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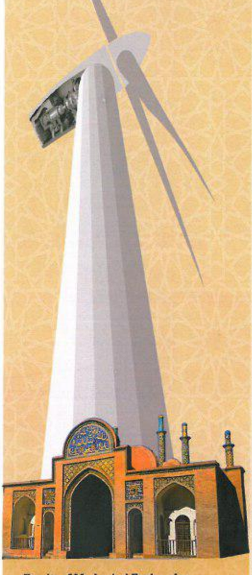

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Design of a Handheld and Smart Device to Attenuate Hand Tremor by Active and Passive Control

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Abstract

In this paper an innovative device as a noninvasive method to suppress the hand tremor is studied. The usage of this device is as a spoon and can help patients with hand tremor to eat with less difficulty. In this paper the design of mentioned device is discussed and its performance as a passive device is evaluated. Then to improve application of the device for suppressing the hand tremor, an actuator is added to the system and an active control is applied to it. Then, performance of the device with active control is evaluated and discussed. Based on studies done in this research, by using the presented device for a hand path like it uses for eating, the passive system can attenuate the undesired hand tremor up to 55.39%. In similar situation, the hand tremor of patients using the equivalent device with active controller can be reduced up to 95.97%.

Keywords: Hand tremor, Parkinson, Tremor attenuation.

Introduction

Tremor is defined as an involuntary movement of a body part[1]. Unfortunately millions of people all over the world suffer from tremor caused by different diseases such as Parkinson, Essential tremor and etc. [2]. Usually tremor first affects hands and then other parts such as legs, head and etc. Tremor seriously affects the usual life of patients, they may have problems in eating, drinking, writing etc. [3]. Approximately 6.3 million people around the world suffer from the Parkinson disease [4]. Usually, the Parkinson disease leads to hands and legs tremor with a frequency between 3 and 6 Hz [5]. Essential tremor is one of the most common movement disorders. The population of patients with the Essential tremor in the USA is estimated about 7 million people, which is close to 2.2% of the USA population [6]. Essential tremor usually cause tremor in hands, head, and voice with a frequency of 5 to 12 Hz [5].

Unfortunately there isn't any certain treatment for diseases such as Parkinson and Essential tremor [7; 8]. The common methods for control of this diseases are drugs and brain surgery [8; 9]. Drugs are often used to control and manage different types of tremor but the responses of patients to the drugs are different. In addition, pharmacotherapy may cause different side effects such as depression, confusion, fatigue, weakness, etc. [10]. Further, the surgery is an invasive method and could be dangerous [9]. According to limitations of the discussed treatments, the importance of finding alternatives for attenuating the hand tremor with less adverse effects is obvious. Researchers especially in engineering fields have suggested variety of methods and devices to suppress the hand tremor.

A well-known method to attenuate the hand tremor is adding some mass to the hand [11], also some researchers used viscous beams [12] or gyroscopic force [13] to damp the hand tremor. Although these kind of methods can suppress the hand tremor but they may cause muscle fatigue and also they can affect the voluntary movement too.

The other idea to attenuate the hand tremor is using of dynamic vibration absorbers[14; 15] also some researchers studied a self-tunable dynamic vibration absorbers to reduce the tremor[16]. Also some devices are invented and presented to help patients in some special activities such as eating, writing etc. For example Mojica *et al.* developed a device with two degree of freedoms two help patients when they're writing by damping the tremor with viscous dampers in its joints [17]. Ohara *et al.* developed a helpful meal assistive robot, which actively suppress the hand tremor during eating [18]. Abbasi *et al.* studied a device to suppress the tremor, with two applications: a spoon for eating and a smart pen for using from tablets [19]. It is a smart device that suppress the tremor by diagnosing the voluntary movement and reducing the tremor by active control. Also a new passive absorber device as a bracelet was suggested by Buki *et al.* to suppress the pronation / supination tremor of forearm [20]. In order to help patients with hand tremor to improve their handwriting, a pen with an actuator and active control was introduced by Ou *et al* [21]. As a new approach, MR dampers with active control are suggested to be used in an orthosis to decrease the hand tremor [22].Variety of wearable robotic exoskeleton are suggested and developed to attenuate the hand tremor through passive and active control [23-25]. Although these robotic devices can be useful but usually these devices are bulky and annoying for patients beside they can cause muscle fatigue in long use. Some researchers also used functional electrical stimulation to suppress the tremor [26-28].

