Bilateral teleoperation transparency at transient states

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***Abstract*—To perform an epidural, a needle is inserted through the patient's skin and guided between the patient's vertebrae to the yellow ligament, which is resistant. Once the yellow ligament has passed, the needle must stop so that the anesthetic fluid in the epidural space can be injected. What makes this operation complicated is that the resistance of the yellow ligament varies greatly depending on the patient's physiognomy. To enhance the sensations of the anesthetist, we proposed to use a bilateral teleoperation system. The anesthetist manipulates a master arm while a needle is fixed on the slave arm to perform the epidural operation. In this paper, we discuss the tuning of the gains to reach ideal transparency at steady and transient states. Transparency depending on the number of control channels is calculated with the Hannaford matrix. Building on previous works, a new modeling, which allows extremely simple equations, is presented and a new experimental test-bed is proposed.**

Keywords—Teleoperation, Transparency, Mechatronic

I. Introduction

Realizing the ideal bilateral teleoperation system is practically not an easy task. The ideal conditions require an exact knowledge of the master and slave dynamics and an exact measurement of speed and force signals. In addition to obtain ideal transparency at steady and transient states the control structure and the control law has to be taken into account.

Ohnishi et al. [1] gives a good overview of the states of the art about the teleoperated systems during the nineties. Two main approaches can be cited: the Hannaford et al. one [2], the Lawrence et al. [3]. Both approach introduced matrix where the velocity of the master robot and the velocity of the slave robot are combined into equations with forces exerted on each robot. Then a passivity criterion is defined to study the ideal transparency of the teleoperation system.

One of the main issues of a teleoperated system is the time delay for the information transmission between two robots [4], [5], [6]. The sampling effect is analysed in [7]. In [8] the transmission delay is supposed to be unknown and non-constant. Latency issue with different types of wireless communication methods is study in [9]. In this paper, the electronic connections, the proximity of the two robots and the use of a single piece of hardware for the control part allow us to neglect this delay.

Industrial robots have important friction and damping coefficients [10]. Depending on the number of channels of the teleoperation system, this disadvantage can be canceled to obtain ideal transparency at steady states [11].

In [12] [13], the authors discuss the best place to integrate the force sensor between the base of the robot and its end-effector. According to this study, a force sensor placed at the end-effector of the robot, allows a better rejection of the inner frictions. Placing the sensor at the base allows to measure an environment effort at any point of the robot. In this paper the force sensor are at the end-effector of each one degree of freedom (*dof*) prismatic robots [14].

As it is shown in [15] [16] natural transparency of the four-channel is possible at steady states. This is not the case with the two-channel position to position (*PP*) or the force to position (*FP*) or the position to force (*PF*) teleoperation architecture. But in [17] [18], it is shown under particular conditions that transparency at steady states can be achieved with a two-channel force to force (*FF*) teleoperation. Even with the four-channel, the ideal transparency at transient states is difficult to realised, but can be enhanced [19].

We have defined a system that allows the controller to be tuned using frequency analysis to achieve the desired performance of each robot. The position and strength of each robot depend on the environment and the interaction between each robot [20]. Transparency conditions at steady states and transient states are studied. To carry out this study a modeling which allows extremely simple equations compared to [11] and [21] is used. Consequently, it becomes very easy to get the analytical results to check the transparency at steady states and transient states; this will be the main contribution of this paper.

This paper is outlined as follows: Section II describes the modeling of a robot-*i*. Section III presents our controllers and the four-channel bilateral teleoperation. Section IV deals with the Hannaford formalist applied to the four and the two-channel bilateral teleoperation. Section V focuses on the ideal steady states transparency and to the ideal transient states transparency which brings more constraints.

II. Modeling

Two EMPS (Electro Mechanical Positioning System) robots are considered Fig. 1. The inner flexibility of the robot can be neglected when compared to that of the force sensor. All variables are given in SI units on the load side.

Let us define $F_{mi} = G_{\tau i} I_{ref\,i}$, the force from de motor applied on the load side of the robot-*i* , where $I_{ref\,i}$ is the reference current and $G_{\tau i}$ (N/A) the force constant.

