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ANALYTICAL MODELLING OF A DYNAMIC VIBRATION ABSORBER FOR PARKINSON DISEASE

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ABSTRACT

Parkinson is the most common neurodegenerative disease. It is characterized by the presence of involuntary tremor of human arms. Current treatments as pharmacological and surgery can be invasive for patients due to secondary effects and also high costs are required. In this sense, non-invasives devices have been proposed in order to reduce the tremor amplitude without secondary effects. These devices require a model in order to analyze the dynamic behavior and calculate the optimum parameters. In this article, it is developed an analytical three-dimensional model of a dynamic vibration absorber placed on a human arm. Results show dynamic vibration absorber is effective to reduce the tremor during voluntary motion. However, it is only effective while tremor frequencies are within a narrow range around the tuned frequency used for calculation of absorber parameters.

Index Terms – vibration absorber , Parkinson, analytical model

1. INTRODUCTION

Tremor is described as an involuntary oscillatory motion of body parts, especially forearm, arm and hands [1]. It impacts in physical activities of patients [2]. Parkinson disease (PD) is characterized by the presence of tremor. To date, PD does not have a cure, treatments are addressed to improve quality of life for their daily activities. PD affects more than six million people in worldwide[3]. In Peru, there are 30 0000 peoples with PD, which represents an 1% of population, and each year 3000 new cases are reported [4]. Current treatments seek the reduction of tremor. They are classified in pharmacological, surgery, therapeutical and non-invasives [5]. Pharmacological and therapeutical are the conventional treatment; however, if it is required, more invasive treatments, as deep brain simulation, ultrasound, are used with a 50% of tremor reduction[6]. Pharmacological treatments have reported a 54.1 … 59.9% of tremor amplitude reduction [7]. Nevertheless, more than 52% leaves this treatment due to its effects [5], [8]. Surgery treatment is significantly better. However high costs and access to the technology and patient preferences are their limitations [2], [9]. Moreover, not all the patients are able to receive this treatment due to medical conditions requirements.

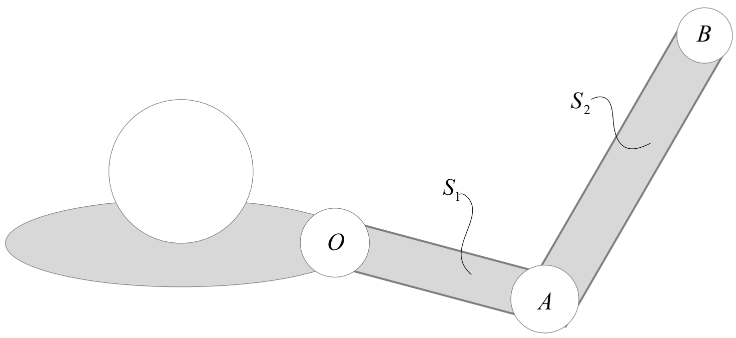
Non-invasive proposals are wearable devices which have been developed with the aim to reduction the tremor amplitude, but minimizing negative effects in daily activities [10]. These devices are classified in passive, semi-active and active according to the device tunning capacity. Passive devices are usually characterized by using a mechanical concept since it does not require a power source [11]–[13]. Active devices are able to change their parameters as a function of patient requirements since one of its parts consists of an actuator controlled by an algorithm in real time [6], [14], [15]. Semi active devices are a balance between these types. Most passive devices use the concept of vibration absorption, it consists of an additional mechanical system whose parameters are tuned to dissipate the energy income through disturbances forces. Two commercially available devices which uses this concept are Tremelo and Steadi One, they consist of tuned mass dampers and report 85%, and 85…90% tremor reduction respectively [11], [12], [16]. Another mechanical concept was developed in Task-Adjustable Passive Orthosis(TAPO), it consists of an air-filled glove which can control an artificial stiffness of hand movement through the air pressure inside [13]. It reported a 74…82% tremor reduction tested for 3 specific tasks [13].

Design of these devices requires a mathematical model in order to calculate physical dimensions and analyze the dynamic behavior under different conditions. Since the addition of mass to the human arm can impact the voluntary and natural motion of a person, it is important to choose the optimum parameters for design. In this article, we develop an analytic model of a dynamic vibration absorber placed on human arm in three dimensions. The equations of motion are obtained by using Lagrange equations while the tremor force is simulated as a perturbation signal in addition to voluntary forces.