In this study, the design of a new device for suppressing the patients' hand tremor is considered. This device can help patients to eat with less difficulty. The equations of this system are derived and performance of device as a passive system and active system is evaluated and the results are compared and at the end there is a conclusion.

Mechanical Design

The designed and introduced device in this paper is a spoon, which can be used by patients with hand tremor. A schematic picture of this device is shown in Figure 1. The design of this spoon is based on the principles of vibration of continues beams. As its shown in Figure 1, the device consists of two parallel clamped beams with a common end mass, this end mass as is shown is the spoon. Also there is a smaller beam in the structure as a dynamic vibration absorber. The two parallel beams are studied as clamped guided beams like that they were studied by Afsharfard [29].

In this device, if the clamped guided beams are designed properly they can act as an isolator and suppress the vibration which is caused by base excitation. In this study the base excitation of structure is hand tremor, so by the use of this spoon the effect of hand tremor on the tip of the spoon will be attenuated passively. To find the appropriate parameters for beams the governing equations of motion for the system are derived. In doing so, first, the potential and kinetic energy of the system are calculated as follows:

$$\pi = \int_0^{L_{B1}} EI_{B1}\left(\frac{\partial^2 w_1}{\partial x^2}\right)^2 dx + \frac{1}{2}\int_0^{L_{B2}} EI_{B2}\left(\frac{\partial^2 w_2}{\partial x^2}\right)^2 dx \tag{1}$$

$$\begin{aligned} T = {} & \int_0^{L_{B1}} \rho A_{B1}\left(\dot{w} + \frac{\partial w_1}{\partial t}\right)^2 dx + \frac{1}{2}M_s\left(\dot{w} + \left.\frac{\partial w_1}{\partial t}\right|_{x=L_{B1}}\right)^2 + \ldots \\ & \frac{1}{2}M_h\dot{w}^2 + \frac{1}{2}I_s\left(\left.\frac{\partial^2 w_1}{\partial x \partial t}\right|_{x=L_{B1}}\right)^2 + + \frac{1}{2}I_t\left(\left.\frac{\partial^2 w_2}{\partial x \partial t}\right|_{x=L_{B2}}\right)^2 + \ldots \\ & \frac{1}{2}\int_0^{L_{B2}} \rho A_{B2}\left(\dot{w} + \left.\frac{\partial w_1}{\partial t}\right|_{x=L_{B1}} + \frac{\partial w_2}{\partial t}\right)^2 dx + \ldots \\ & + \frac{1}{2}M_t\left(\dot{w} + \left.\frac{\partial w_1}{\partial t}\right|_{x=L_{B1}} + \left.\frac{\partial w_2}{\partial t}\right|_{x=L_{B2}}\right)^2 \end{aligned} \tag{2}$$

where L_{B1}, L_{B2} and are the length of beams B_1 and B_2 respectively. Also EI_B and ρA_B are the beam flexural stiffness the mass per unit length for beam respectively. The non-conservative virtual work of the system is written as (3).

$$\delta W_{nc} = F\delta w - 2\int_0^{L_{B1}} c_{B1}\frac{\partial w_1}{\partial t}dx\,\delta w_1 - \int_0^{L_{B2}} c_{B2}\frac{\partial w_2}{\partial t}dx\,\delta w_2 \tag{3}$$

where c is viscous damping coefficient Note that, in the above equations, F indicates the external load. Using the separation of variable method, displacement of the beam can be given as (4) and (5).