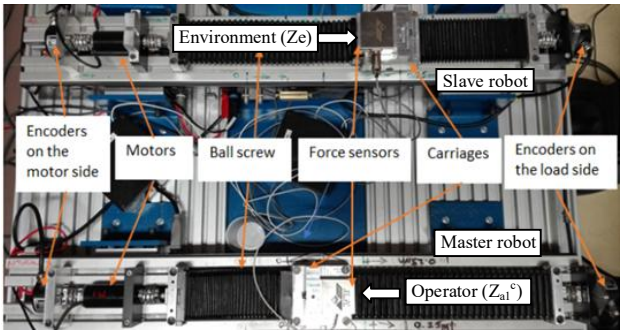

Fig. 1 EMPS robot main components

This sensor is a spring with a stiffness coefficient K_{ri}, which is given by the manufacturer and has been checked experimentally. On Fig. 2, the position δ_i is the relative deformation of the force sensor spring defined in order to have $F_i = 0$ when $\delta_i = 0$. The considered mechanical system has two dofs : a rigid dof q_i and a flexible dof δ_i.

The position q_i of the end effector of the robot and the position x_i of the end-effector are such that: $x_i = q_i + \delta_i$ (1)

M_i is the mass of carriage and the equivalent mass in translation of the motor and the screw inertia (kg), f_{vi} is the viscous damping coefficient ($N/(m/s)$) and f_{ci} is the Coulomb friction (N). m_i is the mass (kg) of the force sensor and the tool. The friction forces on this body are neglected in front of the external forces.

With respect to the reference frame fixed to the robot, the dynamic model of the horizontal mechanical device is:

$$F_i^* = m_i \ddot{x}_i + F_i \quad and \quad F_i = K_{ri}(x_i - q_i)$$
$$F_i + F_{mi} = M_i \ddot{q}_i + f_{vi}\dot{q}_i + f_{ci} sign(\dot{q}_i) \qquad (2)$$

with F_{mi} the actuation force on carriage mass M_i and F_i^* the interaction force from the environment on mass m_i.

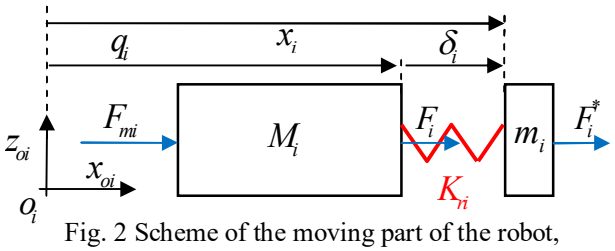

Fig. 2 Scheme of the moving part of the robot, the force sensor and tool

In the following, let us differentiate the force F_i^* applied on the system by the environment and the force $F_i = K_{ri}(x_i - q_i)$ measured by the force sensor. The interaction force F_i^* applied on the system and the velocity $\dot{x}_i$ are linked by the impedance of the environment: $Z_{ei} = \frac{F_i^*}{\dot{x}_i}$. This environment consists of the actions of the operator for the master robot and the reactions of the obstacle for the slave robot.

III. Control Design

A. Focus on a single robot

In classical applications, we consider a light tool and the mass m_i is neglected. The Coulomb friction f_{ci} is assimilated to a constant perturbation, corrected by the integral action of the inner loop. Thus the robot-i model can be described by Fig. 3.

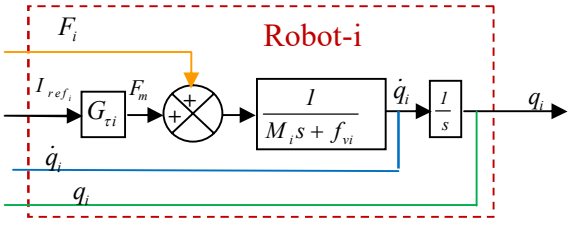

Fig. 3 Model of the robot-i

The considered controller is presented in Fig. 4 for robot-i and uses an inner IP velocity loop allowing us to tune the dynamic behaviour of the robot. The aim of these outer loops is to tune the apparent impedance of the robot around an equilibrium position.

Because, the frequency range of the force done by the human hands is ten times smaller than the bandwidth of the velocity loop, around an equilibrium point $F_i^* \simeq F_i = -K_{ri} q_i$. The apparent impedance Z_{ai}, calculated around an equilibrium position leads us to choose: $F_{iref} = 0$ and $q_{iref} = 0$. For the robot-i, it comes:

$$Z_{ai} = \frac{F_i}{\dot{q}_i} = \left(M_i s + (f_{vi} + K_{vi} t_{vi}) + \frac{K_{vi}}{s} + \frac{K_{vi}}{s^2} k_{pi} \right) \left(1 + \frac{k_{ei} K_{vi}}{s} \right)^{-1}$$

With $Z_{ai} = M_{ai} s + B_{ai} + \frac{K_{ai}}{s}$, we have M_{ai} the apparent mass, B_{ai} the apparent viscous friction coefficient and K_{ai} the apparent stiffness. According to the definition of these coefficients, the outer force loop and the outer position loop can be used to tune the apparent stiffness and the apparent viscous fiction coefficient of the system.

