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One-DOF Arm Movement Guidance Using Vibrotactile Feedback

Supavut Chantranuwathana[1]* Pongstorn Sornumpol[2]
[1,2]Department of Mechanical Engineering, Faculty of Engineering,
Chulalongkorn University, Bangkok 10330
*E-mail: supavut.c@chula.ac.th

Abstract

One of the most serious problems for the visually impaired persons is the lack of surrounding information. Vibrotactile signal applying to skin is an alternative method which could supply them with the necessary data to overcome this difficulty. In earlier papers by the authors, a simple motion guidance system using vibrotactile actuator was proposed along with a human response model and preliminary experimental results showing promises of the proposed system. A mathematical model was approximated as a transfer function containing a gain, an integrator, and a time delay. In this paper, however, a new method of obtaining the model is presented. Since it is found that, because of a sine signal with fixed frequency was used as an input signal earlier, the test subjects can anticipate changes in the signal which results in an unreasonably low time delay in the model. This is avoided by using a sine sweep signal as the input. In addition, this paper expands on the design of the guidance system. Discussions on the guidance system based on control theories are presented. Control systems designed are mainly based on the Nyquist stability criterion, frequency response methods, and PID tuning rules for system with time delay. The controllers were evaluated with simulation and experiments. It was found that a PD guidance system combined with a dead zone is appropriate for guiding arm movements. Finally, behavior of the human model is compared with the crossover model principle. The results suggested that the model proposed in this work is not conformed to the principle.

Keywords: Vibrotactile Feedback, Motion Guidance

1. Introduction

A simple motion guidance system based on vibrotactile signals applying to skin was proposed for the visually impaired persons in the earlier papers by the authors [1-2]. A one-degree-of-freedom arm movement guidance system using the frequency (f) of the vibration as the input signal to guide rotation of the forearm (θ) as shown in Figure 1 was studied. Among a few types of signals [3-6], the frequency signal (10-50Hz) was chosen as the input signal to guide the visually impaired person as to which direction and how fast he or she should move. A transfer function model from the input signal (f) to the output signal (θ) was obtained experimentally and was approximated as a gain, an integrator, and a time delay [1-2].

In this paper, a new method of obtaining the model is presented. Since it was found that, because of a sine signal with fixed frequency was used as an input signal earlier, the test subjects can anticipate changes in the signal which results in an unreasonably low time delay in the model. When the delay is compared with the time before which the subject starts moving after receiving an input signal at the beginning of each experiment, it was found that the difference is considerable. In this paper, this is avoided by using a sine sweep signal as the input.

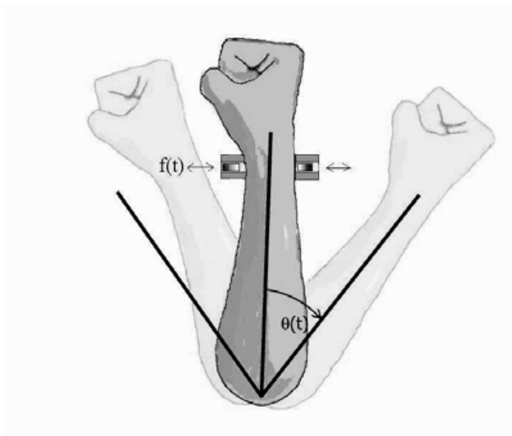

Figure 1, Input and output of the vibrotactile guidance system investigated

In addition, this paper presents a guidance system designed based on control techniques. The objective is to find an effective guidance system to guide the arm from one angular position to another. The guidance system uses the measured angular position of the arm and compares that to the desired position and act accordingly which can be written in a standard feedback control configuration shown in Figure 2. The guidance system is called a controller in the standard control terminology. Nyquist stability criterion was applied to find the bound on the loop gain of the system. Among the controllers considers are an on-off controller, P controller, PD and a PID controllers. A dead zone was also found to be helpful in reducing oscillatory responses near the desired position.

Finally, remarks about the model obtained compared to the crossover model principle [7] is provided. This is important because the principle can be used to estimate the loop gain in a closed loop setting. However, the result found was not supportive of the principle.

2. Vibrotactile guidance system

A vibrotactile guidance system studied in this work is used to guide movement of the forearm in a single degree-of-freedom rotation as shown in Figure 1. In particular, the forearm is constrained to rotation around the elbow. The objective of this guidance system is to guide the forearm to desired locations. Two vibration signal generators (vibrotactile) are attached to either side of the wrist. The subject is asked to rotate his or her arm in the direction of vibration at his or her wrist and the speed of movement should be related to the intensity of the perceived vibration, in general the higher the frequency the faster the subject should move. The system schematic diagram is shown in Figure 2.

