Frequency Response Based Analysis and Designing of Bilateral Control System

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***Abstract*- Bilateral control is one of the high-tech control technologies available in transmitting haptics information from one point to another point successfully. In past few years, a fair amount of researches has been carried out with different control strategies, hence bilateral control has been implemented practically in various fields recently. In most of the practical scenarios, time delays, chattering effects and unwanted vibrations lead to deficiencies and inaccuracies which badly affect to the successful implementation of a bilateral control system. Although many researches were carried out to compensate the time delays and chattering effects, eliminating unwanted vibration of a bilateral control has never been discussed. In this study, a method has been proposed to design a bilateral control system which works finely in a particular frequency band. In order to achieve the target, a frequency response analysis to a conventional bilateral control system is carried out showing the effect of system parameters to its operationality, and frequency band is determined for a particular set of system parameters. Finally, the validity of the proposed method is demonstrated through simulation.**

Keywords-Bilateral Control, Disturbance observer(DOB), Critical Frequency, Frequency Response

I. INTRODUCTION

Humans have five sensors eye, ear, nose, tongue and skin so that those are sensitive to five sensations called visual, acoustic, odor, taste and haptics. Although each and every human are capable of feeling above sensations separately, what science concerns is to transmit those sensations that one person feels to another who may be far from each other. Currently transmission of the sensations such as vision and hearing has been successfully implemented using audio and video technologies.

In most of the industrial applications, unilateral control techniques are used to transmit position and force signals from human operator to the machine at the working environment. In that scenario tactile information is transmitted in only one direction, i.e. from the operator to machine or robot. But there are some industrial applications where tactile information should be transmitted in both directions, i.e. from operator to the robot as well as from the robot to the operator. In applications such as Minimal Invasive Surgeries (MIS) where more accurate and sensitive movements are needed, surgeon gets the visual feedback using a small camera called Laparoscope, while giving necessary position and force commands through an unilateral control system[1]. But in this kind of applications bilateral control is ideal so that the surgeon feels the reaction forces encountered during the operation. Other than that bilateral operation should be implemented in cases where human operators interest in the reaction feeling from the working environment which are not accessible due to hazardousness, space restrictions and high temperature or distance barriers. Even though the bilateral concepts are proposed for such applications to a certain extent, more researches are required to improve the operationality and accuracy.

In a bilaterally controlled system, two main manipulators can be identified which are called ‘Master’ and ‘Slave’. Master is at the operator’s end by which the force and position commands from the operator are identified, and transmit to the slave manipulator which actually perform the task at the working environment. Slave is responsible to follow the commands of the master manipulator as well as to identify the reaction force by the load. This reaction force is then reflected back to the master manipulator which in returns feed the operator with this reaction force. So the objective of the bilateral control is achieved as the operator identifies the nature of the object at the working environment while being in a total different environment [1].

For achieving full transparency in a conventional bilateral control system, all the motions and reactions at slave environment are normally being reflected back to the operator’s end as it is. But there are some applications where all those movements and forces are not necessary to be reflected back to the operator. Only the signals which are in a selected frequency band are needed to be transmitted to the operator for the purpose of easiness and preciseness in operation.

If a practical example, Minimally Invasive Surgery is taken into account, medical surgeon is the operator and patient’s surgery area is the object to be performed. In between the operator and the object, robot manipulators act as master and slave which are operated bilaterally. When the surgeon tries to cut or drill something while the operation goes on, he may feel cutting or drilling resistance back as well as rigorous cutting vibrations. When engaging in such sensitive operation, this kind of vibration may lead to any false movement which in returns cause to a huge disaster. In addition, there are some industrial applications where smooth operations need to be implemented in a vibrating environment. If the master manipulator also mimics the vibrating motions of the slave manipulator, then the operator will no longer be capable of performing any smooth actions further.

In this paper, frequency response of a bilateral control system and effect of system parameters to its frequency band have been analyzed. Hence authors have proposed a novel approach of determining the frequency response for a given bilateral control system, which can be used for the particular applications discussed above, with predetermined system parameters.