2. ANALYTICAL MODELLING

2.1 Biomechanical 3D modelling of an arm

The human arm was modelled with 5 degrees of freedom, Figure 1, since it is allowed to represent any motion in a 3D space. Upper arm and forearm were modelled as rigid bodies linked by joints at shoulder and elbow. The shoulder joint has 3 degrees of freedom: θ_1 is the rotation angle in XY plane, θ_2 is the rotation angle in a normal axis to the plane composed by upper arm axis and the vertical axis z, θ_3 is the ration angle around the upper arm axis. It is used a first rotational system linked to the upper arm composed by the unitary vectors $\hat{e}_x^{S_1}$, $\hat{e}_y^{S_1}$ and $\hat{e}_z^{S_1}$. The motion of the forearm was described respect to rotational system fixed to the upper arm. θ_4 is the rotation angle of the elbow between the upper arm and the forearm and θ_5 is the rotation angle in the forearm axis. The hand was modelled as a punctual mass since the analysis was focused on tremor produced at the arm. The dynamic vibration absorber was placed on the forearm in a transversal direction to its axis. For this model, the absorber is able to rotate fixed to the forearm axis and to have a relative motion in the transversal axis denoted by x_r . After the absorber implementation, the complete system had 6 degrees of freedom.



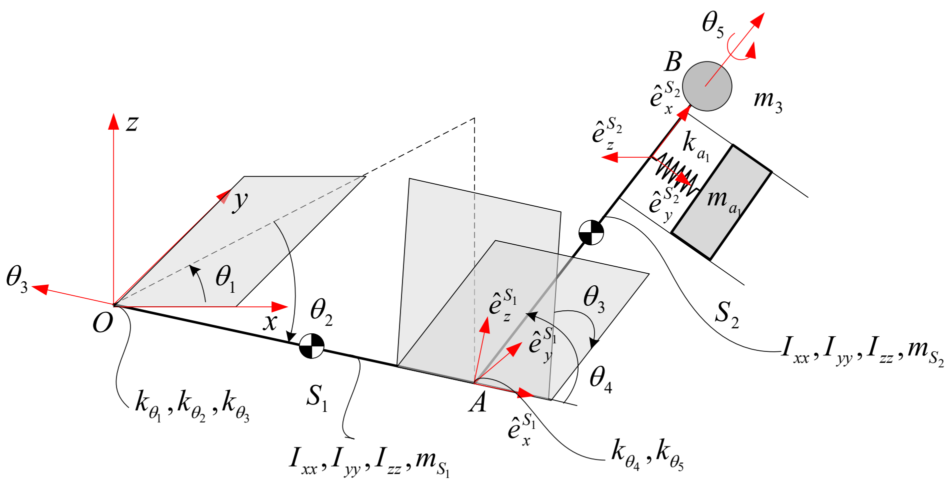


Figure 1. Human arm model

2.1.1 Position coordinates

The elbow position $\vec{r}_A$ is described by *Eq. 1* over time with respect to an inertial reference system.

$$\vec{r}_A = \begin{bmatrix} l_{S_1} cos(\theta_2) cos(\theta_1) \\ l_{S_1} cos(\theta_2) sin(\theta_1) \\ l_{S_1} sin(\theta_2) \end{bmatrix} \qquad \text{Eq. 1}$$

The hand position $\vec{r}_B$ is obtained by added the relative position between hand and elbow to the elbow position. It was used the rotational system fixed to the upper arm, *Eq. 2*. For the absorber position calculation $\vec{r}_a$, the relative displacement x_r is added as a vector in the transversal direction with a rotation fixed to the forearm $\hat{e}_y^{S_2}$, *Eq. 3* .

$$\vec{r}_B = \vec{r}_A + l_{S_2} cos(\theta_4) \hat{e}_x^{S_1} + l_{S_2} sin(\theta_4) \hat{e}_y^{S_1} \qquad \text{Eq. 2}$$

$$\vec{r}_a = \vec{r}_B + x_r \hat{e}_y^{S_2} \qquad \text{Eq. 3}$$

The angular velocity vector of θ_1 coordinate is in z axis over time, thus it can be described as *Eq. 4*

$$\overrightarrow{\omega_1} = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix} \qquad \text{Eq. 4}$$

