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REGULAR PAPER

Influence of human operator on stability of haptic rendering: a closed-form equation

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Abstract

In this paper an analytical stability criterion for linear haptic devices is determined, in the presence of the operator. The model of the haptic device and the virtual environment are assumed as mass-damper and spring-damper, respectively. Two different models for operator's hand are assumed, and the stability boundaries are derived analytically. The main contribution of this paper is the analytical formulation of a closed-form stability equation in the presence of the operator; which can predict the stability boundary with small and even large values of virtual damping and time delay. This closed-form stability criterion can be useful in applications such as haptic rendering of deformable objects using finite element method, where the computational time delay is considerable. The influence of operator's hand and effective mass on the stability is studied analytically and verified by simulations and experiments on a KUKA Light Weight Robot.

Keywords Stability · Haptic device · Analytical criterion · Operator · Effective mass

1 Introduction

Haptic devices are commonly used to simulate a virtual object or surface for the human operator. In most of haptic applications, the virtual environment (VE) is modeled as a discrete-time spring with stiffness (K) and damping (B). The haptic device would have higher transparency when simulating a virtual object with high values of K and B (Adams and Hannaford 1999); however increasing these two parameters may have negative effect on the stability of the system. The ability of simulating contact force in virtual environments is necessary in many applications such as teleoperation (Barbieri et al. 2018; Cerulo et al. 2017; Cheng and Tavakoli 2019), surgery training for medical students (Mashayekhi et al. 2014; Fontanelli et al. 2018; Fazioli et al. 2016), and human–robot interaction (Sadeghian et al. 2012; Najafi et al. 2017; Peng et al. 2018).

In view of an overgrowing interest in the development of virtual environments, there are considerable research activities in the area of stability of haptic systems. Colgate and Schenkel showed that with assumption of passive operator, the necessary and sufficient condition for passivity of a haptic device, with viscous friction of b, sampling time of T and a discrete virtual environment of $H(z)$ is:

$$\frac{T}{2}\frac{1}{1-\cos(\omega T)}\mathrm{Re}\{\left(1-e^{-j\omega T}\right)H\left(e^{j\omega T}\right)\}<b,\quad 0\leq\omega\leq\omega_N \tag{1}$$

where $\omega_N=\pi/T$ is the Nyquist frequency (Colgate and Schenkel 1994). In the case of a virtual environment such as $H(z)=K+B\frac{z-1}{Tz}$ their passivity criterion is determined as follows:

$$KT/2+|B|<b \tag{2}$$

where K and B are virtual stiffness and virtual damping of virtual environment respectively. This criterion—which is valid for small values of virtual damping and time delay—is too conservative in comparison with the stability criteria.

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Stability of haptic devices has been studied by Minsky et al. (1990), under the assumption of a linear mass-damper model for the haptic device and a continuous spring as the VE. They showed that by assuming the time delay is equal to one sampling time (i.e. $t_d = T$), the stability equation would be as follows:

$$KT < b. \tag{3}$$

They experimentally found that the effect of operator's hand with effective mass of m_H, viscous friction of b_H and stiffness of k_H on the stability of the haptic device with effective mass m and viscous friction b, while providing a VE with stiffness of K and damping of B, is as follows:

$$\frac{(K + k_H)T}{2} < B + b + b_H. \tag{4}$$

The factor of 1/2 in this equation was reached from experiments. Brown and Colgate reported a stability boundary for haptic rendering, while taking into account the influence of many parameters of the haptic device, which was consistent with the results of Brown and Colgate (1994).

After a theoretical analysis with the assumption of small values of B and t_d, the following equation for stability was derived by Gil et al. (2009):

$$K < \frac{b + B}{\frac{T}{2} + t_d}. \tag{5}$$

Using the simplification of the influence of sampling and hold with sampling time T equivalent with the time delay $T/2$, the above equation could be written as follows:

$$K < \frac{\sum \text{damping}}{\sum \text{delay}}. \tag{6}$$

Passivity approach is also used to consider effect of Coulomb friction on the boundary of stability in Diolaiti et al. (2006) and improved in Mashayekhi et al. (2014).

For large values of B and t_d the stability boundaries have been plotted by numerically solving nonlinear equations in Gil et al. (2009). Recently linear matrix inequality is used to determine the boundary of stability using Lyapunov–Krasovskii functional (Mashayekhi et al. 2019). Similarly, the effect of the operator's hand on the stability has been studied by numerically solving complicated equations of the system, while neglecting the time delay in Gil et al. (2004) and with time delay in Hulin et al. (2014). In both references the operator's hand has been modeled by a second-order mass-spring-damper model. The influence of the effective mass (i.e. the sum of the effective mass of the operator and the effective mass of the haptic device) on the boundary of stability was studied in Hulin et al. (2014), and stability boundaries were numerically plotted.

In prior work, either the operator was omitted, or a simple mass-spring-damper model of the hand was utilized in the stability analysis (Colgate and Schenkel 1994; Minsky et al. 1990; Brown and Colgate 1994; Gil et al. 2009, 2004; Hulin et al. 2014). Also, the developed formula in prior work was applicable for predicting the boundary of stability only for small values of virtual damping and time delay (Minsky et al. 1990; Gil et al. 2009; Hulin et al. 2014). In the case of large virtual damping and large time delays, the stability boundaries were plotted only numerically (even with mass-spring-damper model of the hand) (Gil et al. 2004; Hulin et al. 2014).

This paper is extension of Mashayekhi et al. (2018) and uses state-space equations to contain analytical study of the stability problem of a haptic device, interacting with an operator without any limitation on the parameters. In Mashayekhi et al. (2018) effect of human operator was not involved in the analysis, and in this paper it is included, both theoretically and experimentally. Any linear model for the hand can be incorporated in the analysis. For instance, inclusion of a five-parameter model of the hand is also presented in the current paper, and a closed-form formulation for predicting the boundary of stability is determined and results are verified by simulations. Based on the developed formulation, the effect of each parameter on the boundary of stability can be determined. In real time applications, after determination of the impedance parameters of the operator's hand, the closed-loop stability can be determined on line. The developed equations are verified by simulations and experiments on a KUKA Light Weight Robot. In addition, the influence of the effective mass of the system on the boundary of stability is studied theoretically and verified by experiments.

The system description and model of the haptic device are presented in the next section. Section 3 presents the proposed stability analysis and resultant stability criterion. In the case of small values of virtual damping and time delay, our theory is simplified to the well-known linear formulation for boundary of stability.

Furthermore, the influence of the operator and the effective mass on the stability is studied next. For validating the stability criterion, simulations and experiments are elaborated in Sects. 4 and 5 respectively. Sections 6 and 7 contain discussion and conclusion respectively.