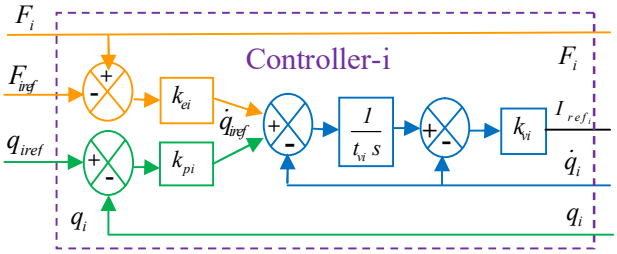

Fig. 4 Controller of speed, position and force of robot-i

With the approximation in papers [21][11] to get the master apparent impedance Z_{a1}^c of the coupled system, we have done the following approximation: $1 << \frac{k_{ei} K_{vi}}{s}$, $f_{vi} << K_{vi} t_{vi}$, $M_i s^2 << K_{vi} t_{vi} s$, so that:

$$Z_{ai} = M_{ai} s + B_{ai} + \frac{K_{ai}}{s} \simeq \frac{t_{vi}}{k_{ei}} s + \frac{1}{k_{ei}} + \frac{k_{pi}}{k_{ei} s}$$

With the new approximation done in this paper: $1 << \frac{k_{ei} K_{vi}}{s}$, $M_i s^2 << K_{vi} t_{vi} s$, it gives a more complicated expression of Z_{ai} used into the calculation of the bilateral teleoperation.

$$Z_{ai} = M_{ai} s + B_{ai} + \frac{K_{ai}}{s} \simeq \left(\frac{f_{vi} + K_{vi} t_{vi}}{K_{vi} k_{ei}} \right) s + \frac{1}{k_{ei}} + \frac{k_{pi}}{k_{ei} s} \qquad (3)$$

But during the demonstration to obtain equation (4), it appears a simplification allowing very simple expression at the end. In a Bode point of view, neglecting or not $f_{vi} << K_{vi} t_{vi}$ gives the same Bode plot in the working frequency base band. Nevertheless neglecting $1 << \frac{k_{ei} K_{vi}}{s}$ and $M_i s^2 << K_{vi} t_{vi} s$ gives two different Bode plot of $1 / Z_{ai}$ as shown on Fig. 10. The difference appears at a frequency greater that 50hz and starts to be significant for a frequency of 80Hz. But, the movement of a human hands and fingers has a maximum frequency of 8Hz [22]. Thus the proposed

approximation of Z_{ai} transfer function is similar to the real one into teleoperation base band.

B. *Four-channel bilateral teleoperation*

Between the two robots there is a four-channel bilateral coupling, see Fig. 5. Each robot-*i* includes the controller and the mechanism as in Fig. 3 and Fig. 4. Let us put Z_e the impedance of the environment. The interaction between the robot and the environment is performed via a force sensor having a stiffness K_{r2}. In this condition, the maximal stiffness of the group {environment + sensor} is K_{r2}.

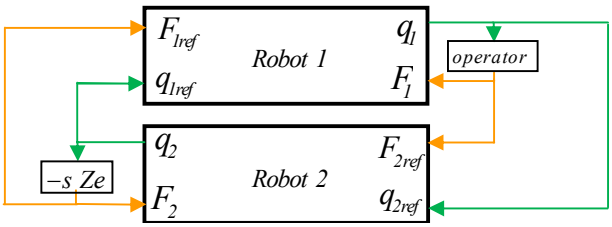

Fig. 5 Four-channel bilateral teleoperation system

The operator feels impedance $Z_{a1}^c = \left.\frac{F_1}{\dot{q}_1}\right|_{F_2=-Z_e\,\dot{q}_2}$ for the coupled system, which depends on the apparent impedance of each robot and how the system is coupled.

This impedance of the coupled system has to be calculated in order to tune the transparency of the system. Based on Fig. 3, Fig. 4, Fig. 5 the linear control system of the two robots, and taking into account the approximation we used for the calculation of Z_{ai} gives :

$$F_i - F_{iref} = Z_{a1}\dot{q}_i - \dot{q}_{iref}K_{ai}/s \tag{4}$$

For the four bilateral teleoperation with $F_{1ref} = -F_2$, $F_{2ref} = -F_1$ and $\dot{q}_{1ref} = \dot{q}_2$, $\dot{q}_{2ref} = \dot{q}_1$, it comes:

$$\begin{aligned} F_1 + F_2 &= Z_{a1}\dot{q}_1 - \dot{q}_2 K_{a1}/s \\ F_2 + F_1 &= Z_{a2}\dot{q}_2 - \dot{q}_1 K_{a2}/s \end{aligned} \tag{5}$$

IV. HANNAFORD MATRIX APPLIED TO OUR MODEL

The four-channel bilateral teleoperation given by Fig. 5 can be study with the modified Hannaford representation given on Fig. 6.