The angular velocity vector of θ_2 coordinate must be perpendicular to the plane composed by the vertical axis and the upper arm axis. The plane can be calculated as the cross multiplication of the unitary vectors, *Eq. 5*.

$$\overrightarrow{\omega_2} = \left(\vec{u}_{S_{1xy}}{}^T \times \vec{u}_{S_1}{}^T \right)^T \dot{\theta}_2 \qquad \text{Eq. 5}$$

The angular velocity vector of θ_3 is in the upper arm axis direction. Thus, it can be described as *Eq. 6*.

$$\overrightarrow{\omega_3} = \vec{u}_{S_1}{}^T \dot{\theta}_3 \qquad \text{Eq. 6}$$

The angular velocity vector of the upper arm body S_1 is calculated as the sum of the angular velocities of each coordinate used to described its motion, *Eq. 7*.

$$\overrightarrow{\omega_{S_1}} = \overrightarrow{\omega_1} + \overrightarrow{\omega_2} + \overrightarrow{\omega_3} \qquad \text{Eq. 7}$$

The angular velocity vector of θ_4 must be perpendicular to the plane composed by the upper arm axis and forearm axis. Thus, plane can be calculated as the cross multiplication of the unitary vectors, *Eq. 8*.

$$\overrightarrow{\omega_4} = \left(\vec{u}_{S_1}{}^T \times \vec{u}_{S_2}{}^T\right)^T \dot{\theta}_4 \qquad \text{Eq. 8}$$

The angular velocity vector of θ_5 is in forearm axis over time. Thus, it can be described as *Eq. 9*.

$$\overrightarrow{\omega_3} = \vec{u}_{S_2} \dot{\theta}_5 \qquad \text{Eq. 9}$$

The angular velocity vector of the upper arm body S_2 is also calculated as the sum of the angular velocities of each coordinate, *Eq. 10*.

$$\overrightarrow{\omega_{S_2}} = \overrightarrow{\omega_4} + \overrightarrow{\omega_5} \qquad \text{Eq. 10}$$

2.1.2 Lagrange formulation

Kinetic energy is composed by translation and rotational motion. For the translational motion, the kinetic energy can be calculated as the sum of the kinetic energy of each body, *Eq. 11*. The velocity of each rigid body is represented as the velocity of the mass center. $\vec{v}_{1g}$ is the velocity of upper arm's mass center, $\vec{v}_{2g}$ is the velocity of forearm's mass center and $\vec{v}_{3g}$ is the velocity of hand modelled as a punctual mass.

$$T_{trans} = \frac{1}{2} m_1 v_{1g}{}^2 + \frac{1}{2} m_2 \vec{v}_{2g}{}^T \vec{v}_{2g} + \frac{1}{2} m_3 \vec{v}_{3g}{}^T \vec{v}_{3g} + \frac{1}{2} m_a \vec{v}_a{}^T \vec{v}_a \qquad \text{Eq. 11}$$

The rotational kinetic energy is calculated by multiplying each squared angular velocity component, with respect to the inertial system, with the mass inertia with respect to the same axis, *Eq. 12*.

$$T_{rot} = \vec{\omega}_{S_1}.^2 \times \begin{bmatrix} \frac{1}{2} I_{S_{1xx}} & \frac{1}{2} I_{S_{1yy}} & \frac{1}{2} I_{S_{1zz}} \end{bmatrix}^T + \vec{\omega}_{S_2}.^2 \times \begin{bmatrix} \frac{1}{2} I_{S_{2xx}} & \frac{1}{2} I_{S_{2yy}} & \frac{1}{2} I_{S_{2zz}} \end{bmatrix}^T \qquad \text{Eq. 12}$$

The total kinetic energy is calculated as the sum of translational and kinetic energy, *Eq. 13*.

$$T = T_{trans} + T_{rot} \qquad \text{Eq. 13}$$

Potential energy is calculated from the equilibrium position, thus there was not considered gravity effects, *Eq. 14*.

$$V = \frac{1}{2}k_{\theta_1}\theta_1^2 + \frac{1}{2}k_{\theta_2}\theta_2^2 + \frac{1}{2}k_{\theta_3}\theta_3^2 + \frac{1}{2}k_{\theta_4}\theta_4^2 + \frac{1}{2}k_{\theta 5}\theta_5^2 + \frac{1}{2}k_a x_r^2 \qquad \textit{Eq. 14}$$

The lagrangian is defined by the difference between the kinetic and potential energy, *Eq. 15*.

$$L = T - V \qquad \textit{Eq. 15}$$

Each differential equation of the system can be calculated with Lagrange Equation, *Eq. 16*. The selected generalized coordinates are rotation angles used for describing the model.