2 System description

A haptic robot may have several degrees of freedom. However, while it is in the contact with the operator's hand for simulating a virtual object, its contact point and links are in rather constant positions, or they may have only small movements around a steady configuration. Therefore, the dynamic of the robot can be linearized in the contact point, as a one degree of freedom system with mass and damper. For example when using a surgery training robot (such as VirSense Mashayekhi et al. 2014), total workspace obviously has a significant volume. But in the contact point of the tool to the patient (maybe skin of the patient), there are small movements round the contact point, compared with the entire workspace of the haptic device. So the dynamic of the haptic device can be linearized round the contact point. This assumption is also used in other applications such as simulating, virtual assembly, training, rehabilitation and robot control.

This reasonable assumption has been frequently utilized in the literature in stability or passivity analysis (Colgate and Schenkel 1994; Gil et al. 2004, 2009; Hulin et al. 2014). A schematic view of an operator, interacting with a 1-DOF haptic device is depicted in Fig. 1.

The haptic device with effective mass (m) moves under the effect of the operator's force and force of the VE (F_{VE}). F_{VE} is the force to be simulated as the virtual environment, which is modeled as a discrete spring (B) and discrete damper (K). This force is applied to the robot after a time delay of t_d and then hold in a zero-order-hold with sampling time of T. The time delay can originate from different sources, including force computation, communication, motor control and sensor delays. Time delays in a closed control loop system can be added up to a single time delay of t_d without affecting the transfer function of a linear system (Hulin et al. 2014). This time delay is assumed to be constant.

The operator's hand also has several degrees of freedom. In this paper, two different verified models, obtained from available literature are utilized for the operator's hand, and a closed-form stability formulation is determined in each case. In the first model, the hand is linearized round the operating point, and approximated by a linear mass, spring and damper system. This approximation has been verified experimentally in references such as (Mussa-Ivaldi et al. 1985). The second

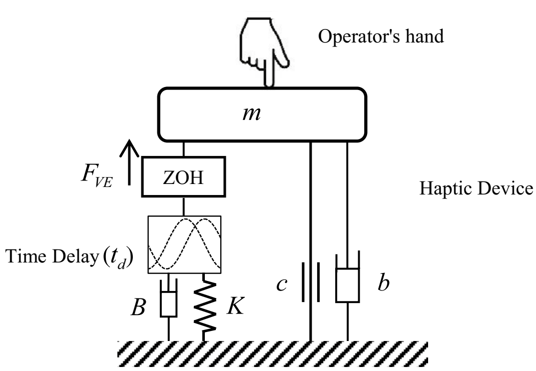

Fig. 1 Schematic view of a 1-DOF haptic device

model of the hand is a five-parameter model, presented by Speich et al. (2005). This model which is more complicated, has been used with the aim to show that any linear model for the hand can be used in developed stability analysis, and its effect on the stability can be determined analytically.

Coulomb (c) and viscous (b) frictions of the robot dissipate energy from the system. The links of the robot are assumed to be rigid, without any internal vibration. Also, the actuators are assumed to be continuous, without saturation. It is assumed that there is no velocity sensor or velocity observer, and the backward difference is used to estimate the velocity without any filtering.

References (Diolaiti et al. 2006; Abbott and Okamura 2005) have shown that Coulomb friction could dissipate the generated energy due to quantization in sensors. Later, more precise analysis by Mashayekhi et al. showed that these two nonlinear effects could cancel each other in the stability analysis (Mashayekhi et al. 2014).

3 Stability criterion

In this section a stability criterion is derived, first without considering the operator and then with taking it into account. The required velocity information in the feedback loop is computed by using simple backward difference, as follows:

$$\dot{x}(k) \approx \frac{x(k) - x(k-1)}{T}. \tag{7}$$

Because of fast sampling rate in the haptic devices—in comparison of their dynamic—(Basdogan et al. 2004), this term can be approximated by $\dot{x}(t - T/2)$. In addition, the effect of ZOH can be approximated by a delay equal to half of the sampling time (i.e. $t_d = T/2$). Then the position (x) and velocity ($\dot{x}$) have a delay of $t_d + T/2$ and $t_d + T$, respectively. Thus F_{VE} equals to:

$$F_{VE}(t) = Kx(t - t_d - T/2) + B\dot{x}(t - t_d - T). \tag{8}$$

From Newton's second law, the acceleration of the haptic device is:

$$\ddot{x} = -\frac{b}{m}\dot{x} - \frac{F_{VE}}{m}. \tag{9}$$

By assuming two states $x_1 = x$ and $x_2 = \dot{x}$ (9), can be written in state-space form as the following equation:

$$\begin{cases} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\frac{b}{m}x_2 - \frac{K}{m}x_1\left(t - t_d - T/2\right) - \frac{B}{m}x_2\left(t - t_d - T\right). \end{cases} \tag{10}$$

Defining $\mathbf{x} = [x_1, x_2]^T$, this equation can be rewritten in the state-space form as:

$$\dot{\mathbf{x}} = \mathbf{A}_1\mathbf{x} + \mathbf{A}_2\mathbf{x}(t - t_d - T/2) + \mathbf{A}_3\mathbf{x}(t - t_d - T) \tag{11}$$

where $\mathbf{A}_1$ to $\mathbf{A}_3$ are 2×2 matrices, defined as:

$$\mathbf{A}_1 = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{b}{m} \end{bmatrix}, \quad \mathbf{A}_2 = \begin{bmatrix} 0 & 0 \\ -\frac{K}{m} & 0 \end{bmatrix}, \quad \mathbf{A}_3 = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{B}{m} \end{bmatrix}. \tag{12}$$

Equation (11) has the following characteristic equation (Wu et al. 2010):

$$\det\left(\lambda \mathbf{I}_{2\times 2} - \mathbf{A}_1 - \mathbf{A}_2 e^{-(T/2+t_d)\lambda} - \mathbf{A}_3 e^{-(T+t_d)\lambda}\right) = 0, \tag{13}$$

where $\lambda = \sigma + j\omega$ is the eigenvalue of the characteristic equation, and ω is the frequency which starts from zero. The haptic device is stable for $\sigma < 0$, and is unstable for $\sigma > 0$. Thus, the boundary of stability is in a situation where $\sigma = 0$, which means $\lambda = j\omega$. Equation (13) is transcendental, which makes it difficult to solve in general. By substituting $\mathbf{A}_1$, $\mathbf{A}_2$ and $\mathbf{A}_3$ from (12), Eq. (13) becomes:

$$\det\begin{bmatrix} \lambda & -1 \\ \frac{K}{m}e^{-(T/2+t_d)\lambda} & \lambda + \frac{b}{m} + \frac{B}{m}e^{-(T+t_d)\lambda} \end{bmatrix} = 0, \tag{14}$$

or:

$$\lambda\left(\lambda + \frac{b}{m} + \frac{B}{m}e^{-(T+t_d)\lambda}\right) + \frac{K}{m}e^{-(T/2+t_d)\lambda} = 0. \tag{15}$$