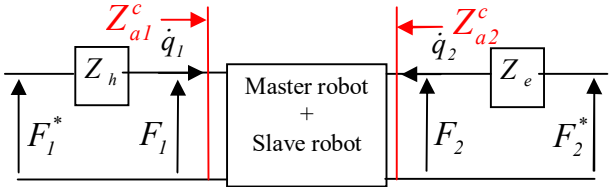

Fig. 6 Modified Hannaford representation for teleoperation

In the Hannaford [2] representation, $\dot{q}_2$ has an opposite sign. The proposed representation has the advantage to get more symmetrical equation without changing anything. Calculation can be done easily by changing the indices $i, j = 1,2$ and $Z_h \leftrightarrow Z_e$ to deduce results without calculation when apparent impedance Z_{ai}^c calculation has to be done.

This representation gives the following equations:

$$\begin{aligned} F_1 &= F_1^* - Z_h\dot{q}_1 \\ F_2 &= F_2^* - Z_e\dot{q}_2 \end{aligned} \tag{6}$$

where impedances Z_h and Z_e are linked with the dynamics of the master and slave robots when the operator and the environment are in contact.

The master-slave system can be represented by two-port network models such as the hybrid model :

$$\begin{bmatrix} F_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ F_2 \end{bmatrix} \tag{7}$$

where the hybrid parameters h_{ij} are functions of the master and slave dynamics and their control parameters.

The apparent impedance of the master is defined as:

$$Z_{a1}^c = \left.\frac{F_1}{\dot{q}_1}\right|_{F_2^*=0} = \frac{h_{11} + (h_{11}h_{22} - h_{12}h_{21})Z_e}{1 + h_{22}Z_e} \tag{8}$$

With our modified representation, the Hannaford criterion [2] of transparency is not modified and given by :

$$h_{12}h_{21} = -1,\ h_{22} = 0,\ h_{11} = 0 \tag{9}$$

So that the operator, at steady states and transient states, feels impedance : $Z_{a1}^c = \left.\frac{F_1}{\dot{q}_1}\right|_{F_2^*=0} = Z_e$

A. *Four-channel bilateral teleoperation with Hannaford*

Hannaford hybrid parameters are obtained with (5), (6), (7)

$$\begin{aligned} h_{11} &= \frac{Z_{a1}Z_{a2} - K_{a1}K_{a2}/s^2}{Z_{a2} + K_{a1}/s}, \quad h_{12} = -1 \\ h_{21} &= \frac{Z_{a1} + K_{a2}/s}{Z_{a2} + K_{a1}/s}, \quad h_{22} = 0 \end{aligned} \tag{10}$$

The apparent impedance of the robot-*1-2* is given by:

$$Z_{a1} = M_{a1}s + B_{a1} + \frac{K_{a1}}{s}, \quad Z_{a2} = M_{a2}s + B_{a2} + \frac{K_{a2}}{s}$$

Equation (9) is checked if $h_{12}h_{21} = -1 \Leftrightarrow h_{21} = 1$, consequently, at low frequency $h_{21} \underset{s\to 0}{\approx} \frac{K_{a1} + K_{a2}}{K_{a1} + K_{a2}} = 1$ and

$$h_{11} \underset{s\to 0}{\approx} \frac{B_{a1}K_{a2} + B_{a2}K_{a1}}{K_{a2} + K_{a1}} \underset{B_{a1}=B_{a2}}{=} B_{ai} \underset{k_{ei}\to\infty}{\to} 0 \ \text{or} \underset{K_{a1}=K_{a2}}{=} \frac{B_{a1} + B_{a2}}{2} \underset{k_{ei}\to\infty}{\to} 0$$

Including transient states, the ideal transparency depends on the apparent viscous friction coefficients B_{a1}, B_{a2} of the slave robot and the master robot.

