and lower boundary of realistic boundaries respectively. The band of realistic performance boundaries is defined as the difference between the upper and lower boundaries. The accuracy of these boundaries relies on number of subjects participating in this experiment. If the experimental data is a normal-distribution one, thirty subjects are sufficient to represent all population (the t-distribution will approach normal-distribution when samples are equal or more than thirty). If we use 99 percent confidence interval, we can conclude that 99 percent of users would feel realistically when the displayed impedance is within this boundary.

3.2 Experimental procedure

The experimental procedure is carried out step-by-step as follow:

Step 1: Defining a reference virtual environment impedance ($Z_e(z)$) that we want to determine the realistic performance boundaries,

Step 2: Simulating this reference environment on a haptic system (without virtual coupling). Users have to use these interacting forces generated from ($Z_e(z)$) as references,

Step 3: Using the same device to simulate another environment called an adjustable virtual environment which has different impedance from the reference virtual environment. Users are required to adjust parameters of this environment until he or she feels as if interacting with the reference environment. Meanwhile, stiffness and damping of this adjusted virtual environment (k_{e_adj}, b_{e_adj}) are observed,

Step 4: Calculating the mean ($\overline{X}$) and the standard deviation (SD) of k_{e_adj} and b_{e_adj} among n users. Using the confidence interval (CI) theory to determine the range of stiffness and damping that have 99 percent confidence interval.

The $\overline{X}$ and SD are determined as follow:

$$\overline{X} = \frac{\sum_{i=1}^{n} x}{n}, SD = \sqrt{\frac{\sum_{i=1}^{n} (x - \overline{X})^2}{\nu}}, \ \nu = n - 1. \quad (14)$$

The upper bound (x_{UCI}) and lower bound (x_{LCI}) of the 99 percent confidence interval of data (x) can be found by

$$x_{LCI} \le x_{confidence} \le x_{UCI}, \text{ and}$$

$$\overline{X} - t_{\alpha/2,v}(\frac{SD}{\sqrt{n}}) \le x_{confidence} \le \overline{X} + t_{\alpha/2,v}(\frac{SD}{\sqrt{n}}) \quad (15)$$

where n is number of sample, $x_{confidence}$ is confidence interval, $t_{\alpha/2,v}$ is the t-distribution value which have 99 percent confidence interval and $\alpha = 1 - (0.01 \times CI)$.

Step 5: Simply substituting the minimum and maximum of the range of stiffness and damping into the virtual environment model.

We obtain the lower boundary as

$$Z_e(z) = (m_e s + b_{e\_LCI} + \frac{k_{e\_LCI}}{s})|_{s \to \frac{2(z-1)}{T(z+1)}}, \quad (16)$$

and the upper boundary as

$$Z_e(z) = (m_e s + b_{e\_UCI} + \frac{k_{e\_UCI}}{s})|_{s \to \frac{2(z-1)}{T(z+1)}}. \quad (17)$$

The realistic performance boundaries are determined by substituting $eq^{\underline{n}}$ (16) and $eq^{\underline{n}}$ (17) into $eq^{\underline{n}}$ (13). A plot of $Z_h(z)$ in $eq^{\underline{n}}$ (13) versus frequencies is readily obtained.

4. Experimental results

In our experiment, ten subjects were performed with the high bandwidth force display using one degree of freedom (1-DOF) virtual environment. Five cases of reference virtual environment impedance are varied from nearly free motion impedance to nearly constraint impedance. Note that very low impedance is the case that b_e and k_e are 0.1 N.s/m and 10 N/m respectively; low impedance is the case that b_e and k_e are 1 N.s/m and 1000 N/m respectively; medium impedance is the case that b_e and k_e are 10 N.s/m and 10000 N/m respectively; high impedance is the case that b_e and k_e are 25 N.s/m and 25000 N/m respectively and very high impedance is the case that b_e and k_e are 50 N.s/m and 50000 N/m respectively. Our environment was simulated as a virtual wall as shown as a dotted line in Fig.6.