$$w_1(x,t) = \sum_{i=1}^{\infty} q_{1i}(t).\phi_{1i}(x) \tag{4}$$

$$w_2(x,t) = \sum_{i=1}^{\infty} q_{2i}(t).\phi_{2i}(x) \tag{5}$$

Furthermore ϕ_i is free vibration mode shape in i^{th} mode and q_i is the time response in i^{th} mode. Note that the modal response can be written as (6) and (7).

$$q_{1i}(t) = A_1\cos(\omega_{1i}\,t) + B_1\sin(\omega_{1i}\,t) \tag{6}$$

$$q_{2i}(t) = A_2\cos(\omega_{2i}\,t) + B_2\sin(\omega_{2i}\,t) \tag{7}$$

where ω_i is the un-damped natural frequency of the i^{th} vibration mode and can be obtained using the following relations:

$$\omega_{1i}^2 = \lambda_{1i}^4\,EI_{B1}\Big/\left\{m_1 L_{B1}^4\right\} \tag{8}$$

$$\omega_{2i}^2 = \lambda_{2i}^4\,EI_{B2}\Big/\left\{m_2 L_{B2}^4\right\} \tag{9}$$

Where λ_i is the eigenvalue of the i^{th} vibration mode, also m_1 and m_2 are given by equations (10) and (11):

$$m_1 = \rho A_{B1} \tag{10}$$

$$m_2 = \rho A_{B2} \tag{11}$$

Regarding to boundary conditions for the Euler-Bernoulli clamped-free and clamped-guided beams with tip mass and using the eigenvalue analysis the following relations can be obtained:

$$1 - \cos\lambda_{1i}\cosh\lambda_{1i} - \frac{m_1 L_{B1}}{M_s\lambda_{1i}}\left(\cos\lambda_{1i}\sinh\lambda_{1i} + \cosh\lambda_{1i}\sin\lambda_{1i}\right) = 0 \tag{12}$$

$$\begin{aligned} & 1 + \cos\lambda_{2i}\cosh\lambda_{2i} + \frac{M_t\lambda_{2i}}{m_2 L_{B2}}\left(\cos\lambda_{2i}\sinh\lambda_{2i} - \sin\lambda_{2i}\cosh\lambda_{2i}\right) - \\ & \frac{\lambda^3 I_t}{mL^3}\left(\cosh\lambda\sin\lambda + \sinh\lambda\cos\lambda\right) + \frac{\lambda^4 M_t I_t}{m^2 L^4}\left(1 - \cos\lambda\cosh\lambda\right) = 0 \end{aligned} \tag{13}$$

Regarding to the above relations, the vibration mode shapes can be obtained as follows:

$$\phi_{1i}(x) = C_{1i}\begin{Bmatrix} \cos\left(\lambda_{i1}x/L_{B1}\right) - \cosh\left(\lambda_{i1}x/L_{B1}\right) + \ldots \\ \sigma_{1i}\left[\sin\left(\lambda_{i1}x/L_{B1}\right) - \sinh\left(\lambda_{i1}x/L_{B1}\right)\right] \end{Bmatrix} \tag{14}$$

$$\phi_{2i}(x) = C_{2i}\begin{Bmatrix} \cos\left(\lambda_{2i}x/L_{B2}\right) - \cosh\left(\lambda_{2i}x/L_{B2}\right) + \ldots \\ \sigma_{2i}\left[\sin\left(\lambda_{2i}x/L_{B2}\right) - \sinh\left(\lambda_{2i}x/L_{B2}\right)\right] \end{Bmatrix} \tag{15}$$

Where the coefficients σ_{1i} and σ_{2i} are calculated as shown in equations (16) and (17).

