Active Tremor Control in 4-DOFs Biodynamic Hand Model

A. As'arry, M. Z. Md. Zain, M. Mailah, M. Hussein, Z. M. Yusop

***Abstract*—**This paper exhibits the performance of the active vibration method in suppressing human hand tremor. The Active Force Control (AFC) and classic Proportional-Derivative (PD) controller are proposed to control the linear electromagnet actuator and applied onto a four Degree-of-Freedoms (4-DOFs) biodynamic model of the human hand to investigate the performance of the controller. The PD controller was designed by using heuristic and optimization method. The Signal Constraint block available in Simulink Response Optimization Toolbox was employed as an optimization technique. Compared to the heuristic method, this proves to be a far more time and energy efficient approach to obtain satisfactory results. Findings show that the combination of AFC and classic PD controller provides a significant improvement in reducing tremor error. The simulation work could be used as the initial stage to study and develop an anti tremor device.

***Keywords*—**Active Force Control, Active Tremor Control, Tremor.

I. Introduction

NEUROLOGICAL disorder such as tremor is an involuntary or rhythmic uncontrollable oscillation of body parts which is to visible for Parkinson Disease (PD) patients. The severe illness most commonly occurs at the hand and head. Tremor may happen to anyone [1] and most PD patients do not realize the early stage of their tremor until the tremor becomes worse. The involuntary movement for a healthy person (physiological tremor) should be small and clearly visible when a person is anxious, furious, too cold or frightened. However, for neurological diseases person, such as Parkinson's disease there is a significant uncontrollable hand tremor movement [2]-[3]. Thus, it makes the patient experience difficulties which interfere with performing daily activities such as writing, lifting objects, placing the object on the target point and etc [4]. In addition, the person feels embarrassed to face other people and worse they prefer to stay at home rather than outside. Consequently, it may give negatively impact on their quality of life, mood and independence. Tremor may be caused by smoking habits, taking caffeine, alcohol, using certain drugs or hereditary [5]-[6].

The PD symptoms are more specifically caused by the damaged brain cells that disturb the human nerve muscle. This occurs due to the degenerate of dopaminergic neurons in the Substantia Nigra (located in the upper portion of the midbrain) [7]. Dopamine is a vital chemical transmitter in the brain. The shortage of dopamine (>80% of dopamine in the brain) causes less transmission and disrupts the nerve cell connection to control muscle or motor behavior [8].

There is no official statistical data available on people experiencing severe Parkinson disease in Malaysia. According to Malaysian Parkinson's Disease Association (MPDA), it is estimated that about 15,000 to 20,000 patients suffer from PD in Malaysia. While there is no cure for PD currently available and the fact that the proportion of elderly people in the population is increasing, the total number of PD patients is expected to rise to about 25,000 to 30,000 by the year 2020 [9].

The available medicine treatment may lessen the tremor progress. However, most treatment methods have their own weaknesses, for example drug therapy may cause a negative long term side effect while surgical therapy provides a high risk because it involves the operation on the brain. Therefore, the idea of using mechanical based non-invasive treatment may be a possible way to counter the effect of tremor.

In this simulation study, the electromagnet type used as smart actuator for active tremor control in suppressing hand tremor. The performance of the Active Force Control (AFC) scheme in controlling the actuator to suppress hand tremor will be investigated. The AFC strategy selected as a controller due to its simple control law and proven vibration cancellation capabilities either in simulation or experimental [10, 11]. From the previous study, it was found that the tremor amplitude for a PD person is in the range between ±10mm [12]. Thus, a mathematical model of four degree-of-freedoms (4-DOFs) system is introduced to represent the biodynamic response (BR) of the palm of the human hand.

Manuscript received June 27, 2011: Revised version received June 27, 2011.

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II. Biodynamic Model of the Human Hand

The biodynamic response (BR) of human hand is used to observe the relation between force and motion of human tremor. Thus, the mechanical model which is the combination of mass-spring-damper system is utilized to represent a 4-Degree of Freedoms (4-DOFs) model of human hand tremor, specifically at the palm.

Previous study state that two muscles (thenar and first dorsal interosseous) cause the source of tremor from the brain to the palm [3]. Thus the 4-DOFs palm model be the subject of interest in this study due to the source of tremor at hand occurred at this area.