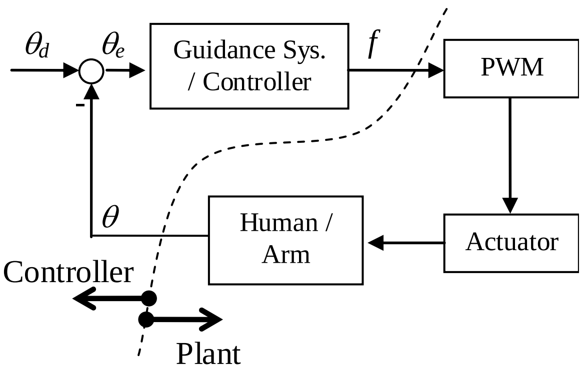

Figure 2, Vibrotactile guidance system schematics

In Figure 2, the system is written using system and control theory terminology. The guidance system (or the controller) uses the error between the desired angular position and the actual position of the forearm to calculate the vibration frequency to be applied by the actuator to the skin of the test subject. The actuator shown in Figure 2 consists of two solenoids used to move its iron core back and fort (details are given in [2]). This motion is generated from a PWM (Pulse Width Modulate) signal generated from command signal (f). A PWM signal generated from a sinusoidal f is shown in Figure 4. When the signal f is high, the PWM signal will be a rapidly changing signal at the frequency indicated by the value of f. The sign of the signal f is used to direct the vibration to either one of the two actuators. The plant to be controlled (or guided) consists of the human, the actuator, and the PWM modulator. This paper follows the standard practice in control engineering; i.e., to find the model of the plant and then design a controller. A complete description of the system can be found in [1-3]. The next section describes the experimental setup used to find the model of the plant.

2.1 System identification

Linear model is assumed for the plant with the vibration frequency signal f as input (Hz) and the angular position of the forearm θ (degree) as the output. To obtain the model, a frequency response method was employed in [1-2]. In particular, a frequency response model of the plant was measured at various frequencies using a number of sinusoidal input signals. According to the linear system theory, the output of a linear system subject to a sinusoidal input will eventually be a sinusoid signal of the same frequency. Ratio of the amplitude of the sinusoidal input signal and that of the output and the phase difference of the two can be used to find the model of the plant.

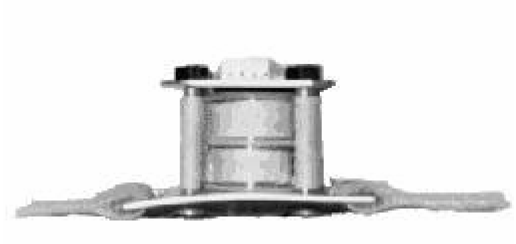

Figure 3, The vibrotactile signal generator (actuator)

A mathematical model was founded as a transfer function containing a gain, an integrator, and a time delay. In this paper, however, a new method of obtaining the model is presented. Since, it was found that the time delay obtained is quite small when compared to the time before which the subject starts moving after receiving an input signal at the beginning of each experiment. Further investigation showed that the human test subject can easily anticipate the input signal which has a fixed frequency. As a result, phase lag in the response is generally at its greatest during the beginning of each experiment but gets reduced as time increases. The result is an unreasonably low time delay.

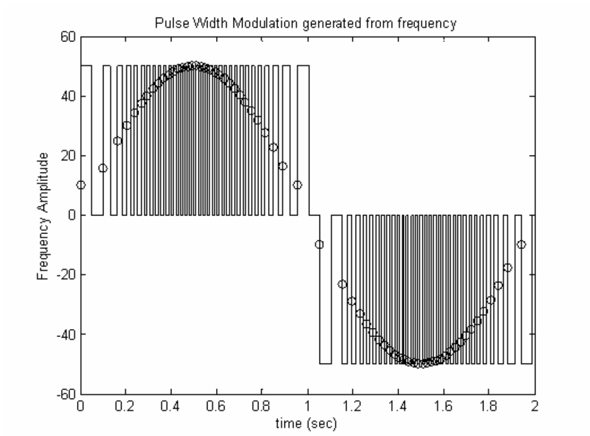

Figure 4, PWM signal generated from a sinusoid command f

In this work, a sine sweep signal was used as the input in place of the sine signal. The sine sweep signal used changed from low frequency to high and back to low frequency again. As a result, it is difficult for the test subjects to anticipate. The sine sweep signal input was measured as well as the forearm position. A frequency response of the plant can be easily obtained using the Fast Fourier Transform to approximate the contents of sinusoidal signal at various frequencies in the input and the output signal. At each frequency, ratio of the amplitude of the sinusoid component at that frequency of the input and that of the output and the phase difference of the two signals can be used for each test subjects to find the model of the plant. A single experiment can be used compared to a multiple runs each with the input at a single frequency in the earlier works [1-2].