$$\sigma_{1i} = \frac{\left(\sin\lambda_{1i} - \sinh\lambda_{1i}\right) + \dfrac{M_s\lambda_{1i}}{m_1 L_{B1}}\left(\cos\lambda_{1i} - \cosh\lambda_{1i}\right)}{\left(\cos\lambda_{1i} + \cosh\lambda_{1i}\right) - \dfrac{M_s\lambda_{1i}}{m_1 L_{B1}}\left(\sin\lambda_{1i} - \sinh\lambda_{1i}\right)} \tag{16}$$

$$\sigma_{2i} = \frac{\sin\lambda_{2i} - \sinh\lambda_{2i} + \dfrac{M_t\lambda_{2i}}{m_2 L_{B2}}\left(\cos\lambda_{2i} - \cosh\lambda_{2i}\right)}{\cos\lambda_{2i} + \cosh\lambda_{2i} - \dfrac{M_t\lambda_{2i}}{m_2 L_{B2}}\left(\sin\lambda_{2i} - \sinh\lambda_{2i}\right)} \tag{17}$$

It should be noted that the modal response is the time variable parameters. Therefore, the Lagrange equations can be expressed in equations (18) and (19).

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_{1i}}\right) - \frac{\partial T}{\partial q_{1i}} + \frac{\partial \pi}{\partial q_{1i}} = F - 2\dot{q}_{1i}\int_0^{L_{B1}} c_{B1}\phi_{1i}^2\,dx \tag{18}$$

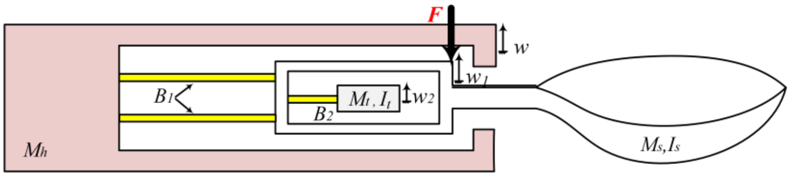
$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_{2i}}\right) - \frac{\partial T}{\partial q_{2i}} + \frac{\partial \pi}{\partial q_{2i}} = -\dot{q}_{2i}\int_0^{L_{B2}} c_{B2}\phi_{2i}^2\,dx \tag{19}$$

For the first mode of vibration (i=1) and regarding to the Lagrange equations and the relation of the kinetic and potential energies, the following equations of motion can be obtained:

$$m_{11}\ddot{q}_1 + C_1\dot{q}_1 + K_1 q_1 = F - m_{w1}\ddot{w} - m_{12}\ddot{q}_2 \tag{20}$$

$$m_{22}\ddot{q}_2 + C_2\dot{q}_2 + K_2 q_2 = -m_{w2}\ddot{w} - m_{12}\ddot{q}_1 \tag{21}$$

The coefficients of the above equations are as presented in equations (22) and (30):



B_1: Beam_1
B_2: Beam_2

Figure 1: schematic picture of designed spoon

$$m_{11} = 2m_1\int_0^{L_{B1}} \varphi^2{}_1 dx + m_2 L_{B2}\,\varphi_1^2\Big|_{x=L_{B1}} + \ldots$$
$$M_t\,\varphi^2{}_1\Big|_{x=L_{B1}} + M_s\,\varphi^2{}_1\Big|_{x=L_{B1}} + I_s\left(\varphi_1'\Big|_{x=L_{B1}}\right)^2 \tag{22}$$

$$m_{12} = m_2\,\varphi_1\Big|_{x=L_{B1}} \int_0^{L_{B2}} \varphi_2\, dx + M_t\,\varphi_2\Big|_{x=L_{B2}}\,\varphi_1\Big|_{x=L_{B1}} \tag{23}$$

$$m_{22} = m_2\int_0^{L_{B2}} \varphi^2{}_2 dx + M_t\,\varphi^2{}_2\Big|_{x=L_{B2}} + I_{tip}\left(\varphi_2'\Big|_{x=L_{B2}}\right)^2 \tag{24}$$

$$m_{w1} = 2m_1\int_0^{L_{B1}} \varphi_1 dx + M_s\,\varphi_1\Big|_{x=L_{B1}} \ldots$$
$$+m_2 L_{B2}\,\varphi_1\Big|_{x=L_{B1}} + M_t\,\varphi_1\Big|_{x=L_{B1}} \tag{25}$$