Equation (15) is the new form of the characteristic equation of the haptic device. By substituting $\lambda = j\omega$ and knowing that $e^{j\omega} = \cos(\omega) + j\sin(\omega)$, the characteristic equation is simplified as:

$$\begin{aligned}&\left[b\omega + B\omega\cos\left((T + t_d)\omega\right) - K\sin\left((T/2 + t_d)\omega\right)\right]j \\ &\quad + \left[B\omega\sin\left((T + t_d)\omega\right) + K\cos\left((T/2 + t_d)\omega\right) - m\omega^2\right] \\ &= 0.\end{aligned} \tag{16}$$

Solving these two equations versus K and B leads to:

$$\begin{cases} K = \dfrac{b\omega\sin\left((T+t_d)\omega\right) + m\omega^2\cos\left((T+t_d)\omega\right)}{\cos(T\omega/2)} \\ B = \dfrac{m\omega\sin\left((T/2+t_d)\omega\right) - b\cos\left((T/2+t_d)\omega\right)}{\cos(T\omega/2)}. \end{cases} \tag{17}$$

By using (17) the stability boundary for the haptic device can be easily plotted for small and even large values of B and t_d. To have a realistic sense, the stability boundaries are plotted for Phantom 1.0 haptic device, with effective mass of $m = 0.072$ kg, viscous friction of $b = 0.005$ Ns/m, sampling time of $T = 1$ ms for several values of $t_d = [0, 1, 2]$ ms, which are shown in Fig. 2.

From Fig. 2 it can be concluded that increasing the time delay has a negative effect on stability and pulls down the stability boundary. As mentioned in the Introduction, stability boundaries have been plotted for large values of B and t_d by numerically solving some complicated equations in (Hulin et al. 2014; Gil et al. 2009); whereas here they are plotted using a pair of simple analytical equations (i.e. (17)). The resultant closed form equations can play an important rule is haptic systems such as haptic rendering of virtual environments, teleoperation etc.

The starting point in Fig. 2 corresponds to $\omega = 0$. This point can be readily calculated by substituting $\omega = 0$ in (17) as: $(B, K) = (-b, 0)$, which also was determined in Hulin et al. (2014) and Gil et al. (2009).

In (17) ω varies from zero to a special value which makes K equal to zero:

$$K = \frac{b\omega\sin\left((T + t_d)\omega\right) + m\omega^2\cos\left((T + t_d)\omega\right)}{\cos(T\omega/2)} = 0. \tag{18}$$

This equation holds on two points. The first one is $\omega = 0$, which is the starting point in Fig. 2. The second one is the end point of the curves:

$$b\sin\left((T + t_d)\omega\right) + m\omega\cos\left((T + t_d)\omega\right) = 0. \tag{19}$$

By defining a new parameter $X = (T + t_d)\omega \geq 0$, the following equation will be obtained:

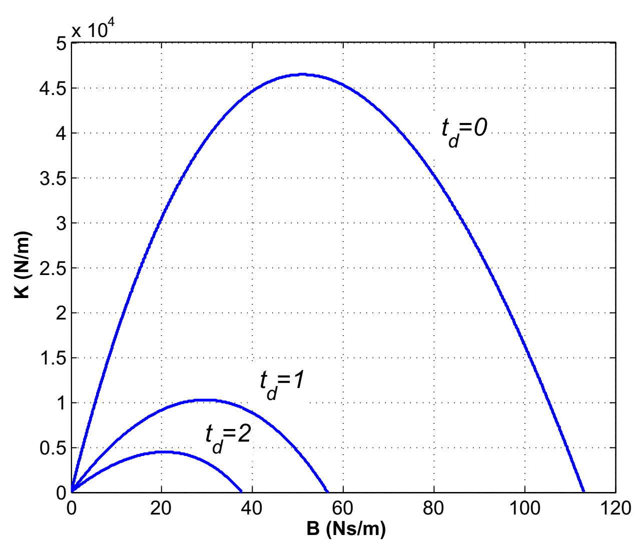

Fig. 2 Stability boundary of Phantom 1.0 haptic device with time delays of $t_d = [0, 1, 2]$ ms

$$-\tan(X) = \frac{m}{b(T + t_d)} X. \tag{20}$$

Equation (20) has two answers: $X = 0$, and another answer is in the interval of $X \in (\pi/2, \pi)$. Using curve fit approach, a good approximation for $-\tan(X)$ is:

$$-\tan(X) \cong \frac{p_1 X^2 + p_2 X + p_3}{X + q_1} \text{ for } X \in (\pi/2, \pi) \tag{21}$$

where $p_1 = -0.4087$, $p_2 = 1.325$, $p_3 = -0.07507$ and $q_1 = -\pi/2$.

Replacing (21) into (20), after defining a new variable $a = m/(b(T + t_d))$ and solving the resultant equation for X, maximum value of ω is determined as follows:

$$\omega_{\max} = \frac{1}{T + t_d} \times \frac{-(p_2 - aq_1) - \sqrt{(p_2 - aq_1)^2 - 4p_3(p_1 - a)}}{2(p_1 - a)}. \tag{22}$$

In fact, for plotting the boundary of stability, (e.g. Fig. 2) ω starts from zero, and goes to the final value of $\omega_{\max}$ calculated by (22).

In the case of small values of virtual damping and time delay (17), can be simplified to the linear stability criterion (5).

3.1 Effect of mass

As mentioned in the Introduction, numerical methods have been used in literature for considering the influence of the effective mass on the stability. By using the method developed in this paper, the influence of the effective mass on the boundary of stability can be analytically studied by using (17). As a case study, stability boundaries for Phantom 1.0 haptic device with different effective masses of $m = [0.5, 1, 2] \times 0.072$ kg are plotted in Fig. 3a, b for $t_d = 0$ and $t_d = 10$ ms respectively.

From Fig. 3 it is clear that increasing the effective mass has a positive effect on the stability of the haptic device and makes the system more stable (*i. e.* increases the stability margin). This result is consistent the practical experiments: a heavy grip makes the system more stable, while a light grip is the most challenging (Diolaiti et al. 2006). All plots are starting from the common point of $(K, B) = (0, -b)$. It means that for small values of B, m has no significant influence on the stability—the results which was shown analytically in the previous subsection.