II. BILATERAL CONTROL

In bilateral control, position and force information between two manipulators are controlled simultaneously. The manipulator in the operator side is called the master and the manipulator in the slave side is called the slave. The master manipulator is controlled by control information which is defined by the operator, and the slave manipulator is controlled according to control information of master side. Then control information of the slave side is transmitted back to the master side to realize the operator, the nature of the slave environment [2][4]. The basic concept of bilateral control is depicted in Fig. 1.

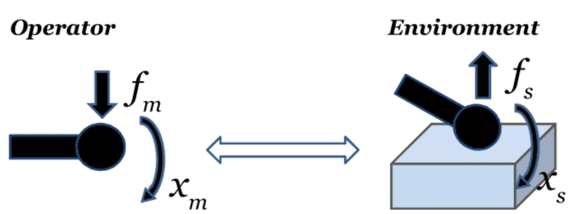

Fig. 1. Basic concept of bilateral control

For the control purposes, two motions have to be considered: contact motion and non- contact motion. In contact motion, in which slave manipulator is in contact with an object, both position and force information have to be controlled separately to achieve the objective; while in non-contact motion force control is automatically adjusted by position control.

In an ideal bilateral control system, haptics sensation is artificially achieved and both position and force information should be matched between master and slave manipulators. The above idea has been expressed in (1) and (2) which elaborate the basic concept of bilateral control [2] [3].

$$x_m - x_s = 0 \tag{1}$$

$$f_m + f_s = 0 \tag{2}$$

Where x_m and x_s denote the master and slave positions while f_m and f_s denote the forces applied on master and slave manipulators respectively. Acceleration is a common factor for both position and force, therefore (1) and (2) are transformed to (3) and (4) where $\ddot{x}_m$ and $\ddot{x}_s$ indicates accelerations of the master and slave manipulators respectively.

$$\ddot{x}_m - \ddot{x}_s = 0 \tag{3}$$

$$\ddot{x}_m + \ddot{x}_s = 0 \tag{4}$$

Equation (1) and (2) suggest that both position and force should be controlled simultaneously to achieve the objective of the bilateral control. But according to (3) and (4), for this to be happened both master and slave accelerations should be zero which is not viable in practical cases. Hence the ideal position and force control could never be achieved simultaneously in one axis. Acceleration has been used as the control parameter to address this issue [5] [6].

The position and force control have been described in acceleration dimensions in equation (5), which is derived from (3) and (4) in which subscripts dif and com denote the differential mode and common mode respectively. Differential mode represents the position relationship between master and slave manipulators and the common mode represents the force relationship.

$$\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \ddot{x}_m \\ \ddot{x}_s \end{bmatrix} = \begin{bmatrix} \ddot{x}_{dif} \\ \ddot{x}_{com} \end{bmatrix} \tag{5}$$

$\ddot{x}_{dif}$ and $\ddot{x}_{com}$ are controlled as in the (6) and (7) respectively.

$$\ddot{x}_{dif} = 0 \tag{6}$$

$$\ddot{x}_{com} \rightarrow 0 \tag{7}$$

The equation (6) gives the idea that position controlling is attained in the acceleration dimension using a position controller. This is also depicted in Fig. 2; a PD controller has been used as the position controller. Further, equation (7) shows force control in acceleration dimension and the arrow indicates common mode corresponds to zero after few sample times later than differential mode [5].In our system, sample time is very small (100μs), therefore it can be assumed that both common mode and differential mode corresponds to zero simultaneously. Thus position and force information have been transferred to differential and common modes to control independently and simultaneously in acceleration dimension.