B. *Two-channel bilateral teleoperation with Hannaford*

Based on the previous study, a two-channel bilateral teleoperation system can be defined by limiting the interaction between the two robots. In the preceding section, each robot is controlled according to the position of the other robot as well as the force it exchanges with its environment. However, here each robot will be controlled with only one of these channels of information.

a) *Force to Force (FF)*

If the robot-*i* is controlled thanks to the effort of the other robot, the force reference F_{iref} will be defined, but not the position reference q_{iref}. It implies that in (3) $k_{pi} = 0$, the

direct consequence is $K_{ai} = 0$ into (4) and (3). Hannaford hybrid parameters are obtained with(5), (6), (7) :

$$h_{11} = Z_{a1} \text{ et } h_{12} = -1 \; ; \; h_{21} = \frac{Z_{a1}}{Z_{a2}} \text{ et } h_{22} = 0 \qquad (11)$$

With the two-channel (*FF*), $Z_{a1} = M_{a1}s + B_{a1}$, $Z_{a2} = M_{a2}s + B_{a2}$, thus equation (9) is checked if $h_{12}h_{21} = -1 \Leftrightarrow \frac{Z_{a1}}{Z_{a2}} = 1$, consequently, at low frequency

$h_{21} \underset{s\to 0}{\approx} \frac{B_{a1}}{B_{a2}} \underset{B_{a1}=B_{a2}}{=} 1$ and $h_{11} \underset{s\to 0}{\approx} B_{ai} \underset{k_{ei}\to\infty}{\to} 0$

The ideal transparency, including transient states, depends on the apparent viscous friction coefficients B_{a1}, B_{a2} of the slave robot and the master robot.

b) Position to Position (PP)

If the robot-*i* is controlled thanks to the position of the other robot, the position reference q_{iref} will be defined, but not the force reference, which will be set to zero into (4). Hannaford hybrid parameters are obtained with (5), (6), (7) :

$$h_{11} = \frac{Z_{a1}Z_{a2} - K_{a1}K_{a2}/s^2}{Z_{a2}}, \; h_{12} = -\frac{K_{a1}/s}{Z_{a2}}$$
$$h_{21} = \frac{K_{a2}/s}{Z_{a2}}, \; h_{22} = \frac{1}{Z_{a2}} \qquad (12)$$

With the two-channel (*PP*), $Z_{a1} = M_{a1}s + B_{a1} + \frac{K_{a1}}{s}$, $Z_{a2} = M_{a2}s + B_{a2} + \frac{K_{a2}}{s}$, thus equation (9) is checked if $h_{12}h_{21} = -1 \Leftrightarrow \frac{-K_{a1}K_{a2}}{s^2 Z_{a2}^2} = -1$, consequently, at low frequency: $h_{12}h_{21} \underset{s\to 0}{\approx} -\frac{K_{a1}}{K_{a2}} \underset{K_{a1}=K_{a2}}{=} -1$ (13)

and $h_{11} \underset{s\to 0}{\approx} \frac{B_{a1}K_{a2} + B_{a2}K_{a1}}{K_{a2}} \underset{K_{a1}=K_{a2}}{=} B_{a1} + B_{a2} \underset{k_{ei}\to\infty}{\to} 0$

$$h_{11} \underset{s\to 0}{\approx} \frac{B_{a1}K_{a2} + B_{a2}K_{a1}}{K_{a2}} \underset{B_{a1}=B_{a2}}{=} B_{ai}\left(1 + \frac{K_{a1}}{K_{a2}}\right) \underset{\substack{k_{ei}\to\infty \\ k_{p2}\geq k_{p1}}}{\to} 0 \qquad (14)$$

and $h_{22} \underset{s\to 0}{\approx} \frac{s}{K_{a2}} \underset{\substack{k_{p2}/k_{e2}\to\infty \\ k_{p2}>k_{e2}}}{\to} 0$ (15)

The transparency, including transient states, depends on the apparent viscous friction coefficients B_{a1}, B_{a2} and the apparent stiffness coefficients K_{a1}, K_{a2} of both robots. This is the worst case. Four parameters have to be managed with the position to position (*PP*) two-channel control law to go toward good transparency at transient states.

- *Experimental result of the two-channel (PP)*

These robots were identified for this study in [23]. The parameters are: M_1 = 105*kg*, f_{v1} = 313*N/(m/s)*, f_{c1} = 13*N*, $G_{\tau 1}$ = 12 *N/A* and K_{r1} = 2 10^4*N/m* for the master robot and M_2 = 102*kg*, f_{v2} = 340*N/(m/s)*, f_{c2} = 18 *N*, $G_{\tau 2}$ = 12*N/A* and K_{r2} = 4 10^4*N/m* for the slave robot. Both robots are controlled thanks to an input/output DSpace card. A single system is controlling both robots, which are located in the same small area, minimizing the time delay. The experiments are performed with the following protocol: the operator applies a specific effort on robot 1 while maintaining contact. The robot 2 is in contact with a stiff environment. This passive environment can push the robot when it is in contact, but not pull it. Two external force sensors are placed on the end-effector of the robot, measuring the efforts of the operator and the stiff environment. And there is no problem of discretization because the sampling rate of the system is 100 times higher than the working frequency. The new experimental tested bed includes analyses of bode of the Hannaford parameters.