In the 4-DOF model, masses m_1, m_2, m_3, and m_4 have been attributed to mass due to epidermis, dermis, subcutaneous tissue and the muscle, respectively. The coupling elements k_1 and c_1 are considered to represent the visco-elastic properties of epidermis and dermis tissue. The strong coupling between the dermis and the subcutaneous tissue has been related to element k_2 and c_2. However, the elements k_3 and c_3 are considered to represent weak coupling between the subcutaneous tissue and the muscle. The element k_4 and c_4 relate to coupling between muscle and the bones [13].

Theoretically, human hand tremor exists due to the damage on human brain that disturbs the motor function (muscle) without any external force applied at the hand. Hence, in the simulation 4-DOFs model the source of force should be placed at the muscle (at m_4) and this can be called as 'internal force' that was used to induce the vibration. The applied force at the palm can be seen in the Figure 1.

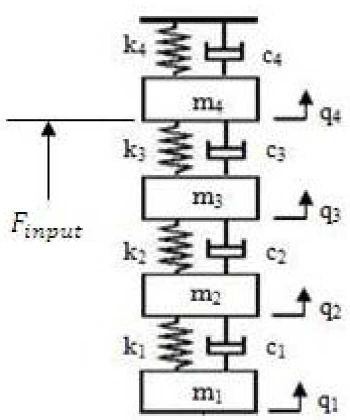

Fig. 1: Four DOFs palm model.

The basic equation of motion of the 4-DOFs at the palm of human hand may be expressed as

$$m\ddot{q} + c\dot{q} + kq = F \tag{1}$$

where m, c and k represent mass, damping and stiffness element. The $\ddot{q}, \dot{q}, q$ and F are parameters of acceleration, velocity, displacement response and force, respectively.

In order to fully characterize the 4-DOFs palm model, it is important to derive the mathematical model before translating the model in simulink block structure. Thus the full equations of motion for the 4-DOFs palm model shown in Figure 1 are:

$$m_1\ddot{q}_1 = -k_1(x_1 - x_2) - c_1(\dot{x}_1 - \dot{x}_2) \tag{2}$$

$$\begin{aligned} m_2\ddot{q}_2 = -k_1(x_2 - x\ \ ) - c_1(\dot{x}_2 - \dot{x}_1) - \\ k_2(x_2 - x_3) - c_2(\dot{x}_2 - \dot{x}_3) \end{aligned} \tag{3}$$

$$\begin{aligned} m_3\ddot{q}_3 = -k_2(x_3 - x_2) - c_2(\dot{x}_3 - \dot{x}_2) - \\ k_3(x_3 - x_4) - c_3(\dot{x}_3 - \dot{x}_4) \end{aligned} \tag{4}$$

$$\begin{aligned} m_4\ddot{q}_4 = -k_3(x_4 - x_3) - c_3(\dot{x}_4 - \dot{x}_3) - \\ k_4x_4 - c_4\dot{x}_4 + f \end{aligned} \tag{5}$$

Simplified, the equation of motion therefore can be expressed as,

$$m_1\ddot{q}_1 + c_1\dot{q}_1 - c_1\dot{q}_2 + k_1q_1 - k_1q_2 = 0 \tag{6}$$

$$\begin{aligned} m_2\ddot{q}_2 - c_1\dot{q}_1 + (c_1 + c_2)\dot{q}_2 - c_2\dot{q}_3 - \\ k_1q_1 - (k_1 + k_2)q_2 - k_2q_3 = 0 \end{aligned} \tag{7}$$

$$\begin{aligned} m_3\ddot{q}_3 - c_2\dot{q}_2 + (c_2 + c_3)\dot{q}_3 - c_3\dot{q}_4 - \\ k_2q_2 - (k_2 + k_3)q_3 - k_3q_4 = 0 \end{aligned} \tag{8}$$

$$\begin{aligned} m_4\ddot{q}_4 - c_3\ddot{q}_3 + (c_3 + c_4)\dot{x}_4 - \\ k_3x_3 + (k_3 + k_4)x_4 = f(t) \end{aligned} \tag{9}$$

Table 1 shows the parameters used to emulate the 4-DOFs hand tremor in the vertical plane.

Table 1. Parameters of skin anatomy at human hand [13].