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_i \qquad \textit{Eq. 16}$$
$$\vec{q} = [\theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4 \quad \theta_5]^T$$

Then, the differential equations can be grouped as the form shown in *Eq. 17*, where $[M]$ is the matrix of mass, $[K]$ is the stiffness matrix, $\{\Theta\}$ is the generalized coordinates vector which are the rotation angles from the model and $\{Q\}$ is the generalized forces vector.

$$[M]\{\ddot{\Theta}\} + [K]\{\Theta\} = \{Q\} \qquad \textit{Eq. 17}$$

In this model, the arm motion is controlled by torques at the joints for each generalized coordinate. The perturbation caused by Parkinson was simulated as a periodic signal acting on upper arm axis represented by the coordinate θ_3. In this sense, the perturbation signal $p(t)$ was added to $\{Q\}$, *Eq. 18*.

$$\{Q\} = \begin{Bmatrix} F_1(t) \\ F_2(t) \\ F_3 + p(t) \\ F_4(t) \\ F_5(t) \\ 0 \end{Bmatrix} \qquad \textit{Eq. 18}$$

3. RESULTS

The set of differential equations of motion was simulated in MATLAB r2023a®. The geometrical and physical parameters of the human arm used for the simulation were obtained from [17] and are shown in Table 1. Since it was not available the stiffness of joints for different directions of rotations, it was used the same value for the whole shoulder and elbow as a first approach. Parkinson's tremor frequency has been reported previously as a complex combination of signals with different characteristic frequency over time but with high energy distribution near to low frequencies [18]. In this sense, the vibration absorber was tuned to 3.5Hz, because low frequencies are related to high displacement. This value also corresponds to the range reported in previous studies for Parkinson disease in low frequencies 3…5Hz [6], [19], 4…6Hz [19] [20].

Table 1. Simulation parameters

Parameter	Unit	Value
m_1	kg	2.07
m_2	kg	1.16
m_3	kg	0.54
l_1	m	0.364
l_2	m	0.299
k_{θ_1}	Nm/rad	180
k_{θ_2}	Nm/rad	180
k_{θ_3}	Nm/rad	180
k_{θ_4}	Nm/rad	250
k_{θ_5}	Nm/rad	75
m_a	m	0.05 m_2
f_{abs}	Hz	3.5

3.1 Natural frequencies of arm

The equations of motion were used to calculate the response in frequency domain. Figure 2 shows each coordinate response to a tremor excitation frequency with and without absorber implemented. The natural frequencies were 3.79, 5.24, 9.45, 10.17, 18.67Hz without absorber and 3.45, 3.83, 5.24, 9.43, 10.07 and 18.67Hz with absorber. The amplitude of the excitation signal was set as unitary and it was applied a logarithmic function to the response. Each peak of high amplitude corresponds to a natural frequency of arm. For no absorber implemented case, there were 5 peaks while there were 6 peaks for the case with absorber. It can be seen the addition of the absorber produced a high reduction of the amplitude at frequency 3.5Hz where it is tuned for each coordinate. This absorption appears in the response of each coordinate. The exception was the absorber displacement coordinate x_r. In this case, the displacement was high at this absorption frequency. Likewise, it can be noticed that the absorber produced a new natural frequency between the first and second original natural frequencies.