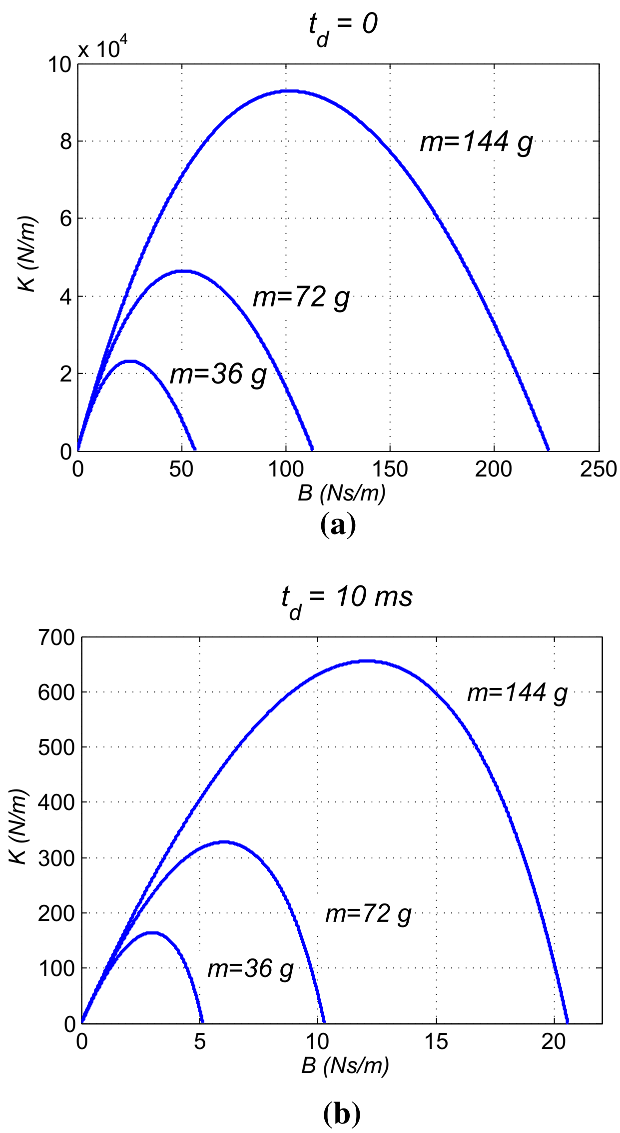

Fig. 3 Effect of mass on stability boundary of Phantom 1.0 for delays of 0 and 10 ms

3.2 Operator effect

Haptic devices are in contact with operators when an operator feels a virtual object by a haptic device. Obviously, the operator's hand is itself a dynamic system interacting with the haptic robot, affecting the boundary of stability. In the reviewed literature, two different scenarios have been used to take the influence of the operator into account:

(1) Since the operator is a passive element in the frequencies that instability may occur, it cannot insert energy to the system and only absorbs energy from the haptic device, which in turn makes it more stable. Thus, the first scenario is removing the hand from the stability analysis. In fact, this is "a worst-case scenario" analy-

sis. In practical applications, the operator can makes the haptic device more stable. This scenario has been used in references such as (Gil et al. 2009; Diolaiti et al. 2006; Mashayekhi et al. 2018, 2019).

(2) The second scenario is to consider the effect of the operator's hand in stability analysis. For this purpose, in the reviewed literature only a linear mass-spring-damper model has been utilized for the hand. For small values of time delay and virtual damping, a linear formulation has been derived. While for large values of time delay and virtual damping, numerical methods have been used to plot the stability boundaries.

Based on the reviewed literature, it is clear that the effect of the operator on the stability of haptic rendering has not been properly studied yet. In this section the effect of the operator's hand on the boundary of stability is analytically studied. For this purpose two different models are utilized: (1) A second-order mass-spring-damper model, and (2) A five-parameter model. The output of this method is a closed-form formula, which relates all parameter together, without any limitation on them.

3.2.1 Second-order mass-spring-damper model

There is considerable literature where the operator's hand has been modeled as one degree of freedom mass-spring-damper with effective mass of m_H, effective viscous friction of b_H and stiffness of k_H (Gil et al. 2004; Hulin et al. 2014). The transfer function between displacement of the hand and the applied force by the hand is as follows:

$$\frac{X_H(s)}{F_H(s)} = \frac{1}{m_H s^2 + b_H s + k_H}. \tag{23}$$

Using this model, it can be easily showed that the effective mass and viscous friction of the hand are added to the effective mass and viscous friction of the haptic device, respectively.

The presented method in this paper can be extended to analytically consider the effect of the operator on the stability. In this case the acceleration of the haptic device is calculated as follows:

$$\ddot{\boldsymbol{x}} = -\frac{B^*}{M^*}\dot{\boldsymbol{x}} - \frac{F_{VE}}{M^*} - \frac{K^*}{M^*}\boldsymbol{x} \tag{24}$$

with $M^* = m_H + m$, $B^* = b_H + b$, $K^* = k_H$ and F_{VE} as before. By following the procedure described in this section, a new formulation for K and B is determined as follows:

$$\begin{cases} K = \frac{B^*\omega\sin((T+t_d)\omega)+M^*\omega^2\cos((T+t_d)\omega)-K^*\cos((T+t_d))}{\cos(T\omega/2)} \\ B = \frac{M^*\omega^2\sin((T/2+t_d)\omega)-B^*\omega\cos((T/2+t_d)\omega)-K^*\sin((T/2+t_d)\omega)}{\omega\cos(T\omega/2)}. \end{cases} \tag{25}$$

This new formulation can predict the boundary of stability in the presence of the operator. In this case, ω will start form a non-zero value of $\omega_{\min} > 0$, which is a function of known system parameters, and ends up to a maximum value of $\omega_{\max}$, which is obviously different from (22). In this case, due to the form of the new equations, finding a closed-from formulation like (22) for $\omega_{\min}$ and $\omega_{\max}$ is a complicated task, but the boundary of stability can be plotted point by point by using a numerical model for the human operator.

Several available parameters for the second-order mass-spring-damper model have been listed in Table 1.

Using (25) stability boundaries can be plotted readily for different operator models (Table 1), which are shown in Fig. 4a, b for $t_d = 0$ and $t_d = 2$ ms respectively. For the haptic device $m = 1$ kg, $T = 1$ ms and $b = 1$ Ns/m are chosen.

From Fig. 4a, b, it is clear that the operator makes the system more stable, regardless of the time delay. Similar results and graphs have been plotted in Gil et al. (2004) and Hulin et al. (2014) by numerically solving some complicated equations, while they are plotted here using a simple analytical equation.