Block diagram of the bilateral control system is depicted in Fig.2. For this research two identical DC motors (inertia

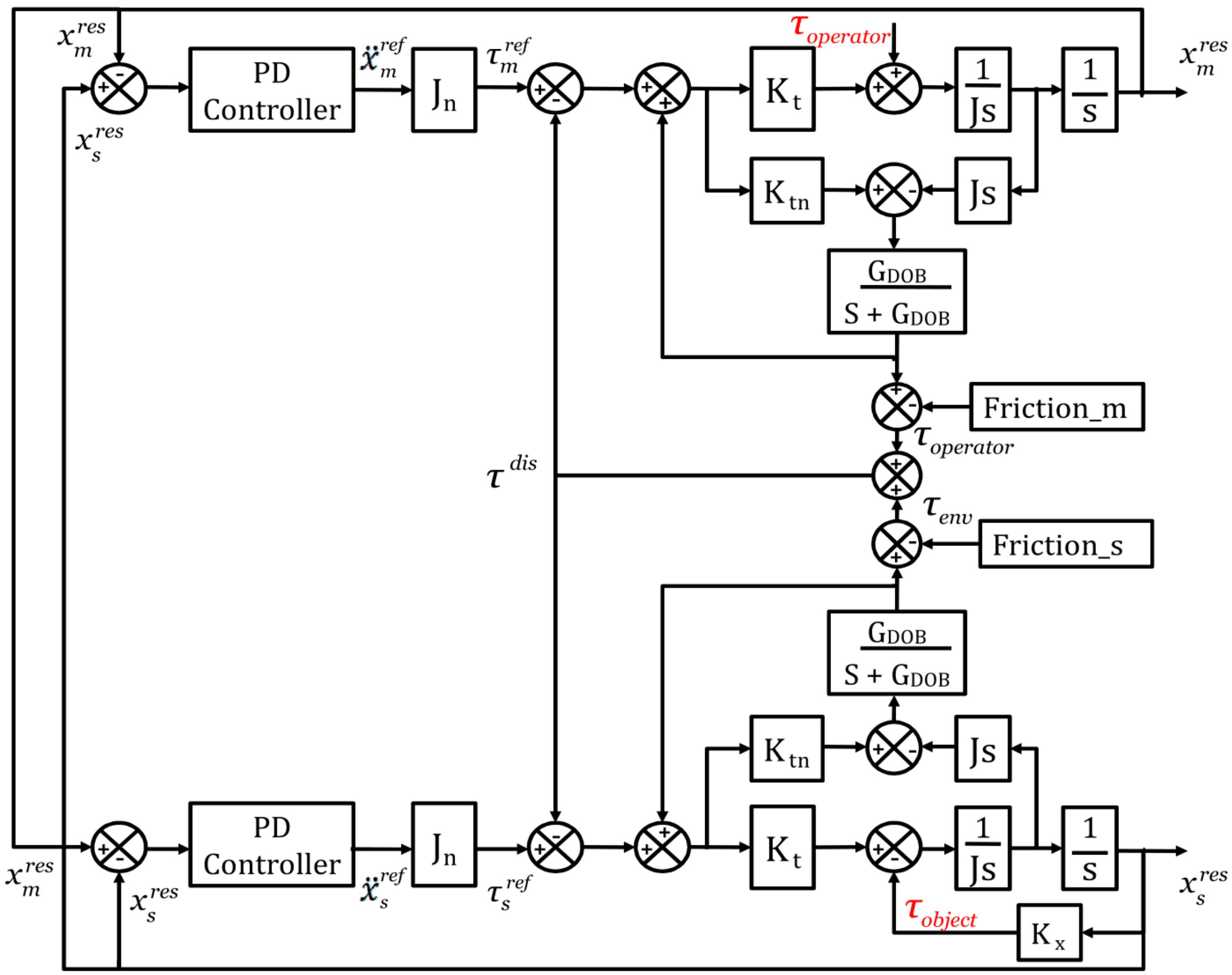

Fig.2. Bilateral control system block diagram

J_n and torque constant K_{tn}) have been used as two manipulators. Two identical PD controllers have been used as the controller between master and slave manipulators. The control block has been designed based on equation (6) and (7). For the simulation purposes, it is considered that slave manipulator touches a spring object which has a spring constant K_x. Disturbance observer (DOB) has been used to enhance the robustness of the system. Reaction force is also sensed by using the DOB [7].