Skin Layer	Mass, m (kg)	Damper, c (Ns/m)	Spring, k (N/m)
Epidermis	0.0043	88.8	678
Dermis	0.105	1.5	185
Subcutaneous Tissue	0.566	0.1	23.9
Muscle	4.3	3.99	34.6

III. Transfer Function of Linear Electromagnet Actuator

Electromagnetic actuator widely used in vibration control such as at the rotating machines [14]-[15], at the beam [16]-[17], suspension system [18] and etc. In this theoretical study, a linear motion electromagnet actuator is selected as the transducer to suppress human hand tremor. The electromagnet field (EMF) generated is proportional to the rate of change of the magnetic flux. The movement of the charge q particle with a velocity $\vec{v}$ in an electromagnetic field will create a current (electric field $\vec{E}$ and magnetic flux density $\vec{B}$) [19]. Thus, the occurence force $\vec{F}$ on moving charge, also known as Lorentz Force can be represented by the equation,

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \tag{10}$$

which consists of electric force and magnetic force. When a current is formed by a very large number of charged particles (the electrons) moving along the wire [19]–[20], the total force is given by integrating,

$$\vec{F} = i\int \vec{d}l \times \vec{B} \tag{11}$$

Meanwhile, the Lorentz Force of the magnetic field acting on the element $dl = rd\theta$ of one turn of the coil with a current i. Thus,

$$F = i\int rd\theta . B \tag{4}$$

The relationship of the electromagnet force f and the current of the coil i can be expresses as,

$$\left|F\right| = i\,2\pi\, n\, rB \tag{5}$$

For this simulation study, the parameters used for electromagnet actuator transfer function are; a) Outer diameter of the coil is 40 mm b) made into a 122-turn coil and 3) the magnetic flux density B is 1.04 Tesla.

IV. PD and Active Force Control (AFC) Controller

There are two main controllers used to control the linear electromagnet actuator which are PD and Active Force Control (AFC) controller. The PD controllers consist of proportional and derivative actions. It is widely used in control system since 1940. It is useful for fast response controller without the effect of steady-state error. The PD algorithm was described as:

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} \tag{6}$$

where *u(t)* is the controller output, *Kp* is the proportional gain, *Kd* is the derivative gain and *e(t)* is the error. In this study, the PD parameters were tuned using heuristic method and simulink block method. Eventhough the Ziegler-Nichols method seems like a proper technique in tuning the parameter than heuristic method, however, the Ziegler-Nichols method does not state ruling strategy for tuning PD controller and permits the usage of the method to calculate PD parameter [21]. After several values (heuristic method) were test to determine the appropriate PD controller, finally the value Kp = 100 and Kd = 32.2 gives good response in suppressing hand tremor.

Meanwhile, an AFC was firstly introduced by Hewit and is widely used since the last three decade [10], [11], [22]. This robust controller is capable of managing a closed loop system with the introduction of disturbances, parameter uncertainties and changes to reduce error [23]. The advantages of using AFC method include utilizing a simple control technique, low computational burden and proven capability in real-time application.

Figure 2 shows the proposed AFC control scheme incorporated with the PD controller to control an electromagnet actuator for suppressing human hand tremor. The main AFC loop is shown in the dash line box. For theoretical simulation, it is assumed that the position sensor gives the perfect modeling ($H_s(s)$ = 1) and the noises in the sensors are totally neglected.