3.2.2 Five-parameter model of the hand

Two different models of hand are presented in Speich et al. (2005): (a) two-parameter, and (b) five-parameter model. The two-parameter model of the hand is identified as:

$$\frac{X_H(s)}{F_H(s)} = \frac{1}{3.6s + 40}. \tag{26}$$

In comparison with the second-order mass-spring-damper model, five-parameter model includes an additional spring and damper, to model more accurately the dynamic behavior of the hand in frequencies below 20–30 Hz. Schematic

Table 1 Impedance parameters of the second-order model of operator's hand

Author	$m_H (kg)$	$b_H (Ns/m)$	$k_H (N/m)$
Lawrence (1993)	17.51	175.1	175.1
Kazerooni et al. (1993)	4.54	12.5	6.83
Kosuge et al. (1993)	1.95	55	2.46
Daniel and McAree (1998)	1	39.5	12.6
Hogan (1989)	0.8	568	5.5
Lawrence and Chapel (1994)	0.5	40	6
Kuchenbecker et al. (2003)	0.15	1000	7.5

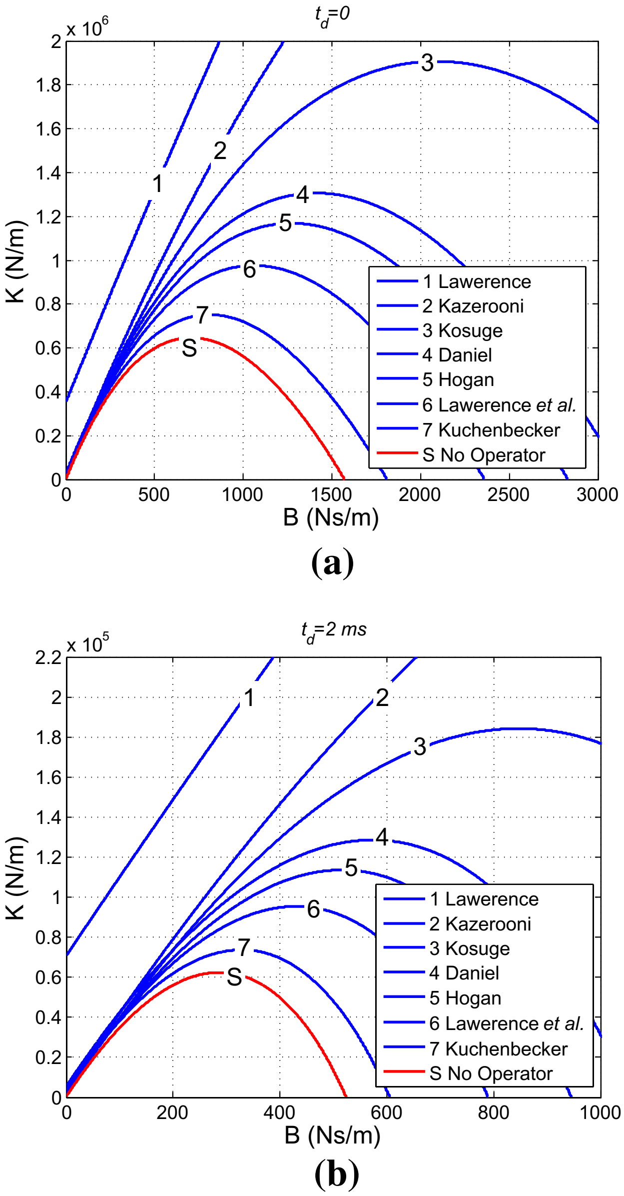

Fig. 4 Effect of operator on the stability with $d = [0, 2]$

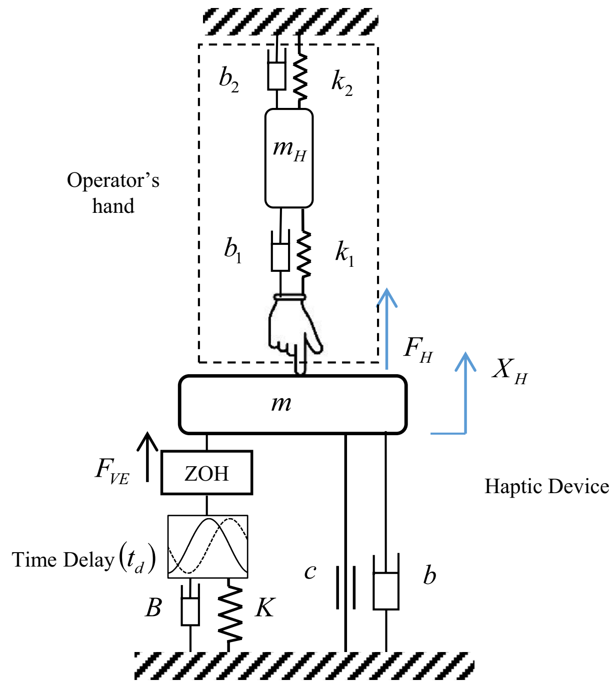

Fig. 5 Five-parameter model of hand and the haptic device

view of this model is depicted in Fig. 5. This model has five-parameters of $b_1 = 4.5\,Ns/m$, $b_2 = 7.9\,Ns/m$, $k_1 = 48.8\,N/m$, $k_2 = 375\,N/m$ and $m_H = 1.46\,kg$ (Speich et al. 2005).

The transfer function between the displacement of the hand and the applied force by the hand is determined as follows (Speich et al. 2005):

$$\frac{X_H(s)}{F_H(s)} = \frac{s^2 + \alpha_1 s + \alpha_0}{\beta_3 s^3 + \beta_2 s^2 + \beta_1 s + \beta_0}, \tag{27}$$

wherein below parameters are defined:

$$\begin{aligned} &\alpha_1 = \frac{k_1 + k_2}{m_H}, \alpha_0 = \frac{b_1 + b_2}{m_H}, \beta_3 = b_1, \\ &\beta_2 = \frac{m_H k_1 + b_1 b_2}{m_H}, \beta_1 = \frac{k_1 b_2 + k_2 b_1}{m_H}, \beta_0 = \frac{k_1 k_2}{m_H}. \end{aligned} \tag{28}$$

In this case, Newton's second law is written for the haptic device as follows:

$$\ddot{x} = -\frac{b}{m}\dot{x} - \frac{F_{VE}}{m} - \frac{F_H}{m}. \tag{29}$$

After simplifications, state-space equation of the haptic system is calculated as the following equation:

$$\dot{\mathbf{x}} = \mathbf{A}_1\mathbf{x} + \mathbf{A}_2\mathbf{x}(t - t_d - T/2) + \mathbf{A}_3\mathbf{x}(t - t_d - T). \tag{30}$$

Due to the transfer function of the hand, in this case $\mathbf{A}_1$ to $\mathbf{A}_3$ are 4×4 matrices, defined as:

$$\mathbf{A}_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{\beta_0}{m} & -\frac{\beta_1+\alpha_0 b}{m} & -\frac{\beta_2+\alpha_0 m+\alpha_1 b}{m} & -\frac{\beta_3+\alpha_1 m+b}{m} \end{bmatrix},$$

$$\mathbf{A}_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{\alpha_0 K}{m} & -\frac{\alpha_1 K}{m} & -\frac{K}{m} & 0 \end{bmatrix}, \tag{31}$$

$$\mathbf{A}_3 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -\frac{\alpha_0 B}{m} & -\frac{\alpha_1 B}{m} & -\frac{B}{m} \end{bmatrix}.$$