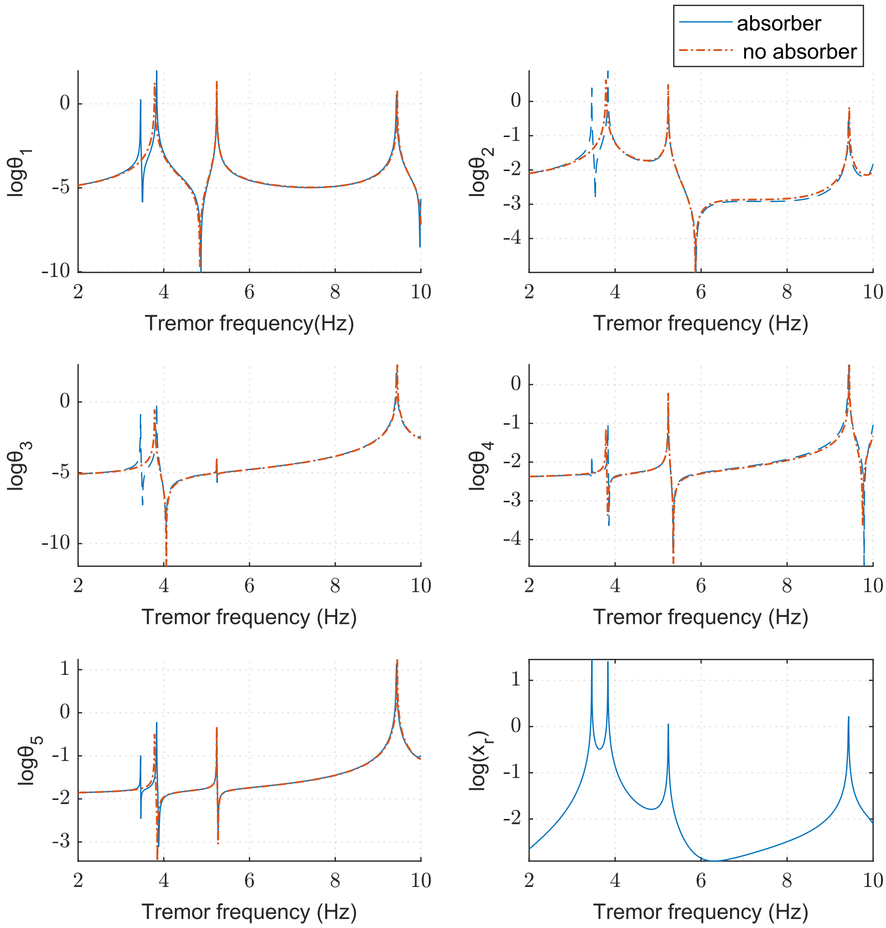
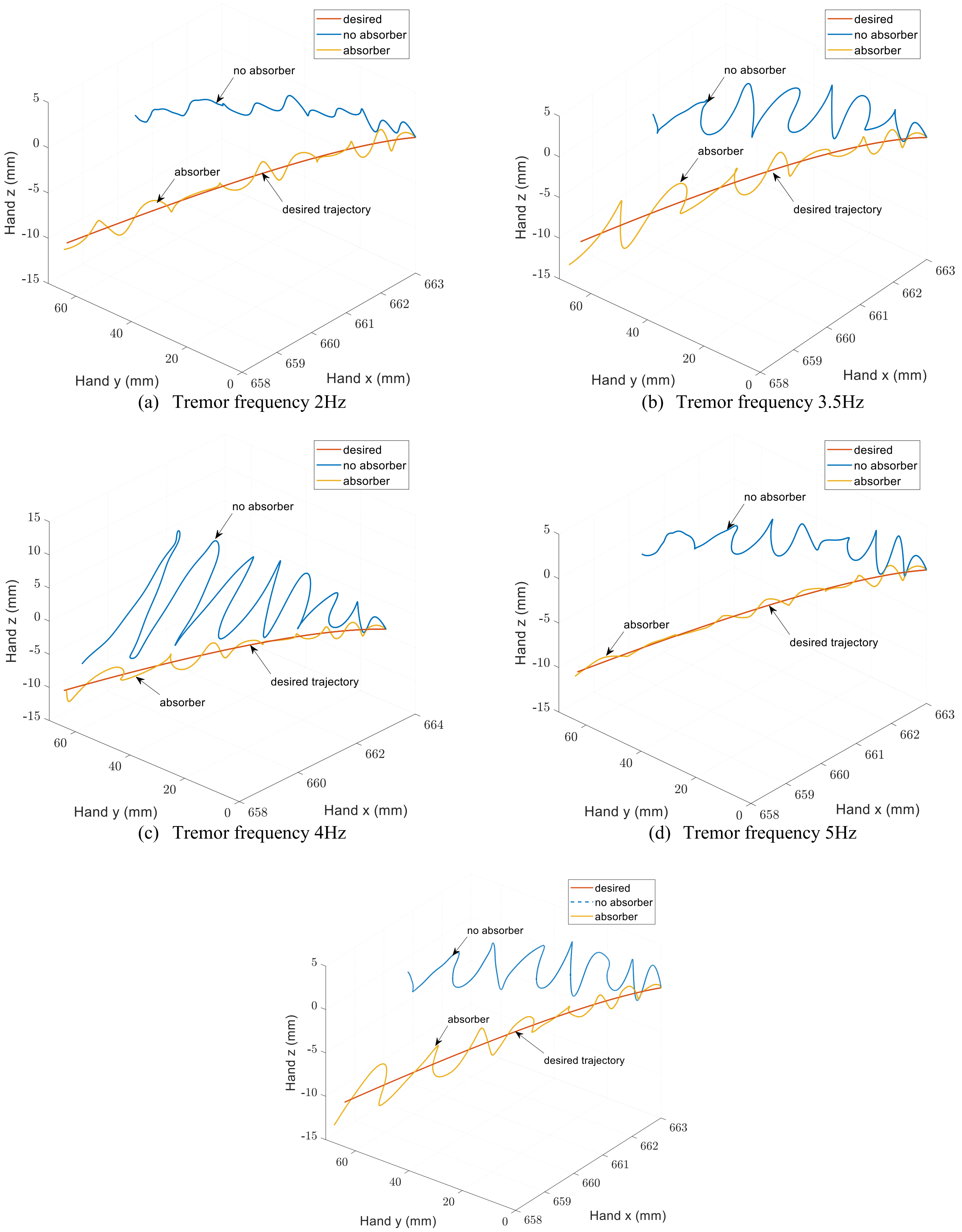