III. DISTURBANCE OBSERVER (DOB)

Disturbance observer is being used to compensate disturbance occurred due to change of parameters of the motor. Motor parameters, Inertia (J_n) and torque constant (K_{tn}) may get changed with the time. Therefore, change of parameters can lead to an additional disturbance when using nominal parameters (because real parameters are not known) [8]. The disturbance observer for a DC motor is illustrated in Fig. 3 in which x, I_a and τ denote the position, armature current and torque respectively. K_t, J, s and G_{DOB} denote torque constant, motor inertia, Laplace operator and cut-off frequency of the low pass filter respectively. Subscript $_n$ denotes the nominal value. Superscripts ^{ref} and ^{res} denote reference and response respectively.

As shown in the Fig. 3, disturbance torque is detected by the disturbance observer and fed it through a low pass filter, because there are spikes in the speed estimation ($\dot{x}^{res}$); as speed is calculated by differentiating the position (x^{res}).

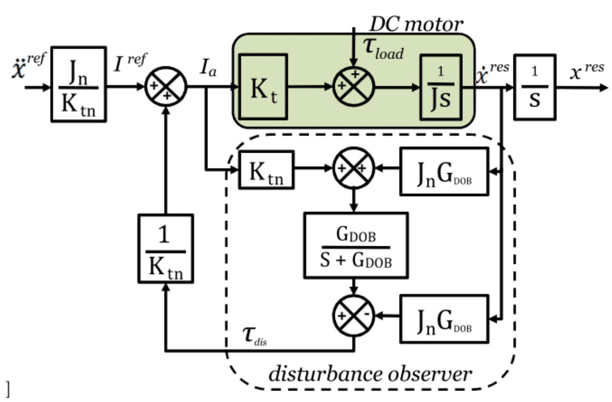

Fig. 3.Block diagram of disturbance observer

more accurate the value of the disturbance torque. To obtain a higher cut-off frequency, a smaller sampling period has to be used. Cut-off frequency (G_{DOB}) of the filter is constrained by (8) [9].

$$rG_{DOB}T \leq 1 \quad (8)$$

Where r denotes the ratio between nominal inertia and actual inertia values, i.e. $\frac{J_n}{J}$ and T denotes the sampling time.

The disturbance observer has also been used to estimate reaction torque by means of a reaction torque observer (RTOB) without using physical torque sensors [10]. This RTOB has many advantages compared with conventional torque sensors, such as higher bandwidth, higher accuracy and simplicity [11].

A. Nominal Torque Constant (K_{tn}) Variations in DOB Gain

In this sub section optimum functionality of the disturbance observer is individually tested for various values of K_{tn}. Transfer function of the disturbance observer between input (τ_{load}) and output (τ_{dis}) can be derived as (9).

$$\frac{\tau_{dis}}{\tau_{load}} = \frac{G_{DOB}\frac{J_n}{J}}{s+\frac{K_t}{K_{tn}}\frac{J_n}{J}G_{DOB}} \quad (9)$$

Bode plot is then analyzed for various values of those parameters as shown in the Fig. 4. Using those results, it can be proved that the disturbance observer works optimally when $K_t = K_{tn}$ because if it is so, the output of the disturbance observer is identical to the input, i.e. 0 dB gain and 0 degree phase shift.

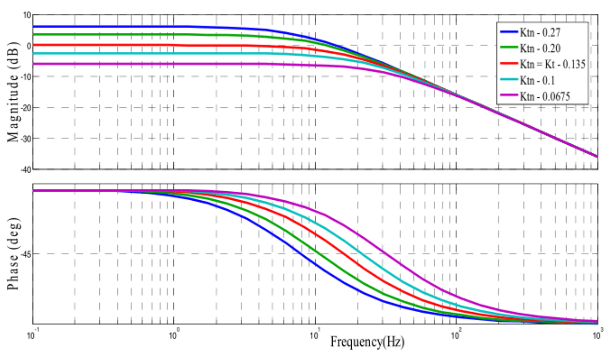

Fig. 4.Bode plot of the transfer function for different K_{tn}

IV. MODELING

Prior analyzing frequency response, conventional bilateral control system for a particular application is modeled and simulated. Exerting a force to an object which generates a reaction torque proportional to the position change of the slave manipulator which is in touch with the object, has been taken as the application. Two rotary DC motors are used as master and slave manipulators while the object is represented by a spring model as (10),

$$\tau_{object} = K_x x \quad (10)$$

Where K_x and x represent the spring constant and position of the slave manipulator respectively. Simplified model of the bilateral control system, which has been used for the simulation, is represented in Fig. 5. K_p and K_d denote the proportional gain and derivative gain of the controller respectively.