Substituting these matrices in (13) and after some simplifications, a new closed-form formulation for K and B is determined as follows:

$$K = \frac{NUM_K}{DEN}, \quad B = \frac{NUM_B}{DEN \times \omega}, \tag{32}$$

where NUM_K, NUM_B and DEN functions are defined in (33) to (35).

$$\begin{aligned} NUM_K &= \Big[m\,\omega^6 + \left(m\,\alpha_1{}^2 + \beta_3\,\alpha_1 - \beta_2 - 2\,\alpha_0\,m\right)\omega^4 \\ &\quad + \left(m\,\alpha_0{}^2 + \beta_2\,\alpha_0 + \beta_0 - \alpha_1\,\beta_1\right)\omega^2 - \alpha_0\,\beta_0\Big]\cos((T+t_d)\omega) \\ &\quad + \Big[\left(b+\beta_3\right)\omega^5 + \left(b\,\alpha_1{}^2 + \beta_2\,\alpha_1 - \beta_1 - 2\,\alpha_0\,b - \alpha_0\,\beta_3\right)\omega^3 \\ &\quad + \left(b\,\alpha_0{}^2 + \beta_1\,\alpha_0 - \alpha_1\,\beta_0\right)\omega\Big]\sin((T+t_d)\omega), \end{aligned} \tag{33}$$

$$\begin{aligned} NUM_B &= \Big[-\left(b+\beta_3\right)\omega^5 + \left(-b\,\alpha_1{}^2 - \beta_2\,\alpha_1 + \beta_1 + 2\,\alpha_0\,b + \alpha_0\,\beta_3\right)\omega^3 \\ &\quad + \left(-b\,\alpha_0{}^2 - \beta_1\,\alpha_0 + \alpha_1\,\beta_0\right)\omega\Big]\cos((T/2+t_d)\omega) \\ &\quad + \Big[m\,\omega^6 + \left(m\,\alpha_1{}^2 + \beta_3\,\alpha_1 - \beta_2 - 2\,\alpha_0\,m\right)\omega^4 \\ &\quad + \left(m\,\alpha_0{}^2 + \beta_2\,\alpha_0 + \beta_0 - \alpha_1\,\beta_1\right)\omega^2 - \alpha_0\,\beta_0\Big]\sin((T/2 \\ &\quad + t_d)\omega), \end{aligned} \tag{34}$$

$$DEN = \cos(T\,\omega/2)\left(\alpha_0{}^2 + (-2\,\alpha_0 + \alpha_1{}^2)\omega^2 + \omega^4\right). \tag{35}$$

As a special case, the effect of the operator's hand is neutralized by substituting $\beta_0 = \beta_1 = \beta_2 = \beta_3 = 0$ in (27). In this case it can be seen that (32) is simplified to (17).

Using (32) the boundary of stability in the presence of the operator can be determined easily for small and even large values of time delay and virtual damping.

It is concluded that by extending the presented method in this paper, the influence of the operator's hand on the boundary of stability can be determined analytically, as long as the hand dynamic can be expressed by a transfer function.

4 Simulations

A Simulink model in MATLAB software has been created, which consists of the continuous time model of the haptic device, discrete time models of the VE, and time delay. Also the available Zero-Order-Hold block of Simulink has been used to take into account the sampling effect. Using this Simulink model, significant amount of simulations were performed to check the validity of (17). For each value of B, the maximum allowable value of K which keeps the system stable is determined. The whole stability boundaries are plotted by repeating simulations for several values of B and different values of t_d. In practical applications, the maximum stiffness of the VE should be less than the minimum stiffness of the haptic device (Dai et al. 2009); otherwise the deformations of the haptic device would be more than penetration of the end effector in the virtual wall, which leads to unrealistic feeling for the operator. In fact, for all common haptic devices cited in Diolaiti et al. (2006), it can be observed that the operation range for small values of time delay is limited due to K_{Robot}.

For validating the effect of the operator's hand on the boundary of stability in haptic rendering, several simulations are performed by utilizing the two-parameter and five-parameter transfer function of the hand. Since the impedance parameters of the hand are much more bigger than the impedance parameter of Phantom 1.0 haptic device, the parameters of the haptic device are assumed as $m = 1\,kg, b = 0.1\,Ns/m$ and $T = 1\,ms$, and the robot's stiffness is assumed to be more than $5000\,N/m$. Using these numerical values, the theoretical stability boundary has been plotted against the simulation results in Fig. 6 for time delays of $t_d = [10, 15, 20]\,ms$ using two and five parameter model of the hand.

In the first sight of view, both two-parameter and five-parameter models can predict the boundary of stability with almost precision and only a small difference exists between result of two-parameter model and simulation results. But a close-up view of the stability boundary in Fig. 7 shows that near the origin, the five-parameter model can predict the boundary with better precision. Because this model has better approximation of the hand's dynamic in frequencies of 20–30 Hz (Speich et al. 2005).

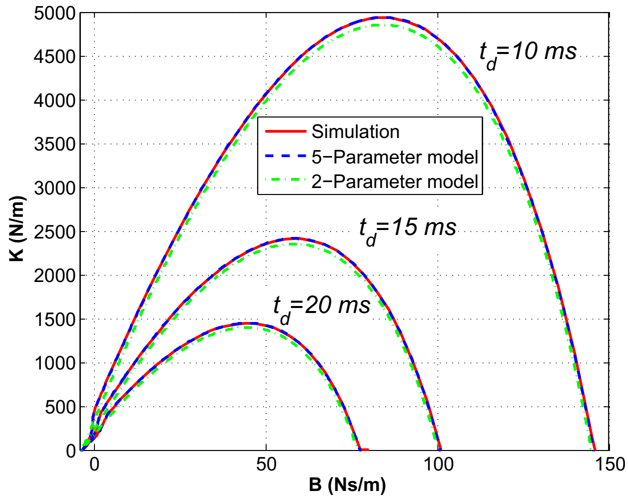

Fig. 6 Stability boundaries determined from simulations (solid lines) and theoretical stability boundaries utilizing the five-parameter model of the hand (dashed lines) and the two-parameter model (dotted line), for different values of time delay

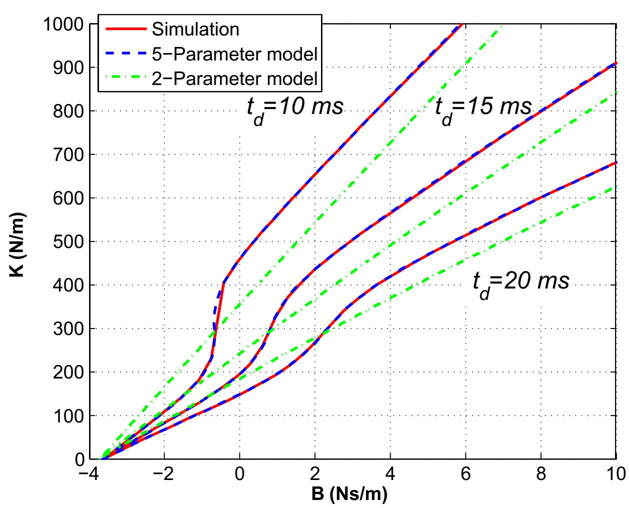

Fig. 7 Close-up view of Fig. 6. In low frequency vibrations, the five-parameter model of the hand has better behavior