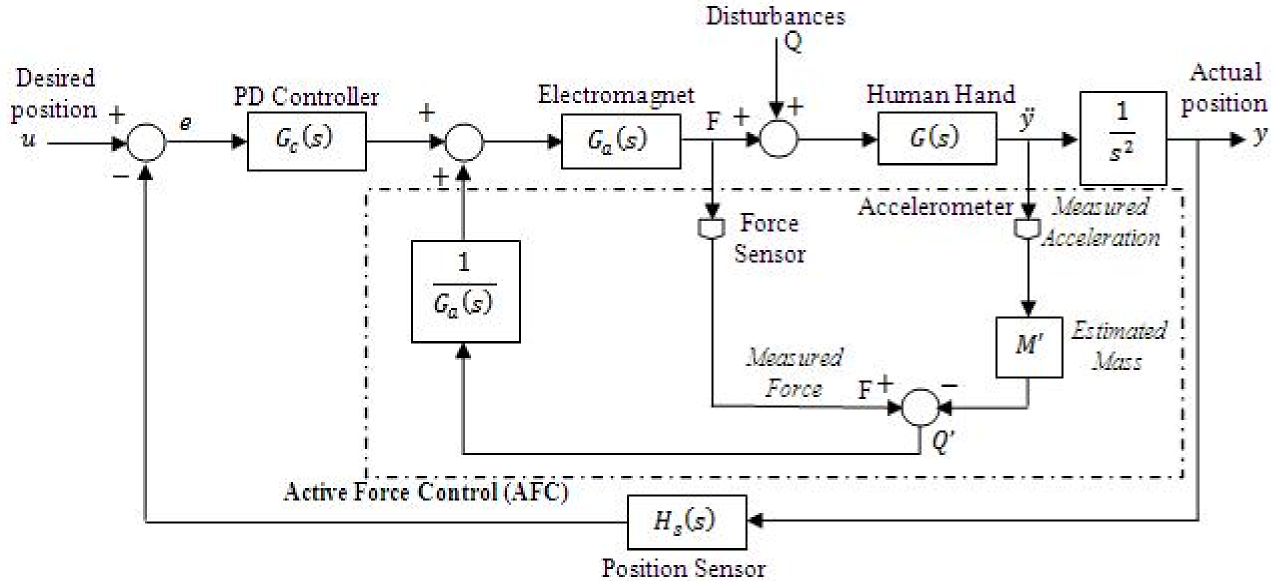

Fig. 2: A schematic diagram of proposed control scheme

The main AFC equation computed the Estimated Disturbance, *Q'* can be express as:

$$Q' = F - M'\ddot{y} \tag{7}$$

where,

F : Applied force of the actuator.

M' : Estimated mass vibration transmissibility.

$\ddot{y}$: acceleration vibration transmissibility.

By using heuristic (trial and error) method, the value of mass estimation M' = 0.001kg. The computation of *Q'* is then passed through an inverse transfer function of the actuator and summed up with PD controller to give the ultimate AFC signal command embedded with an outer control loop. The scheme actually has a two degree-of-freedom controller (classic closed loop and AFC element) that offer an excellent overall system performance provided that the measurement and estimated parameters were appropriately acquired [11].

V. Optimization Technique

Besides heuristic method, the PD controllers were optimized using the Signal Constraint block available in Simulink Response Optimization Toolbox. Signal Constraint is a block where response signals can be graphically constrained and model parameters should be automatically optimized to obtain the performance requirements [21]. As shown in Figure 3, the block was connected at the displacement output. For optimization method, the algorithm use is the Gradient descent. Prior to the beginning of the optimization, the constraint bounds in the Signal Constraints window were adjusted to very minimum upper and lower bounds (±1e-3) as illustrated in Figure 4.

Figure 5 shows the optimization of PD parameters where the value for Kp gain and Kd gain were obtained as Kp = 31.52 and Kd = 37.81 respectively. The optimization technique play some advantages such as does not require experience in control, simple and produces a satisfactory system response with optimal use of effort and time [21],[24].

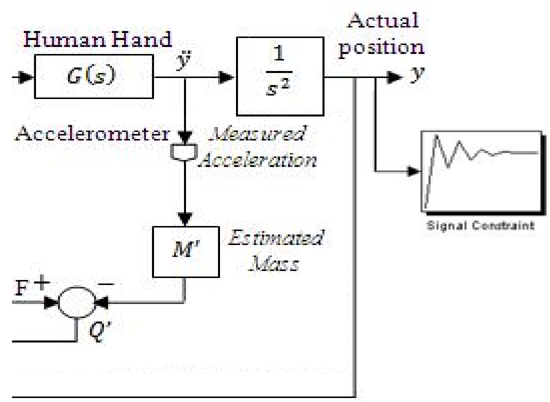

Fig. 3: A block of Signal Constraint applied at proposed control scheme.