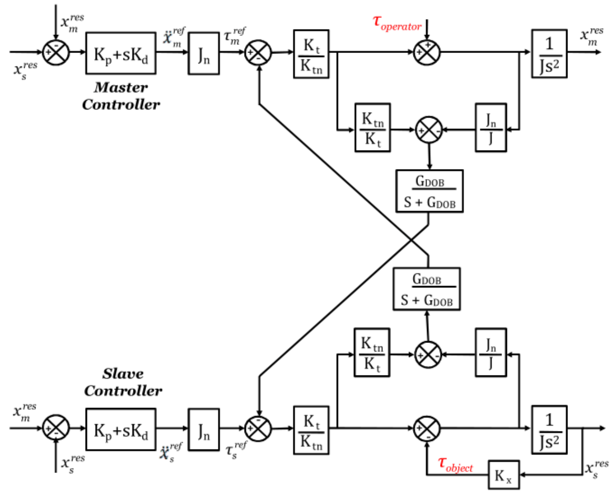

Fig. 5. Simplified block of bilateral control for simulation

When a constant torque (10Ncm) is applied to master manipulator, simulation results show the expected behavior of the system as in Fig. 6; which verifies the validity of the simulation model.

TABLE I
Simulation parameters

Parameters	Symbol	Value	Units
Motor inertia	J_n	0.91	Kgcm^2
Torque coefficient	K_t	13.5	Ncm/A
Spring constant	K_x	5.0	N/cm
Proportional constant	K_p	1000.0	Rad/s
Derivative constant	K_d	80.0	Rad/s
Cut-off frequency of low pass filter	G_{DOB}	100.0	Hz

The transfer function ($G(s)$) between input $\tau_{operator}$ and output τ_{object} has been derived in (11). Optimum case, which occurs at $J_n = J$ and $K_{tn} = K_t$, has been considered for both simulation and for the transfer function. Frequency response for both simulation model and for $G(s)$ is shown in the same Fig.7 which further verifies the validity of the simulation model.

From the Fig.7, it is clear that the system acts as a low pass filter which is already restricted to a certain frequency band. It can clearly be noted that after a particular frequency

$$G(s) = \frac{K_x G_{DOB}[(1+K_d)s^2 + (K_d + K_p + K_d G_{DOB})s + (K_p + K_p G_{DOB})]}{Js^5 + J(G_{DOB} + K_d)s^4 + (2J(K_d + K_p) + K_x)s^3 + ((2JK_p + K_x)G_{DOB} + K_x K_d)s^2 + K_x(2K_d G_{DOB} + K_p)s + 2K_p K_x} \quad (11)$$

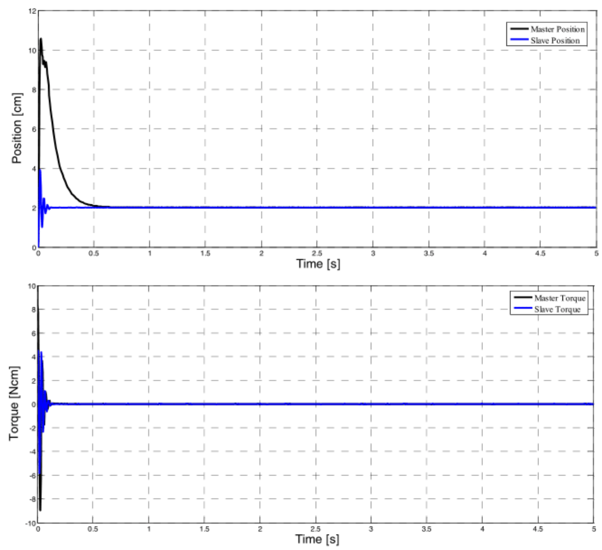

Fig. 6. Torque and position responses of master and slave

value, objective of the bilateral control is not perfectly achieved. This frequency is called as "Critical Frequency", and its value is 9.1Hz for this experiment. Having the capability to change this critical frequency value according to the purpose, is what authors are interested in.