The frequency response (Bode plot) of 10 of the test subjects (normal-vision persons) obtained is shown in Figure 5.

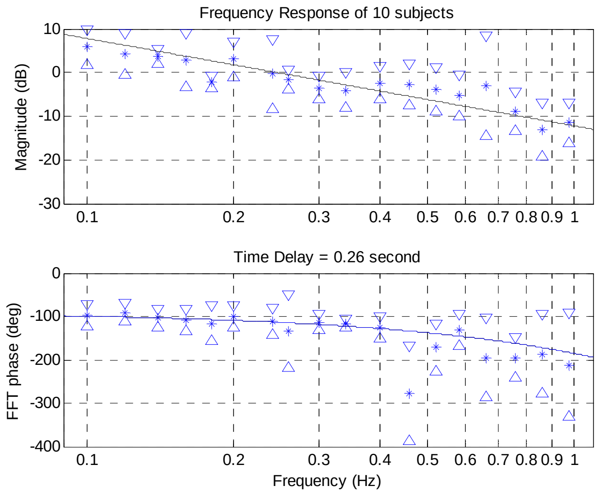

Figure 5, Frequency responses of the test subjects

In the figure, the frequency responses at each frequency is plotted using the average value, the minimum value and the maximum value from the 10 subjects. The solid line shown is the frequency response of the transfer function

$$P(s) = \frac{Ke^{-Ts}}{s} \quad (1)$$

where K = 1.6 (degree/Hz), T= 2.7 (sec) which are the average value from the 10 subjects. The model for each subject was also obtained. The value of *K* and *T* for each of the 10 subjects are shown in Table 1.

Table 1 Example of a table Open loop.

No.	Gain (*K*, Deg/Hz)	Delay (*T*, sec)	PM (Open, Deg)
1	1.4	0.25	70
2	3.1	0.20	54
3	1.9	0.37	51
4	0.71	0.42	73
5	1.6	0.13	79
6	1.6	0.22	70
7	1.53	0.25	68
8	0.88	0.27	77
9	2.1	0.32	52
10	1.6	0.27	66
AVG	**1.6**	**0.26**	**66**
STD.	0.65	0.083	10.2

Table 1 also lists the phase margin (degree) of the system (assuming a unity gain proportional controller). The phase margin is calculated using the following equation, which can be derived from (1)

$$\text{PM} = 90 - (KT)*180/\pi \quad (2)$$

where PM is the phase margin (degree), *K* and *T* is the gain (degree/Hz) and the time delay (sec) of the models. PM will be discussed in a subsequence section.

3. Controller design

Having obtain the models (individual or average), it is straight forward to design a controller. In this work, however, we also investigated the possibility of having a single controller that works reasonable well for all of the subject. This is desirable since obtaining model for each person who is going to use the system might not be desirable in actual applications.

First, we investigate a P controller. Possible range of the gain K_p of the P controller can be found using the Nyquist stability criterion. Following [8], a Nyquist plot of the system (1) using the average value of *K* and *T* is shown in Figure 6. From the figure, the first crossover of the negative real axis is –0.17. This means that $-1/(KK_p)$ must be less than –0.17 to guarantee stability of the closed-loop system. This implies that $0< K_p <3.9$. To design a P controller, we first pick %overshoot at 10%. This asks for a damping ratio of the system at 0.6 which may be obtained if the PM of the system is around 60 degree [8]. Using the equation (2) with *K* replaced by KK_p, it can be easily found that K_p is approximately 1.3 (*K*=1.6, *T*=0.26).