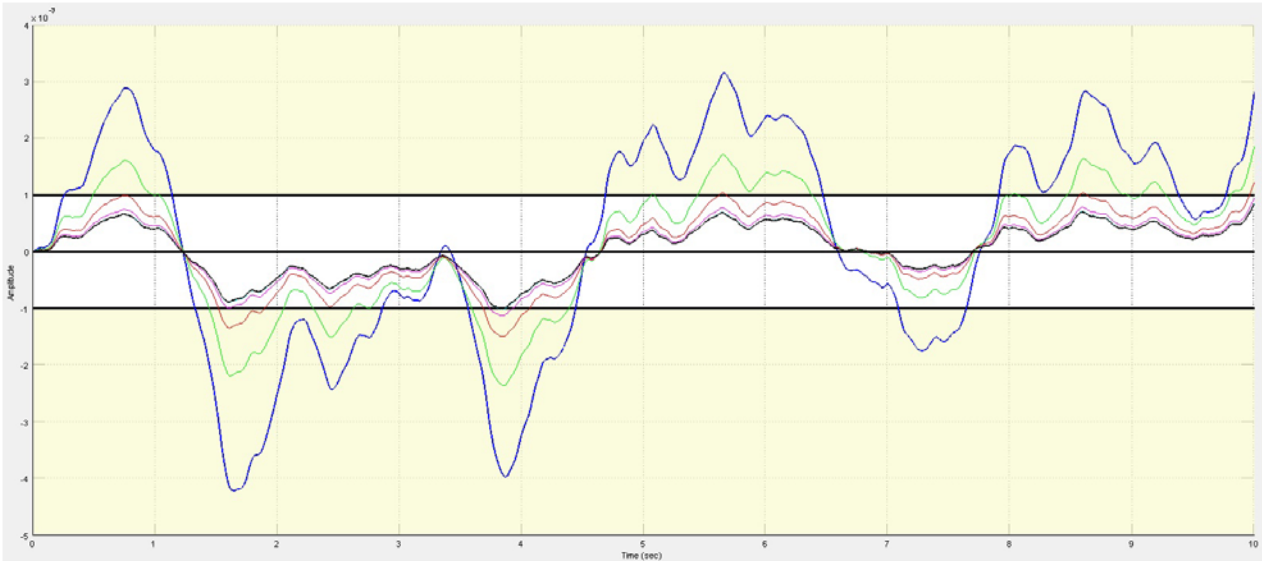

Fig. 4: The optimization process of PD parameters

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                                  max                      Directional   First-order
 Iter   S-count        f(x)    constraint    Step-size     derivative    optimality
    0         1           0         226.1
    1        10           0         108.2         9.98              0          90.2
    2        15           0         15.54           14              0          33.3
    3        20           0        0.1212         12.5              0          10.9
    4        25           0       0.01237         5.52              0         0.438
    5        30           0     0.0001858        0.695              0        0.0125
Successful termination.
Found a feasible or optimal solution within the specified tolerances.