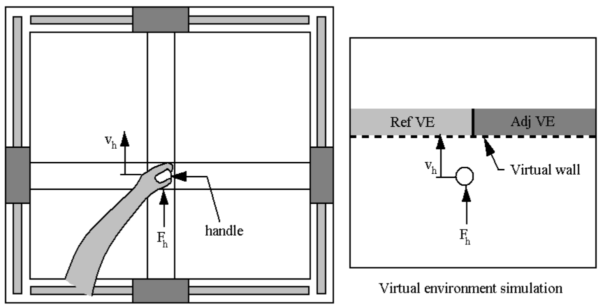


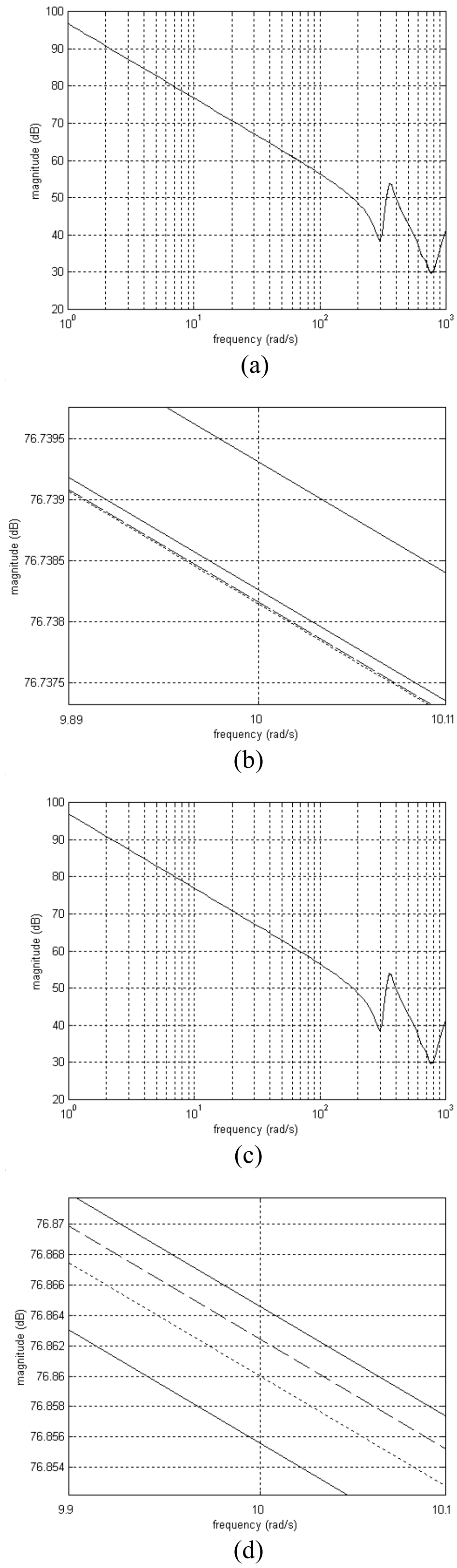
Fig.6 Virtual wall simulation. (Note that Ref VE and Adj VE are reference and adjustable virtual environment respectively)

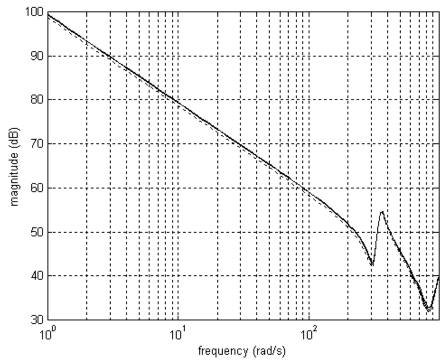
As shown in Fig.6, the adjustable virtual environment is placed beside the reference virtual environment in order to compare the force feedback between these two environments. The updated force corresponding to the adjusted parameters, are displayed in real-time. Therefore, users can perceive the updated forces while adjusting parameters. Users can also adjust parameters of the virtual environment (b_{e_adj}, k_{e_adj}) until he or she feel like interacting with the reference virtual environment. The final adjusted parameters were analyzed by using the confidence interval theory among all subjects and shown in Table.1.

VE	Parameters	Ref VE	LCI	UCI
VE 1	k_e	10	10.808	19.02
	b_e	0.1	0.0356	1.3335
VE 2	k_e	1000	944.85	1017.2
	b_e	1	1.2404	1.5316
VE 3	k_e	10000	8979.9	9954.1
	b_e	10	8.188	13.146
VE 4	k_e	25000	23316	24968
	b_e	25	21.447	27.549
VE 5	k_e	50000	39498	47829
	b_e	50	79.933	112.34

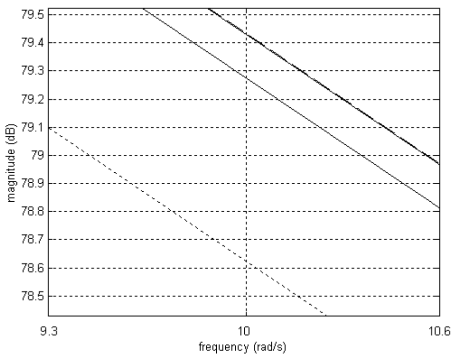
Table.1 Experimental results (Note that VE is virtual environment, stiffness is in N/m and damping is in N.s/m)

From Table.1, the lower and upper bound of parameters are calculated such that the realistic performance boundaries of each reference virtual environment is found. However we will analyze only three cases of virtual environment that represent three different types of interaction as plotted in Fig.7.