5 Experiments

To experimentally verify the stability equations and also to verify the effect of the mass on the stability boundary, the first joint of the KUKA Light Weight Robot 4 has been utilized (Fig. 8). In this robot, the angle of the fourth joint (i.e. θ) has been varied in different experiments to change the effective inertia. It is clear that increasing θ from 0° to 90° decreases the effective inertia of the robot around the axis of rotation of the first joint of the robot (i.e., the joint which has been used as the haptic robot). Each joint

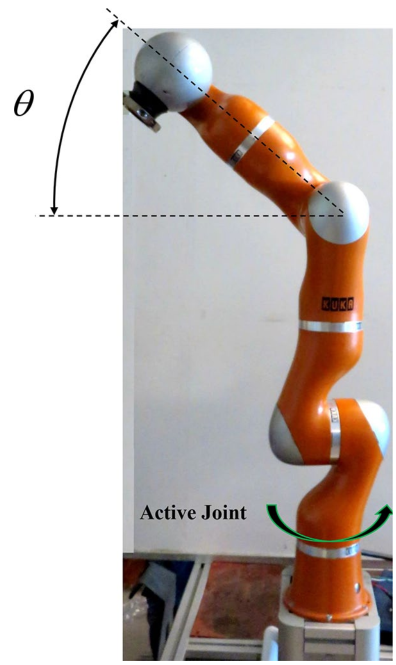

Fig. 8 KUKA robot as experimental device; θ is changed to vary the inertia

has gravity and Coulomb friction compensation, and could track the desired torque command in impedance applications (Ficuciello et al. 2015; Karami et al. 2018). Nonlinearities such as quantization is negligible because of high resolution in position sensors. The direct joint control of the KUKA LWR 4+ are basically PID controllers, and the motors are brushless DC motors with Harmonic Drive transmissions.

The sampling time has been set to 2 ms for all experiments. During the experiments, for each time delay, and then for each value of B, the maximum allowable stiffness of K is determined so that the system remains stable. For this purpose a small initial position is given to the robot by hand, and then the hand is removed quickly so let the robot to move freely, under torque of the VE. The stability condition is as follows: the amplitude of stable oscillations converges to zero, while for unstable oscillations the amplitude diverges. This process is repeated for different values of B and time delay until the stability boundary curves are reached.

Three sets of experiments have been performed. In the first set, θ has been set to be zero and delays of 20 and 30 ms have been accommodated in the control loop artificially (i.e. $d = 10$ and $d = 15$). Theoretical results can be calculated from (17) and compared with simulation and experimental results, as depicted in Fig. 9, which shows a good agreement between them.

In the second set of the experiments, for considering the effect of mass on the boundary of stability, θ has been

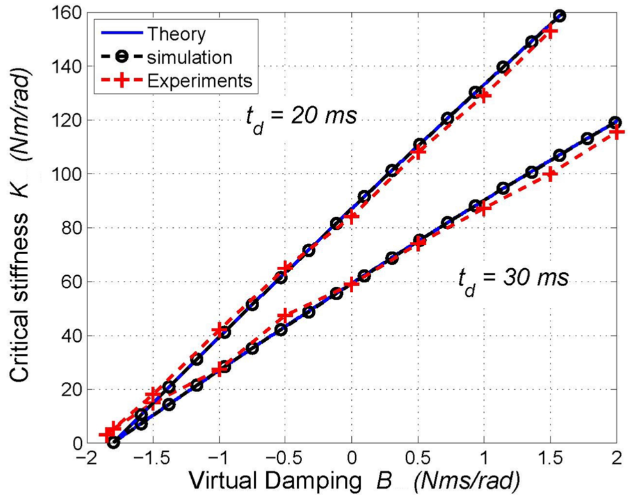

Fig. 9 Stability boundary determined from theory, simulations and experiments for delays of 20 and 30 ms

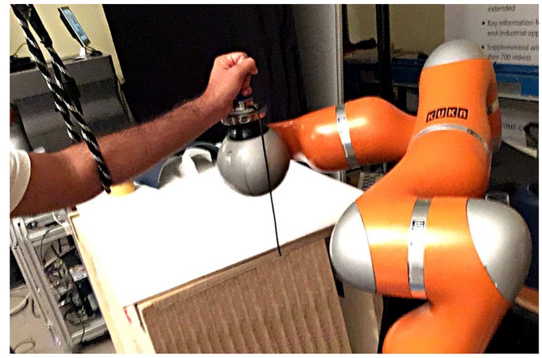

Fig. 11 Experimental setup for stability analysis with operator

changed. Three values of $\theta = [0, 30, 60]^o$ have been chosen, and using the FRI library (Schreiber et al. 2010), the moment of inertia of the robot arm around its axis of rotation has been determined as $I = [0.485, 0.382, 0.142] kgm^2$ respectively. An artificial constant time delay of 50 ms has been considered in the control loop to reduce the maximum value of K and allowing obtaining the whole stability curve. Results of theory, simulations and experiments are compared in Fig. 10. It is clear that increasing the effective mass has a positive effect on stability and makes the system more stable.

Third set of experiments have been performed to study the effect of an operator on the boundary of stability in haptic applications. The KUKA Light Weight Robot was reconfigured as depicted in Fig. 11. The first axis of this robot is simulating a virtual rotational spring and damper, while all other joints are locked. In this configuration, the moment of inertia of the robot around the active axis is $I = 1.445\, kgm^2$.

A *mini45* force sensor was attached to the end-effector of the robot and an operator caught it, while his hand was hanged out with a rope so that he could make his arm relaxed. Direction of his hand was perpendicular to the robot, so that by small rotation of the first joint of the robot, his hand moved perpendicular to his body. A constant time delay of 100 *ms* was artificially applied in the control loop, to reduce the maximum value of K, which in turn yields to reducing the sever and dangerous vibrations for the operator and the robot. For several values of B an initial velocity was applied to the robot by another person, so that the robot started to move under the torque of the virtual environment. To keep the hand passive, the operator was asked to keep his arm relaxed and to not apply any voluntary force by his hand, (Dyck et al. 2013). Angle of the first joint and contact force between the hand and the robot were measured and saved at sampling frequency of 500 Hz. Since the impedance parameters of the hand are constant in time intervals less than 1.2 seconds (Hogan 1989), time intervals of 1 second were used to identify the linear mass-spring-damper model of the hand using *lsqcurvefit* function in MATLAB. Putting estimated numerical values of m_H, b_H and k_H in (25), boundary of the stability in the presence of the operator is determined. Numeric averages of these boundaries have been shown in Table 2 for three situations of: (1) Experiments with operator, (2) Theory with operator, and (3) Theory without operator. Also these results are depicted in Fig. 12.