kP =

   31.5192


kD =

   37.8056
```

Fig. 5: Optimization progress result

VI. Results and Discussions

The proposed control scheme (AFC + PD control) is simulated to investigate the effectiveness of the controller in reducing tremor error. This simulation study is accomplished by using MATLAB and Simulink software. The results may be used for further investigation in real-time application. Figure 3 shows the input force signal which is a combination of sine wave and white noise signal. The combination signals have been selected to characterize the behaviour of real human hand tremor where the signal exhibited is much closer to sinusoidal waveform, rhythm and regularity [25]. In order to get a realistic output displacement of human hand tremor, the value for sine wave signal and white noise signal have been tuned as follows,

- Sine wave – Amplitude [9N]; Frequency [50Hz]
- White noise – Noise Power [0.02]; Sample time [0.001]

As shown in Figure 6, the high input force value (±30N) is required to excite a 4-DOFs human palm due to the location of applying input force at the muscle (see Figure 1). The force energy will decrease from muscle to epidermis layer due to the absorption of the damper at each layer.

Figure 7 shows the comparison of the performance of controller between classic PD controller and PD + AFC controller (heuristic method). The displacement signal for human hand tremor can be seen in the figure and labeled as Hand Tremor. Referring to the figure, the simulation reaction is between -8mm and 5mm which is still within the target displacement amplitude boundary since the actual human postural tremor behavior is within the range of ±10mm [26]-[27].