(e)



(f)

Fig.7 Plot of realistic performance boundaries (solid-line), $Z_h(z)$ (long-dash-line) and $Z_{h\_vc}(z)$ (short-dash-line) when the virtual environment parameters are (a) $b_e = 0.1$ N.s/m, $k_e = 10$ N/m, (b) enlarged figure of Fig.7a, (c) $b_e = 1$ N.s/m, $k_e = 1000$ N/m, (d) enlarged figure of Fig.7c, (e) $b_e = 25$ N.s/m, $k_e = 25000$ N/m, (f) enlarged figure of of Fig.7e.

The short-dash-line is a plot of human perceived impedance of a haptic interface with a static virtual coupling ($Z_{h\_vc}(z)$). The long dash-line is a plot of human perceived impedance of a haptic interface without virtual coupling ($Z_h(z)$) while the solid-lines are upper and lower boundaries. As shown in Fig. 7a, 7c and 7e, these four lines could not be distinguished. Hence, we also plotted Fig. 7b, 7d and 7f as enlarged figures of these four lines at frequency between 9.89 rad/s to 10.11rad/s, between 9.9 rad/s to 10.1rad/s and between 9.3 rad/s to 10.6 rad/s respectively.

5. Discussion

From Fig. 7a, 7c and 7e, it can be seen that the plot of these three different virtual environments have similarly shape but different magnitude. The magnitude is high when the virtual environment has high impedance and low when the virtual environment has low impedance. Due to the flexibility of the high bandwidth force display mechanisms, there are some peaks caused by system resonance at the frequencies above 300 rad/s. The effect of system resonance could be also observed as several knots in Fig.4. However, the frequency range of force feedback that human can perceive is below 100 rad/s. Therefore, we can ignore the resonance effect at such a frequency.

Fig. 7b, plot of $Z_{h\_vc}(z)$ is almost the same line as plot of $Z_h(z)$ but both of them lie below the realistic performance boundaries. Thus, we can conclude that at low impedance virtual environment the effect of virtual coupling on realistic performance is not significant. We also observed that boundaries of impedance allowing human to feel like interacting with the nearly-free motion impedance, are higher than the impedance that the haptic system can display. Therefore, there are minimum impedance boundaries that human can perceive called minimum free motion impedance boundaries.

Fig. 7d shows that both plot of $Z_{h\_vc}(z)$ and $Z_h(z)$ are in the realistic performance boundaries. The plot of $Z_{h\_vc}(z)$ lies below $Z_h(z)$. Thus, we can conclude that human perceived impedance is decreased from the effect of virtual coupling. However, $Z_{h\_vc}(z)$ satisfies the realistic performance boundaries.

In Fig. 7f, both plots of $Z_{h\_vc}(z)$ and $Z_h(z)$ are out of the realistic performance boundaries. It can be seen that the plot of $Z_{h\_vc}(z)$ lies below lower boundary. Thus, users would perceive unrealistic interaction. Since, plot of $Z_h(z)$ lies above the upper boundary, we can conclude that human perception has limitation. As the consequence of this limitation, we can display the realistic interaction of reference virtual environment if the displayed impedance is in the realistic boundaries.

From Fig.7b, 7d and 7f, the band of realistic performance boundaries is the difference between upper and lower boundaries of interaction. This band has some relationship with the virtual environment impedance. It is small when interacting with low impedance environment and large when interacting with high impedance environment. Based on this observation, we can conclude that at low impedance simulation, the ability of human perception to distinguish the difference in virtual environment impedance is higher than one at high impedance simulation.

The human perceived impedance, displayed from the haptic system with an impedance typed virtual coupling, is always smaller than the impedance of the virtual environment. The use of static virtual coupling may affect the realistic performance of the haptic system. The static virtual coupling parameters, which are derived for guaranteeing overall system stability, only suitable for high impedance simulation. However when simulating lower or medium impedance, the human perceived impedance with static virtual coupling may not be within the realistic performance boundaries. Thus, ways to adjust the virtual coupling impedance to satisfy both stability criteria and realistic performance boundaries should be thoroughly investigated.

6. Conclusion and Future works

In this paper, we propose the realistic performance boundaries representing variation of human perceived impedance ($Z_e(z)$). These boundaries which depend on virtual environment impedance are delineated from experimental data. Based on these boundaries, the realistic performance of haptic system can be determined. We have found that the use of static virtual coupling in haptic systems could affect realistic performance. Therefore, our future works are to enhance the realistic performance of haptic systems by adapting virtual coupling parameters according to dynamics of virtual environment.

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