$$m_{w2} = m_2\int_0^{L_{B2}} \varphi_2 dx + M_t\,\varphi_2\Big|_{x=L_{B2}} \tag{26}$$

$$K_1 = 2EI_1\int_0^{L_{B1}} \left(\varphi_1''\right)^2 dx \tag{27}$$

$$K_2 = EI_2\int_0^{L_{B2}} \left(\varphi_2''\right)^2 dx \tag{28}$$

$$C_1 = 2\int_0^{L_{B1}} c_{B1}\varphi_1^2\, dx \tag{29}$$

$$C_2 = \int_0^{L_{B2}} c_{B2}\varphi_2^2\, dx \tag{30}$$

According to dynamic equations (20) and (21), the ratio of acceleration of tip of spoon to acceleration of handle of spoon in different frequencies is shown in Figure 2 as frequency response of system. As it's shown in this figure, the vibration of tip of spoon is decreased in frequency range of 3-12 Hz which is the frequency range of tremor.

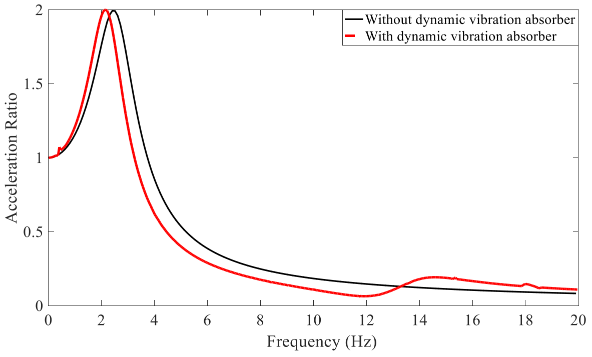


Figure 2: frequency response of system

As shown in Figure 2, by choosing the appropriate configuration for system the effect of hand tremor on tip of spoon can be suppressed passively, this configuration is written in Table 1. In addition, the effect of use of the second beam as dynamic vibration absorber is shown in Figure 2, by comparing the results with and without the dynamic vibration absorber. According to Figure 2 the use of second beam, improved the performance of system by 23% for tremor with frequency of 4 Hz.

Control system

Based on results in Figure 2, because the tremor is reduced by a passive model, the performance of device in suppressing the tremor is related to frequency of tremor. For example in Figure 2, the tremor with frequency of 8 Hz will is suppressed about 83% while a tremor with frequency of 4 Hz is suppressed about 40%. To improve the system and compensate the mentioned weakness, a linear actuator for active control is added to system which its effect is shown by a force F in Figure 1.

The hand movement of a patient with hand tremor consists of voluntary and tremor movement. Based on researches, we know that the frequency of tremor in diseases such as Parkinson and Essential tremor are 3-6 Hz and 5-12 Hz respectively[5]. So to control the device a Butterworth low pass filter with order of 3 and cut off frequency of 2 Hz is used to distinguish the voluntary movement from tremor.

To control the system a PID controller is used. First, two accelerometers should be placed on the tip of the spoon and on the handle of spoon to record the acceleration of these parts, then their position could be calculated. Then by a low pass filter the voluntary movement can be distinguished, then the output of filter is used as desired movement in control loop. The control loop of the system is shown in Figure 3. based on this figure the position of the tip of spoon is used as feedback and the error signal is used as input of PID controller also the output of controller is the amount of force which should be applied to mechanism by actuator.