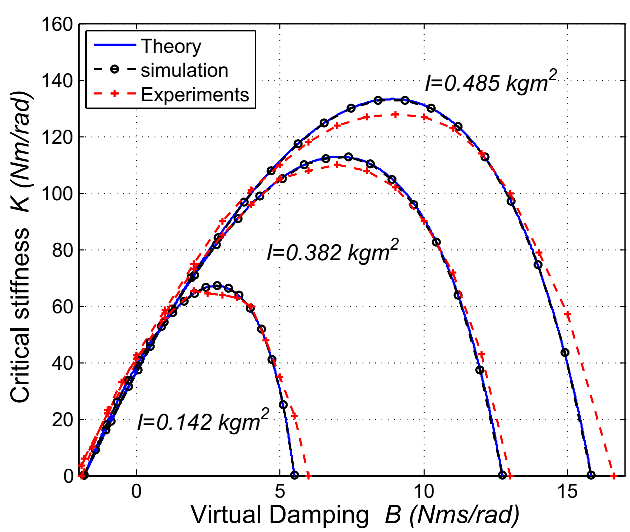

Fig. 10 Effect of mass on stability boundary

The slight difference which is observed between the experimental and theoretical results (both in the presence of the operator) can be due to the nonlinear behavior of the operator's hand, which has been overlooked. For instance, the hand reaction delay and reaction force are slightly different when the mussels experience flexion or extension

Table 2 Numeric results of virtual stiffness ($K(N/m)$) for different situations

	$B(N.s/m)$ Virtual damping						
	0	5	10	15	20	25	30
Experiments with operators	18.8	60.1	87.2	92.3	61.2	–	–
Theory with operators	26.7	66.9	90.1	102.6	83.4	16.6	8.2
Theory without operators	46	78	96	111	93	57	32

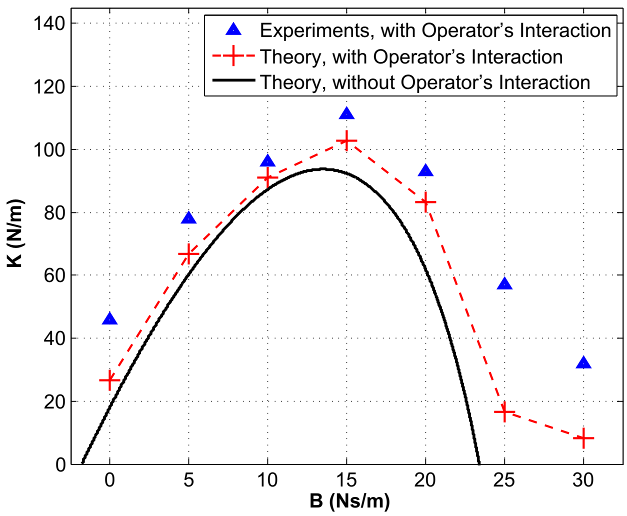

Fig. 12 Experimental effect of the operator on the stability of haptic rendering

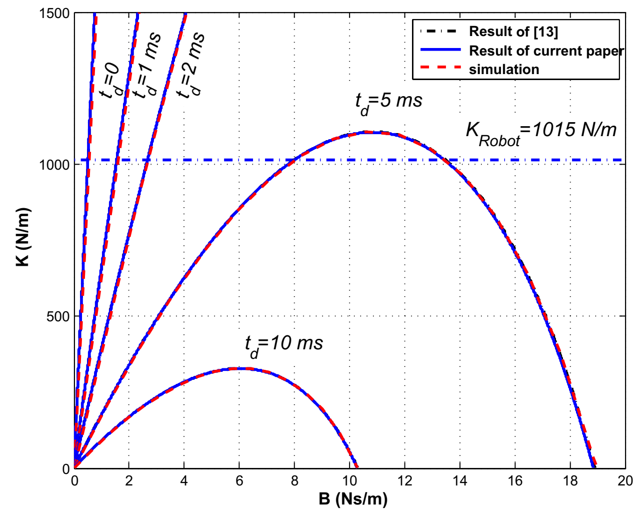

Fig. 13 Stability boundary determined from Mashayekhi et al. (2018) (dotted line), and the current paper (solid line) versus simulation results (dashed line)

movements. This may result to a hysteresis effect, which makes the energy dissipation in reality more than predicted one from the linear models of the hand (Cacioppo et al. 1993). Also it should be mentioned that there are other potential sources for this difference, such as imprecise parameter identification and an overly simplified model of the human arm.

6 Discussion

A comparison between stability formulation determined in this paper and result of Mashayekhi et al. (2018) is interesting. Due to approximating ZOH and sampler with a constant delay of $T/2$ in this paper, stability equation has less power of ω compared with (Mashayekhi et al. 2018), which makes it easier to calculate K and B from (16) without any further simplification. Also in the current paper effect of human operator on the boundary of stability is determined theoretically and experimentally.

Stability boundaries determined from Mashayekhi et al. (2018), the current paper and simulation results are depicted in Fig. 13 for Phantom 1.0 haptic device and delays of $t_d = [0, 1, 2, 5, 10]ms$. Since the maximum value of K should be less than stiffness of the haptic device ($K_{Robot} = 1015\,N/m$), only this area is plotted in this figure.

7 Conclusion and future work

A new formulation for stability analysis of rigid haptic devices was presented. This formulation enables the predicting the stability boundary with good approximation, not only for small values of time delay and virtual damping, but also for large values of them. While prior equations were valid only for small values of time delays and virtual damping. Moreover, the method developed in this study has been used to investigate the influence of the operator on the system stability. For this purpose a two-parameter model, and a five-parameter model of the hand have been utilized. In each case, the closed-form formula for the boundary of stability has been determined and verified. The developed equations can relate all parameters of the operator's hand, virtual environment, haptic device, sampling time and time delay in a unified equation. In real applications when using a special haptic device with different operators, device parameters such as m, b, T and t_d are known. Considering a certain linear model for the hand (for example a five-parameter model, like (27)), and knowing the model parameters for each operator, the boundary of stable operation can be determined quickly based on the presented analytical stability criterion, without any limitation. The developed formulas have been verified by simulations as well as by experiments on a KUKA Light Weight Robot.

The presented method uses state-space approach—which can be used only in linear systems—to determine the stability equations. Thus, only linear dynamics of the operator's hand and the haptic device can be used. But, extending the results of the current paper by using describing function analysis is a part of our future work.

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