Before 5s, the robot 2 is not in contact with the environment thus the force F_2 is equal to 0*N* while a force F_1 is variable. Carriages of both robots are moving and the (*PP*) control law gives a good tracking of velocity and position. After 4s, the robot 2 is in contact with the environment and the tracking of force is good. But for the velocity and position tracking it appears ripples due to the virtual spring effect. To decrease the tracking error of velocity and position, k_{p1}, k_{e1} has to be tuned using (13), (14) and (15).

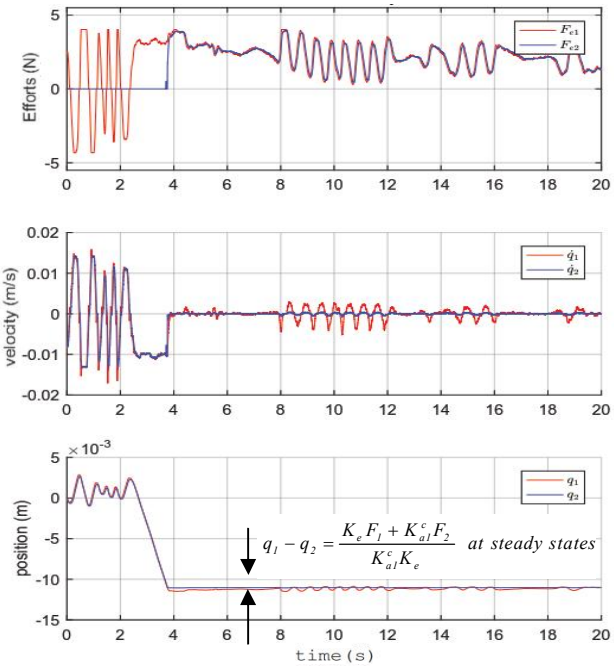

Fig. 7 Two-channel bilateral teleoperation (*PP*)

Let us have a look to the Hannaford condition of transparency, including transient states, gives by (13),(14) ,(15). For the experimental study of the two-channel (*PP*), the apparent viscous value is : $B_{ai} = 1/k_{ei} = 444 \to 53dB$. We choose $k_{pi} >> k_{ei}$, so that the apparent stiffness value is : $K_{ai} = k_{pi}/k_{ei} = 20000 \to 86dB$. Let us recall that the working frequency range of the movement of a human hands and fingers has a maximum frequency of 8Hz [24].

The bode plot of $h_{12}h_{21}$ on Fig. 8 show that, at low frequency, the magnitude go toward zero and the phase margin go to 180°. Thus equation (13) is verified for teleoperation frequency range.

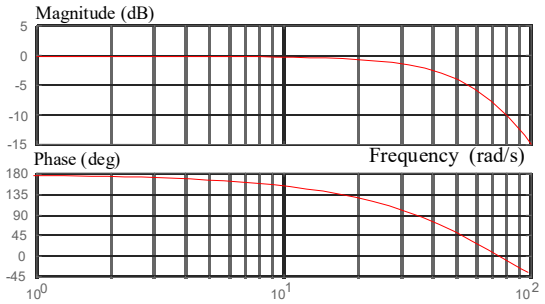

Fig. 8 $h_{12}h_{21}$ Bode diagram (*PP*)

As shown on Fig. 9, the bode plot of h_{11} at low frequency gives a magnitude of $2B_{ai} = 888 \rightarrow 59dB$ and a phase margin of zero. Consequently (14) is not validated at transient states. The solution is to increase $k_{pi} >> k_{ei}$, but $k_{ei} \rightarrow \infty$ the teleoperation system become instable. This result shows the compromise between stability and transient transparency.