The PID control transfer function is written in (31) also the value of coefficients of PID controller is shown in Table 2.

$$PID(s) = K_p + K_I\frac{1}{s} + K_D\frac{N}{1+\dfrac{N}{s}} \tag{31}$$

Table 1: parameters of system

Parameters	Values	Parameters	Values	Parameters	Values	Parameters	Values
E_{B1} (GPa)	69	t_{B1} (mm)	0.12	E_{B2} (GPa)	69	t_{B2} (mm)	0.2
ρ_{B1} (kg/m^3)	2750	w_{B1} (mm)	25	ρ_{B2} (kg/m^3)	2750	w_{B2} (mm)	25
L_{B1} (mm)	60	M_s *(gr)*	100	L_{B2} (mm)	24	M_t *(gr)*	30

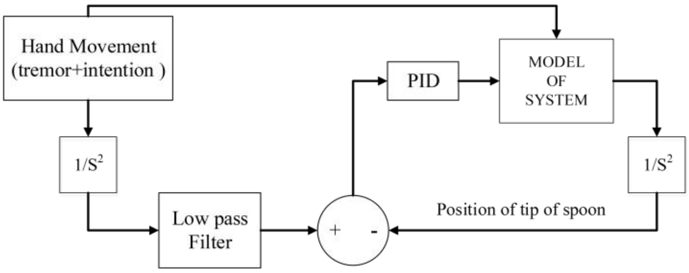


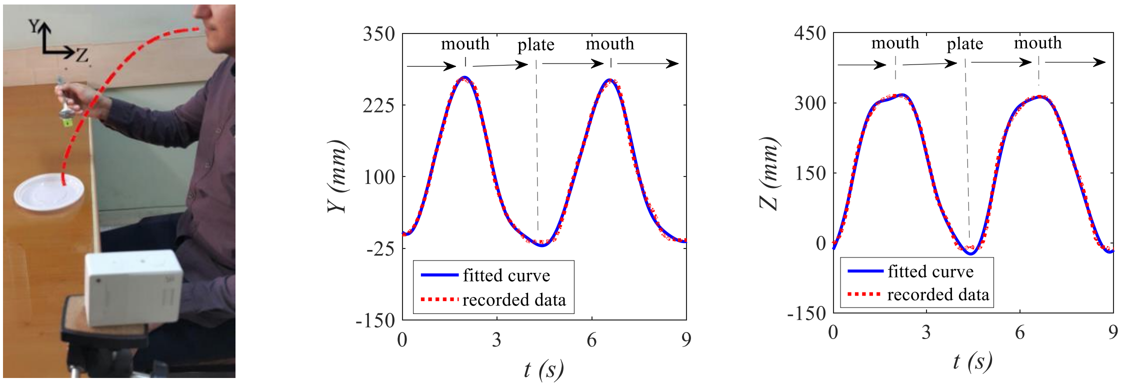
Figure 3: PID loop control used to control the system

Table 2: PID controller coefficients

Coefficient	K_p	K_I	K_D	N
Value	200.643	564.381	40.349	4312.94

Case Study

Application of the designed spoon, in real world, is studied in this section. For this reason, path of hand motion during eating with a spoon is recorded with a 120fps HD camera and two curves are fitted to the recorded hand motions in Y and Z directions. Part (A) of Figure 4 shows the recording procedure of hand motions. Part (B) and part (C) of this figure respectively depicts the recorded hand motion in Y and Z directions. To show movement of a patient's shaky hand, the hand tremor is added to the fitted curve in Y direction. In doing so, a sine function with frequency of 5 Hz and amplitude of 2.5 cm is considered as the hand tremor and it is added to the healthy hand motion.



(A) **(B)** **(C)**

Figure 4: Capture the hand motion (A); three times eating hand motion in Y direction (B); and three times eating hand motion in Z direction (C)

Results

The paths of eating for a shaky hand and a healthy hand, are shown in Figure 5 and Figure 6. Also for comparison, the simulation results of use of the device without active control is shown in Figure 5 .in addition the results of use of the device with active control is shown in Figure 6. As it's shown in these figures both methods successfully suppressed the tremor but the device with active control can attenuate the tremor more effectively. To calculate the reduction of tremor, first, the movement of a shaky hand is filtered by a high pass Butterworth filter with order of 4 and cut off frequency of 2; the output of filter is the hand tremor. Then the controlled signal is filtered by a same filter; in this stage, the output of filter is the remained tremor in tip of the spoon after the control. Then by the use of (32), the numeric value of reduction is calculated.

$$\mathrm{TSS}(\%) = (1 - T_a / T_b\ ) \times 100 \tag{32}$$

Where T_a and T_b are respectively the tremor after and before using the tremor suppression system. This method is applied to both results of passive and active control and the results are shown in Table 3. Based on results in Table 3, by the use of active control, the tremor is attenuated 38.58% more than device with passive control.