During the 10-s simulation time, the displacement response of the human hand tremor for the gap between the reference and PD controller was determined oscillating between ± 2mm. By applying PD + AFC controller, the hand tremor error reduces to ± 20 micron.

Meanwhile, Figure 8 shows the result after conversion to frequency domain. The findings exhibit that human hand tremor frequency occurred at 7.225Hz with amplitude $2.191x^{10-9}$ m^2/Hz. However, when the PD controller is applied, the vibration peak reduce to $5.678x10^{-10}$ m^2/Hz at 7.232Hz. The vibration level significantly improve after apply PD+AFC controller where the highest peak occurred at 8.774Hz with amplitude $3.564x10^{-13}$ m^2/Hz.

In order to evaluate the performance of the optimization method, Figure 9 shows the displacement response of 4-DOFs hand tremor in time domain. For only PD controller, the tremor amplitude oscillated in the range -10 $x10^{-4}$mm to $5x10^{-4}$mm. By adding the AFC scheme, the tremor amplitude slightly reduces from -15 to 10 micron.

Figure 10 indicates the sensible comparison between PD and PD+AFC in frequency domain. The coherence frequency of optimize PD controller occurred at 7.654Hz with amplitude $5.226x10^{-10}$ m^2/Hz. When employ AFC scheme, the vibration peak significantly reduce to $2.843x10^{-13}$ m^2/Hz at 8.164Hz.

Compared to the heuristic method result, the optimization result shows effectiveness in suppressing hand tremor. This is due to the optimization technique able to find the optimum value of the PD parameter when the output displacement result was set bound to ± 1mm. Overall, the findings conclude that when the AFC controller is applied, it gives a significant reduction in active tremor control.

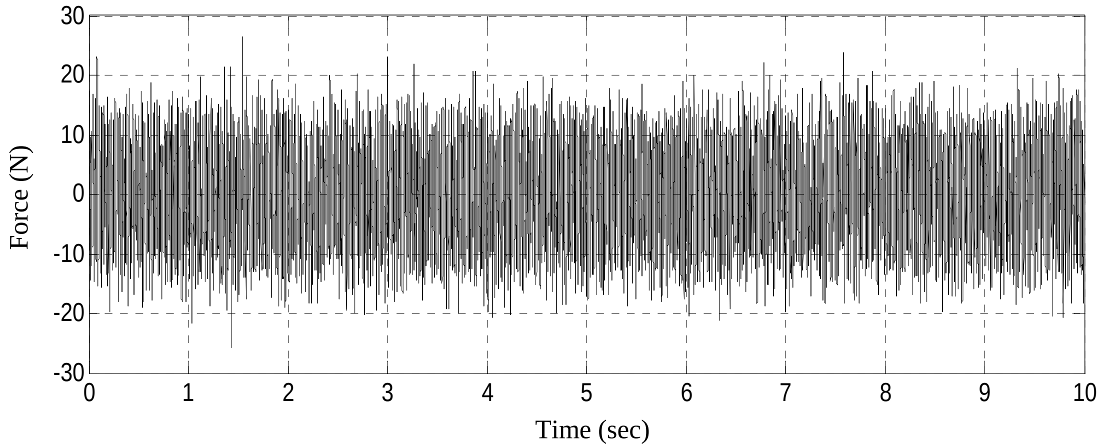

Fig. 6: The combination of sine wave and white noise input force

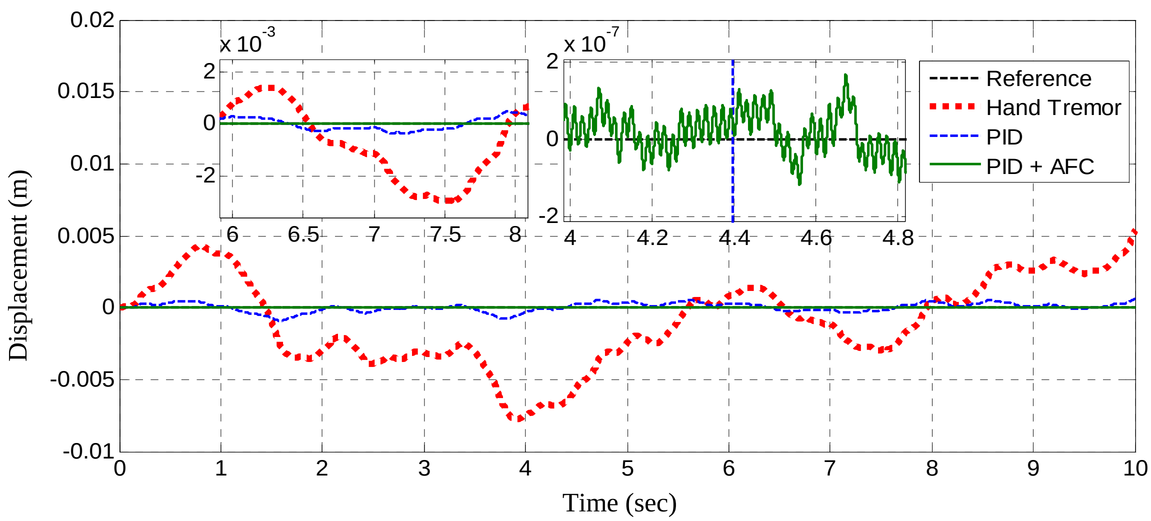