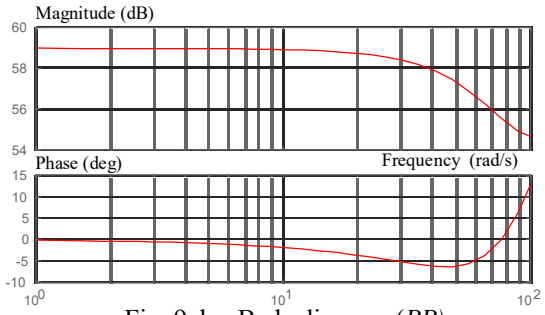

Fig. 9 h_{11} Bode diagram (*PP*)

The last condition of transparency is given by (15). Depending on $K_{ai} = k_{pi} / k_{ei} = 86dB$, the h_{22} magnitude goes toward zero as shown on Fig. 10. It value is around $-86dB$ at a frequency of $1\ rad/s$.

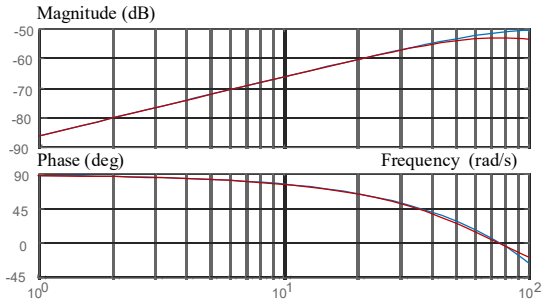

Fig. 10 $h_{22} = 1/Z_{ai}$ Bode diagram (*PP*)

c) Force to Position (FP)

In that hybrid case *FP*, the master is controlled thanks to the effort, so the force reference F_{1ref} is defined, but $F_{2ref} = 0$. The slave robot is controlled in position, so the position reference q_{2ref} is defined, but $q_{1ref} = 0$. It implies that $k_{p1} = 0$ into (3), the direct consequence is $K_{a1} = 0$ into (4) and (3).

Hannaford hybrid parameters are obtained with(5), (6), (7) :

$$h_{11} = Z_{a1},\quad h_{12} = -1,\quad h_{21} = \frac{K_{a2}/s}{Z_{a2}},\quad h_{22} = \frac{1}{Z_{a2}} \qquad (16)$$

With the two-channel (*FP*), $Z_{a1} = M_{a1}s + B_{a1}$, $Z_{a2} = M_{a2}s + B_{a2} + \frac{K_{a2}}{s}$, thus equation (9) is checked if $h_{12}h_{21} = -1 \Leftrightarrow \frac{-K_{a2}}{sZ_{a2}} = -1$. Consequently, at low frequency we have: $h_{12}h_{21} \underset{s\to 0}{\approx} -\frac{K_{a2}}{K_{a2}} = -1$ and $h_{22} \underset{s\to 0}{\approx} \frac{s}{K_{a2}} \underset{\substack{k_{p2}/k_{e2}\to\infty \\ k_{p2}>k_{e2}}}{\rightarrow} 0$. We also have the following result : $h_{11} \underset{s\to 0}{\approx} B_{a1} = \frac{1}{k_{e1}} \underset{k_{e1}\to\infty}{\rightarrow} 0$

The ideal transparency, including transient states, depends on the apparent viscous friction coefficient B_{a1} of the master robot. It also depends on $B_{a2} = 1/k_{e2}$ the apparent viscous friction coefficient of the slave robot, due to the dependence on $K_{a2} = k_{p2}/k_{e2}$ the apparent stiffness of the slave robot.

d) Position to Force (PF)

In that hybrid case *PF*, the master is controlled thanks to the position, so the position reference q_{1ref} is defined, but $q_{2ref} = 0$. The slave robot is controlled in force, so the reference is defined, but $F_{1ref} = 0$. It implies that $k_{p2} = 0$ into (3), the direct consequence is $K_{a2} = 0$ into (4) and (3). Hannaford hybrid parameters are obtained with(5), (6), (7) :

$$h_{11} = \frac{Z_{a1}Z_{a2}}{Z_{a2} + K_{a1}/s},\quad h_{12} = -\frac{K_{a1}/s}{Z_{a2} + K_{a1}/s}$$
$$h_{21} = \frac{Z_{a1}}{Z_{a2} + K_{a1}/s},\quad h_{22} = \frac{1}{Z_{a2} + K_{a1}/s} \qquad (17)$$

With the two-channel (*PF*), $Z_{a1} = M_{a1}s + B_{a1} + \frac{K_{a1}}{s}$, $Z_{a2} = M_{a2}s + B_{a2}$ thus equation (9) is checked if: $h_{12}h_{21} = -1 \Leftrightarrow \frac{-K_{a1}Z_{a1}}{s(Z_{a2} + K_{a1}/s)^2} = -1$, consequently, at low frequency $h_{12}h_{21} \underset{s\to 0}{\approx} -\frac{K_{a1}^2}{K_{a1}^2} = -1$ and $h_{22} \underset{s\to 0}{\approx} \frac{s}{K_{a1}} \underset{\substack{k_{p1}/k_{e1}\to\infty \\ k_{p1}>k_{e1}}}{\rightarrow} 0$ and also we have $h_{11} \underset{s\to 0}{\approx} B_{a2} = \frac{1}{k_{e2}} \underset{k_{e2}\to\infty}{\rightarrow} 0$.