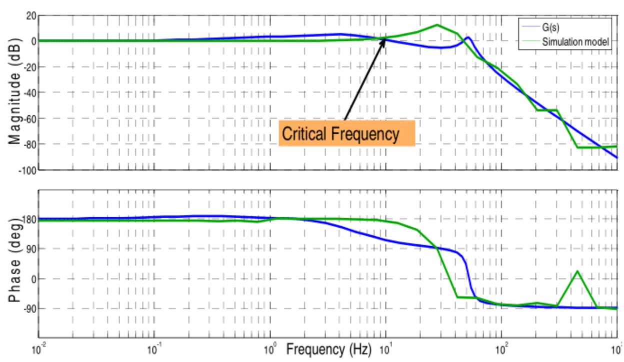

Fig. 7. Bode diagrams of simulation model and $G(s)$

V. Experiment and Results

In this section effect of system parameters to the bandwidth of the system is concerned. Nominal motor inertia (J_n), actual motor inertia (J), nominal motor constant (K_{tn}), actual motor constant (K_t) and the filter constant of disturbance observer (G_{DOB}) are identified as the system parameters. Even in this application, the ideal case ($J_n = J$ and $K_{tn} = K_t$) has been considered, because consideration of real parameters is rather important when designing a bilateral control system for a particular frequency band. Therefore G_{DOB}, J and K_t are taken as system parameters and TABLE I shows the experimental values. Fig. 8 shows the effect of G_{DOB} to system bandwidth.

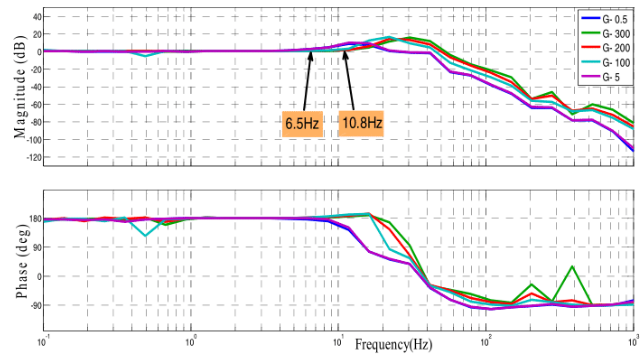

Fig. 8. Effect of filter constant (G_{DOB})

When the filter constant in the disturbance observer (G_{DOB}) is changed in the range of 0.5-300Hz ,critical frequency of the system varies from 6.5Hz to 10.8Hz. But to obtain a higher filter constant, lower sampling period have to be used as in (8), which makes the controller expensive. Then Effect of motor constant (K_t) to the frequency band is also analyzed. As the results shown in the Fig. 9, there is no change in the system bandwidth for various K_t values, i.e. critical frequency remains constant.

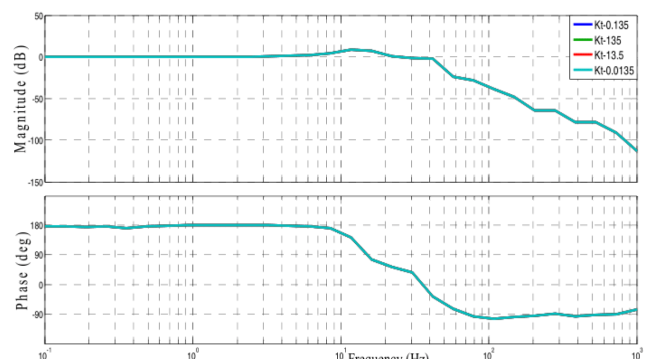

Fig. 9. Effect of torque constant (K_t)

Effect of Inertia (J) to the frequency band is shown in Fig. 10. Critical frequency of the system changes in the range of 4.5- 46.7Hz, for various motor inertia values in the range of 9.1$\times 10^{-6}$ - 9.1$\times 10^{-4}$ Kgm^2.