Fig. 7: Time domain of 4-DOFs palm model using heuristic method.

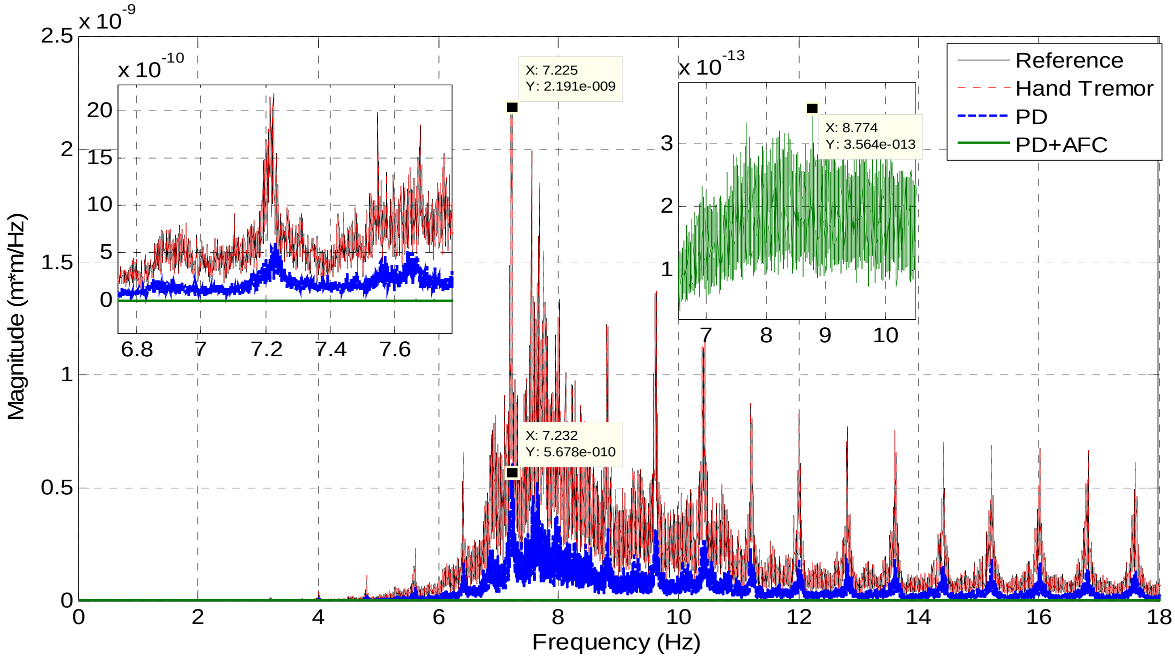

Fig 8: Frequency response of 4-DOFs palm model using heuristic method

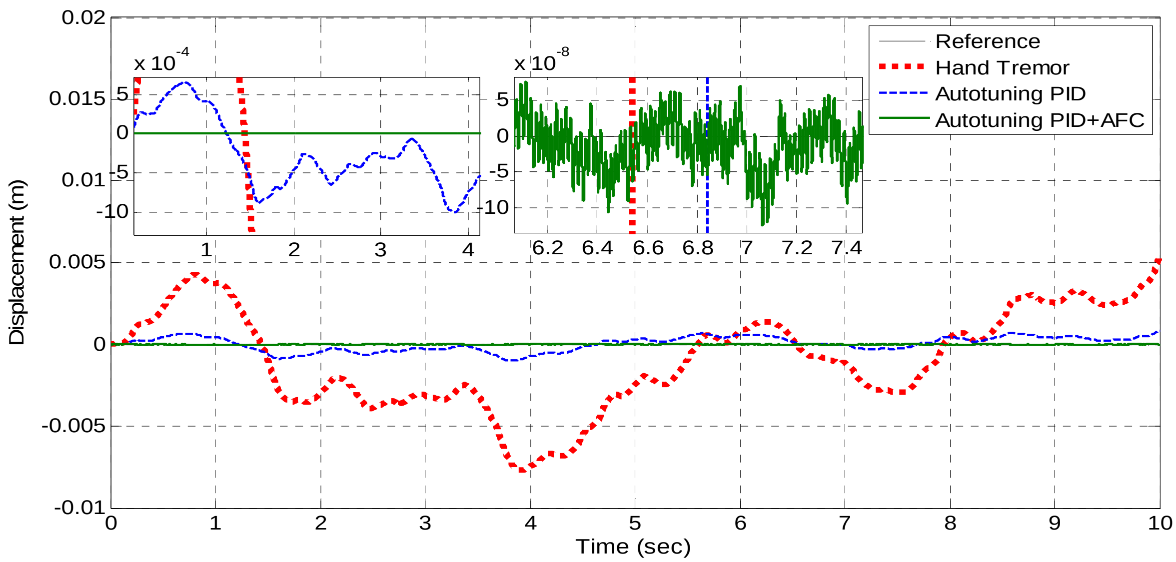

Fig. 9: Time domain of 4-DOFs palm model using Signal Constraint Block

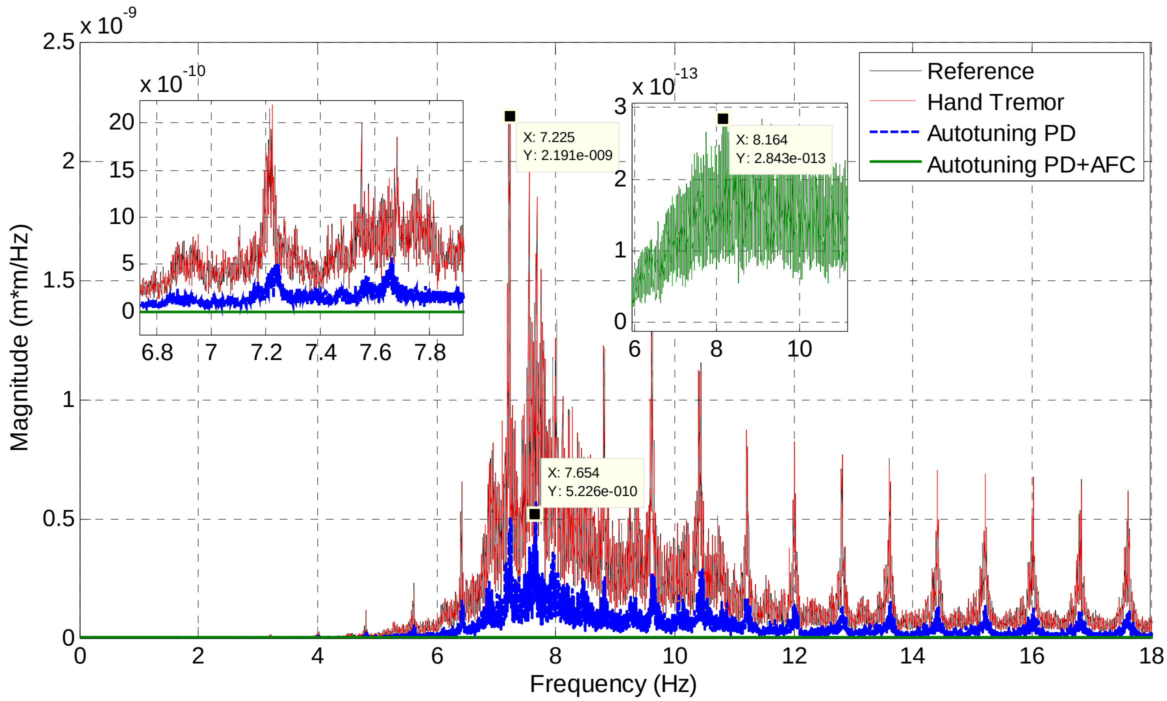

Fig 10: Frequency response of 4-DOFs palm model using Signal Constraint Block

Theoretically, the findings prove that the AFC based scheme is capable of working with linear electromagnet actuator and manages to suppress human hand tremor.

Hence, the outcomes of the study present an important finding and an initial stage that may assist researcher to design and develop anti tremor equipment utilizing linear electromagnet. Furthermore, the AFC controller has been proven to be effective in real time especially in vibration application, thus the idea to develop anti tremor device will be more realistic.

VII. Conclusion

This study provides the investigation of the active vibration method performance in suppressing human hand tremor. From the findings, the combination of active force control (AFC) and classic PD controller shows significant improvement in reducing hand tremor. The optimization method using Simulink block play some advantages such as easier, simple and less time and effort to search the suitable PD parameters. The simulation work could be used in the initial stage to study and develop an anti tremor device.

Acknowledgment

The authors would like to thank the Malaysian Ministry of Science, Technology and Innovation (MOSTI) and Universiti Teknologi Malaysia (UTM) for their continuous support in the research work. This work was financial supported in part by the Malaysia FRGS Fund under Grant number Vot. 78510.

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