The ideal transparency, including transient states, depends on the apparent viscous friction coefficients B_{a2} of the slave robot. It also depends on the apparent stiffness coefficient $K_{a1} = k_{p1}/k_{e1}$ of the master robot. Consequently, it depends on $B_{a1} = 1/k_{e1}$ of the master robot.

V. Steady States and Transient States

Considering the steady states, the apparent impedance Z_{a1}^c can be calculated with $Z_e = K_e/s$, where K_e is the stiffness of the sensor+environment. The steady states transparency is given when the speed of both robots is zero. The apparent stiffness K_{a1}^c felt by the operator at steady states is defined as: $K_{a1}^c = \lim_{s\to 0} s\, Z_{a1}^c$ and can be calculated with (8) and gives the same results that those obtained in [11].

$$
\begin{aligned}
&K_{a1}^{c} \underset{4channels}{=} K_e, \qquad K_{a1}^{c} \underset{2channels\ (FF)}{=} (B_{a1}/B_{a2})K_e \underset{B_{a1}=B_{a2}}{=} K_e \\
&K_{a1}^{c} \underset{2channels\ (PP)}{=} (K_{a1}K_e)/(K_{a2}+K_e) \underset{K_{a1}=K_{a2}>>K_e}{\rightarrow} K_e \\
&K_{a1}^{c} \underset{2channels\ (FP)}{=} (K_{a2}K_e)/(K_{a2}+K_e) \underset{K_{a2}>>K_e}{\rightarrow} K_e \\
&K_{a1}^{c} \underset{2channels\ (PF)}{=} (K_{a1}K_e)/(K_{a1}+K_e) \underset{K_{a1}>>K_e}{\rightarrow} K_e
\end{aligned}
\tag{18}
$$

It appears that $h_{12}h_{21} = -1,\ h_{22} = 0$ Hannaford criterions of transparency are related to steady states transparency ($\dot{q}_1 = \dot{q}_2 = 0$) comparing with equations (18). The perfect transparency at steady states is naturally obtained with the four-channel and possible with the two-channel (*FF*) if $B_{a1} = B_{a2}$.With the two-channel (*PP*), (*FP*), (*PF*), it is only possible to go toward a perfect transparency at steady states by increasing $K_{ai} >> K_e$ and $K_{ai} \rightarrow \infty$.

At transient states, we need to add the $h_{11} = 0$ parameter into the Hannaford criterions of ideal transparency. In that case, it appears that perfect transparency is not possible for the four-channel and the two-channel teleoperation. Assuming a compromise with stability, at low frequency with the four-channel and the two-channel (*FF*) teleoperation system, it is possible to go toward transparency by decreasing $B_{ai} \underset{k_{ei}\rightarrow\infty}{\rightarrow} 0$. With the two-channel (*PP*), (*FP*), (*PF*), at transient states, to reach transparency, at low frequency it is necessary to decrease $B_{ai} \underset{k_{ei}\rightarrow\infty}{\rightarrow} 0$ and at the same time to increase $K_{ai} >> K_e$ and $K_{ai} \rightarrow \infty$, which brings more constraints.

VI. Conclusion

A haptic teleoperation system is presented. The originality of the tuning is done through closed loop of velocity, position and force. The resulting equation (3) of the dynamic gives coefficient that can be seen as the apparent mass M_{ai}, the apparent viscous friction coefficient B_{ai} and the apparent stiffness K_{ai}. The transparency, including transient states, of the teleoperation system is studied with the Hannaford criteria. The apparent viscous friction coefficient is the main obstacle to get a perfect transparency at transient states. While it is possible to have perfect transparency at steady states with the four-channel and the two-channel (*FF*), this is not the case with the two-channel (*FP*), (*PF*), (*PP*). With the two-channel (*FP*), the coefficient of apparent stiffness of the slave robot must be managed. It is that of the master with the two-channel (*PF*). Because the two apparent stiffnesses must be adjusted at the same time with the two-channel (*PP*), it is more difficult to obtain perfect transparency at steady states.

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