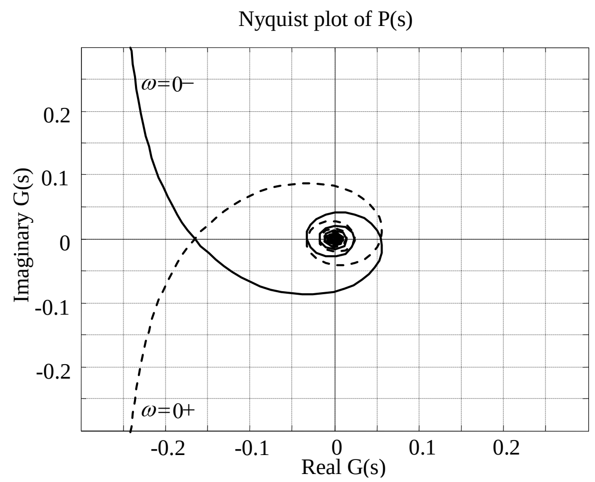

Figure 6, Nyquist plot of the transfer function P(s) with *K* = 1.6 and *T* = 2.6.

After little testing, however, it is quickly realized that a P controller cannot perform well for all of the test subjects. This is illustrated in Figure 7. In the figure, simulation responses of 4 models to a step input (30 degree) with the P controller are shown. The models are the average model, the model of subject #4 which has the smallest *K* (but also the largest *T*), the model of subject #10 which is close to the average value, and the model of subject #2, which has the largest K (with the second smallest *T*). As seen from this figure, the controller is generally acceptable if not for those subjects with high K. To improve the controller, various controllers were investigated. They are the on-off controller, the PD and the PID controller.

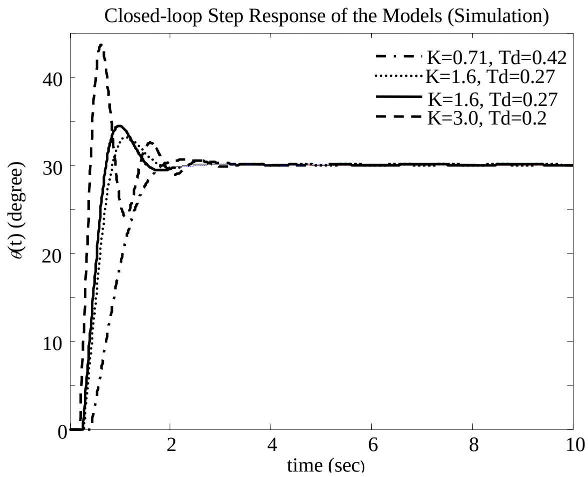

Figure 7, Closed-loop step response of human models with a P controller

With on-off controllers, it was found that the step response is acceptable in actual experiment although it is oscillatory in the simulations. For the on-off controller, f is either 30 or -30 Hz. In [1], it was shown that, although a simulation of the step response of the closed-loop system is oscillatory, the actual experiments showed acceptable responses with 10-20% overshoot. With interaction between the time delay in the model and the on-off controller, step responses found in the simulations exhibited persisting oscillations. In actual testing however, human subjects can quickly guess where the desired location is and converges to that location with a few oscillations around that point.

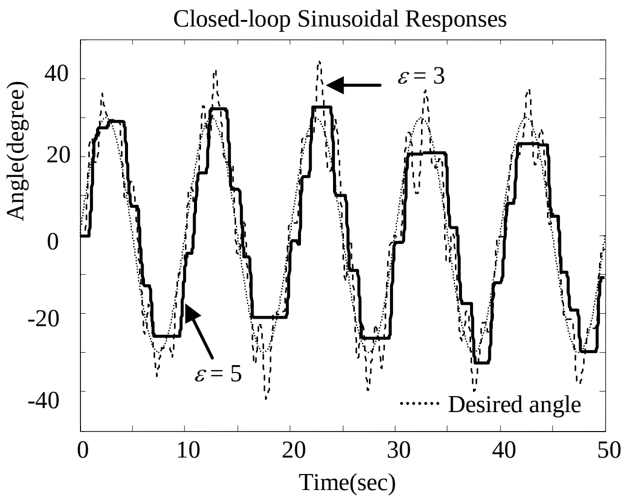

Figure 8, Closed-loop sinusoidal response of a subject #10 with on-off controller

If the desired location is not a constant or if less overshoot is desired, it is possible to modify the on-off control to include a small dead zone of ε degree (3-5 degree) around the desired value such that $f = 0$ when θ is with in ε degree of the desired value. Figure 8 shows that dead zone can reduce the oscillation. In this figure, the desire location is a sinusoidal signal. From a number of experiments, a dead zone around 5 degree is reasonable. Although the results were satisfactory, a few subjects with high time delay may still exhibit oscillatory responses. For example, Figure 9 shows a sinusoidal response of the subject #4 with K = 0.71, T = 0.42, even with dead zone at 5 degree, oscillations can still be seen.