Table 3: The results of use of device

Method	Passive method	Active control
Reduction	57.39%	95.97%

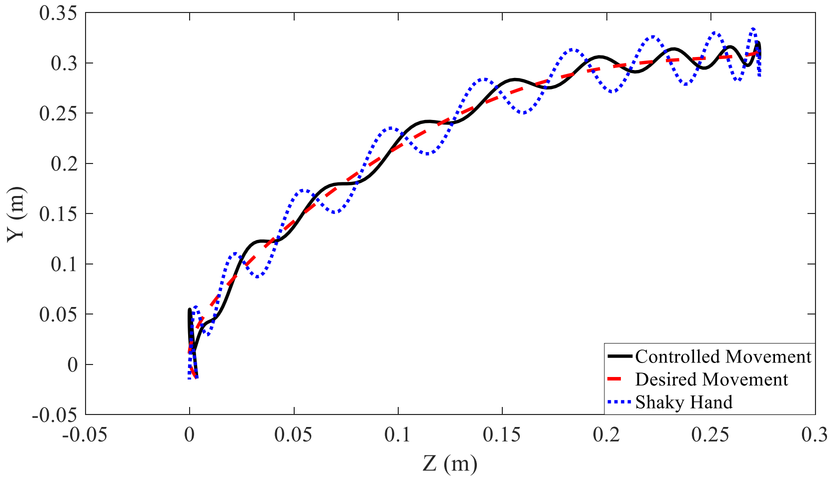


Figure 5: results of use of device with passive control

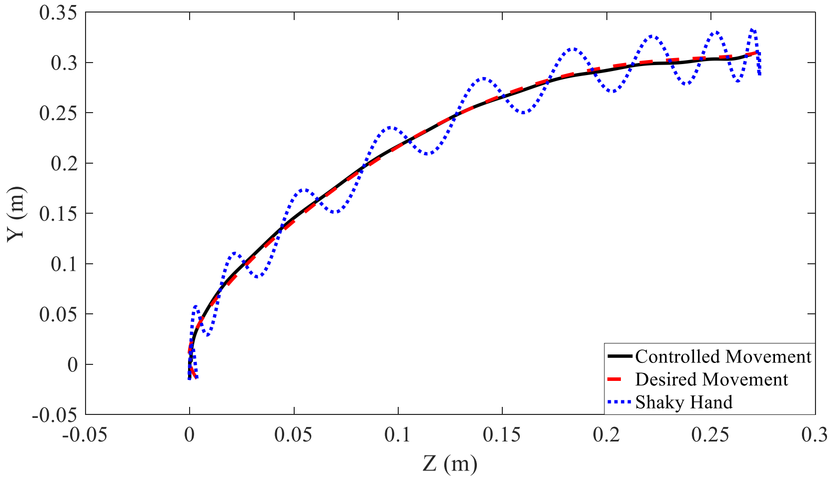


Figure 6: Results of use of device with active control

Conclusion

An innovative device is designed in this study. The mechanism of the device is discussed and governing dynamic equations of system is derived. Then, frequency response of passive system is obtained and it is concluded that the presented system can effectively suppress the hand tremor. For better results a linear actuator was added to system and an active control applied. As a result, the device performance in case of suppressing the hand tremor is remarkably improved. By the use of passive system the tremor was reduced 57.39% and by the implementation of active control the tremor was reduced up to 95.97%. According to results of this study, the presented system for attenuating the hand tremor can be a useful and practical device and can help patients with hand tremor to eat with less difficulty.

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