According to the simulation results, it can be observed that the bandwidth of a bilateral control system can be changed by varying the system filter constant in disturbance observer (G_{DOB}) and motor inertia (J) . But bandwidth is not affected by K_t which is also verified by (11) (transfer function does not contain K_t). Change of G_{DOB} is not enough for the purpose, as the frequency change for various G_{DOB} values is not significant (6.5 - 10.8Hz). Therefore J (the physical parameter) is ideal for varying bandwidth of a bilateral control system in a large range. Critical frequency va lues for chosen J values are shown in TABLE II.

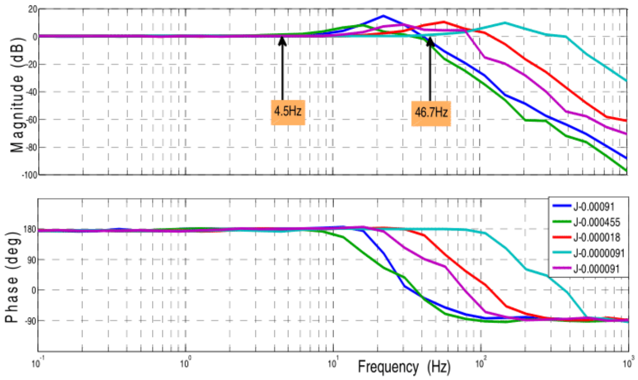

Fig. 10. Effect of motor inertia (*J*)

Although the bandwidth of the system varies with motor inertia; to vary it, either motor has to be replaced or hardware components of motor have to be changed (add/drop). But in this research, authors only concern about selecting the appropriate actuators for a particular application.

TABLE II
Effect of motor inertia

Motor Inertia ($kgcm^2$)	Critical frequency (Hz)
9.1	4.5
4.55	6.6
0.91	9.1
0.18	17.2
0.091	46.7

For the purpose of validating the proposed method, one from the above inertia values is selected ($0.91kgcm^2$). Then a constant torque (10 Ncm) is applied at the master side, and the effect under two sinusoidal signals (as unwanted vibrations) having frequencies of 5Hz and 50Hz is analyzed separately. Results are shown in Fig. 10 & Fig. 11.

The unwanted vibration is transmitted back as it is, for lower frequency (5Hz) than the critical frequency as shown in the Fig. 11, while Fig. 12 is shown the expected reduction of magnitude for a higher frequency (50Hz). However, a small change in torque at the beginning is acceptable as a spring object is used.

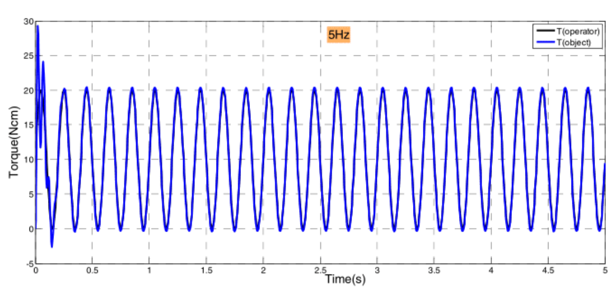

Fig. 11. Input and reaction torque below critical frequency

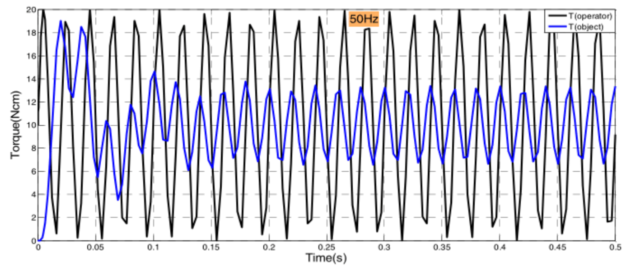

Fig. 12. Input and reaction torque above critical frequency

VI. Conclusion

In this paper, frequency response analysis to a conventional bilateral control system was carried out showing the effect of system parameters to its operationality. Critical frequency of a bilateral control system was identified and introduced it as a novel approach to determine the bandwidth of the system as it is crucial when designing a bilateral control system. A method has been proposed to decide the appropriate system parameters according to the system bandwidth. Simulation results verify the validity of proposed method.

VII. References

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