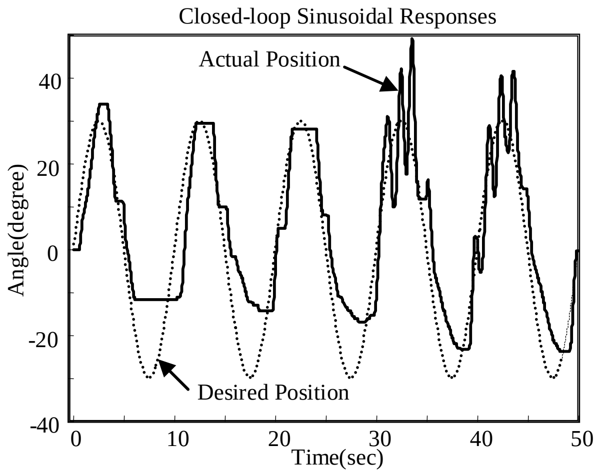

Figure 9, Closed-loop sinusoidal response of a subject #4 with the on-off controller (ε =5)

To reduce the overshoot, the PID and PD were tested. Both Ziegler-Nichols and Tyreus-Luyben methods of tuning PID were used. However, the responses were oscillatory even with dead zone. Figure 10 shows a typical sinusoidal response of the system with a PID controller (shown is subject #10 with K_P = 1.7, K_I = 0.77, K_D = 0.29, and ε =5). Discussions with test subjects revealed that the integrator in the PID controller caused the input f to persist even when the actual forearm position is near the desired value. This greatly confuses the test subjects.

Finally, a PD controller was investigated. Among the controllers studied, the PD controller was found to be the most satisfactory. Shown in Figure 11 and Figure 12 are the step responses and the sinusoidal responses of 3 test subjects with a PD controller with a dead zone. The PD controller has the form

$$f(t) = K_P\, e(t) + K_D\, de(t)/dt \qquad (3)$$

where f is the frequency of the vibration input, K_P is the proportional gain and K_D is the derivative gain of the controller and $e = \theta_d - \theta$, the difference between the desired position and the actual position. The parameters used in the figures are: K_P = 1.77, K_D = 0.29 and ε = 5.

In Figure 11, it can be clearly seen that the PD controller produces no overshoot for all of the three subjects tested. Even for the person with long time delay, there is no visible overshoot in the step responses. Similarly, Figure 12 shows that the sinusoidal responses of the three subjects are less oscillatory when compared to those of the other controllers investigated.

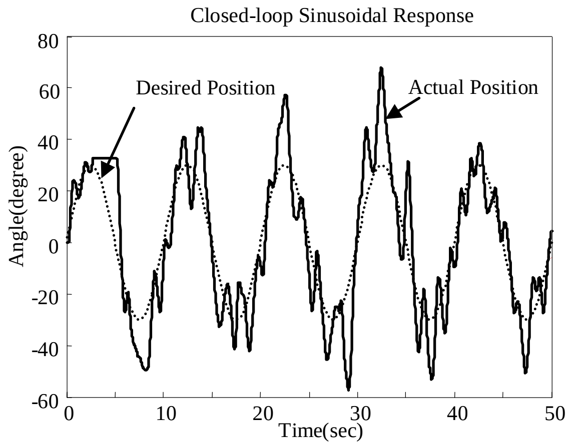

Figure 10, Sinusoidal responses of the subject #10 with a PID controller

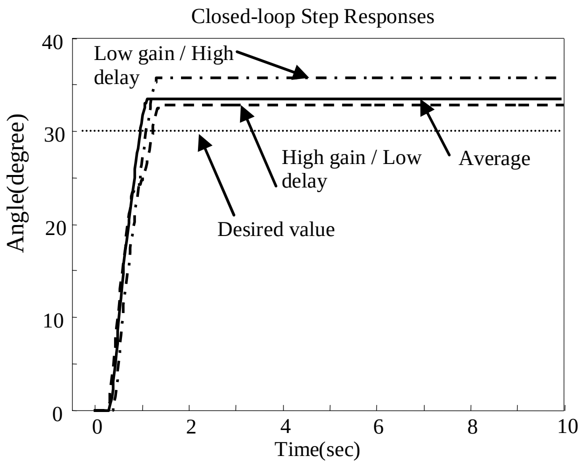

Figure 11, Step response of three subjects with a PD controller

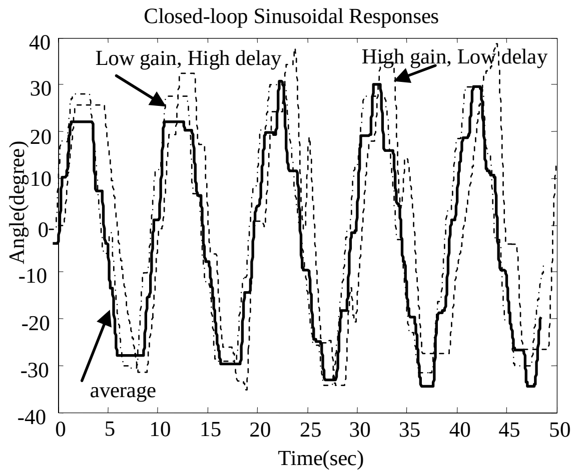

Figure 12, Sinusoidal response of three subjects with a PD controller

4. Remarks on the crossover model principle

For any closed-loop man-machine system, it is expected that the human model conforms to the crossover model principle which states that, for a system with human in the loop, the frequency response of the loop transfer function of the system will have a slope of –20dB/decade around the crossover frequency [7]. A possible explanation is that the human will try to stabilize the system by adjusting his gain so that the slope near the crossover frequency is around –20dB/decade. This means PM of the system will be around 90 degree which will give a satisfactory response for many systems [8].

Since the human model in this work also includes a time delay, the slope at the crossover frequency will be less accurately correlated to PM of 90 degree. In this work, the PM of the system is investigated. The objective is to check on how much PM is for the closed-loop system with the human subjects in the loop. Assuming that the controller is a P controller with unity gain, PM of the system with each of the subject is shown in Table 1. However, the result is obtained from the open-loop experiment. As such, the crossover model principle cannot be applied to this case. It is, however, expected that, when the closed-loop experiments are performed, the human subject will change his response such that PM of the system will move closer to 90 degree.

The closed-loop experiments were carried out using step reference command with a unity gain P controller. As a result, the loop transfer function of the system is the same as the transfer function of the plant. Using the technique described in section 2.1, a transfer function of the plant is obtained. It remains in the form (1) with K and T listed in the Table 2 along with the PM value. However, notice that PM’s were reduced in all subjects and became much less than 90 degree which is not expected according to the crossover model principle.

Consider the PM, it was found that, although the principle suggests that the human subject reduces his or her gain, the gain was actually increased in the closed-loop system. Although the principle suggests that the human subject reduced his gain to move PM from the open-loop value (average at 66) toward 90 degree, the gain is actually increasing in the closed-loop system. In particular, the PM is average at only at 47 degree compared to 90 degree suggested by the principle.

There are two possible explanations. The first is that the task performed in the experiment was repetitive and the subject may be able to anticipate the desired motion. As a result, they can benefit from moving faster (higher gain). The second is that the principle might be applicable only to system where human is the primary controller of the system. In the setup used in this research, the human subject is considered merely as part of the plant to be controlled. Further investigations are needed to confirm the above reasonings. It is interesting to note that if the human is asked to reduce the vibration frequency input at his or her wrist to zero (with the vibration frequency proportional to the amount of position error; i.e., the unity gain P controller), he or she can be regarded as a controller of the system. The question is whether he or she will perform better than the results shown here. One line of reasoning, however, suggests that he or she will not perform better. If crossover model principle is to be uphold, since the controller is the human subject, he or she must reduce his or her gain shown in Table 1 to push PM toward 90 degree. As a result, the response cannot be as good as when the gain is higher in the controller proposed in this paper.

Table 2 Closed-loop

No.	Gain (*K*, Deg/Hz)	Delay (*T*, sec)	PM (Closed, Deg)
1	2.4	0.39	38
2	2.2	0.35	46
3	1.8	0.43	45
4	0.85	0.40	70
5	2.4	0.39	37
6	2.0	0.39	44
7	1.1	0.42	63
8	1.3	0.53	51
9	2.5	0.41	32
10	2.0	0.38	48
AVG	**1.85**	**0.41**	**47**
STD	0.57	0.048	11.6

5. Conclusion

In this paper, a model of human response to a vibrotatile signal is presented. The model is more accurate in its time delay than that of the earlier works by using input signal that is difficult for the test subjects to anticipate. Control theory is applied to design a number of controllers. If was found that a PD controller with a dead zone is best suit for the task of guiding the forearm from one position to another. Finally, behavior of the human model is compared with the crossover model principle. The results suggested that the model proposed in this work is not conforming to the principle.

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