Figure 2. Generalized coordinates response to tremor frequency

3.2 Hand motion during voluntary movement

Parkinson disease produces a perturbation during the daily patient's activities. In order to quantify how the motion affected is, it was simulated the hand motion when a perturbation sinusoidal signal is applied. Figure 3 shows the 3D hand trajectory under perturbation signal with and without absorber. A perturbation signal was added to the required torque in each joint to produce the desired motion over time. It was simulated 4 perturbation frequencies 2, 3.5, 4 and 5Hz. The absorber was tuned to 3.5Hz for each case. The motion started on a specific position. Without absorber, the desired motion was not achieved and high oscillations were presented in each case. It was found higher oscillations for tremor frequency near to a natural frequency, Figure 3b,c,d. With the absorber implemented, the oscillation was significantly reduced during the motion and the final point of the trajectory could be reached in each case; however, small oscillation was still presented. Tremor produced by Parkinson is not composed of one signal, thus it was simulated the response with a perturbation composed by different sinusoidal signals with frequencies 2, 3.5 and 5Hz since they are within the range of Parkinson disease [19] [20]. Figure 3e shows the trajectory under perturbation composed by those signals. The perturbation was applied to the shoulder joint in the upper arm rotation axis. It can be seen that without absorber, there was a high oscillation amplitude during the trajectory and the final position was not reached. For the case with absorber implemented, the oscillation was reduced and the control over the motion improved significantly.



(a) Tremor frequency 2Hz

(b) Tremor frequency 3.5Hz

(c) Tremor frequency 4Hz

(d) Tremor frequency 5Hz

(e) Tremor frequency 2, 3.5 and 5 Hz

Figure 3. Hand trajectory during perturbation signal

4. DISCUSSION

Natural frequencies represent the dynamic characteristics of a system. The number of natural frequencies is equal to the number of degrees of freedom. In this sense, the addition of the vibration absorber adds a degree of freedom to the system and produces a new natural frequency, Figure 1. This new natural frequency depends on the absorber parameters. In general, natural frequencies increase in value as the stiffness of the system increases or they decrease as the mass increases. In this case, the relation between mass and stiffness of the absorber were established with a predominant value of mass in order to produce an absorption frequency of 3.5Hz which is near to the first natural frequency in the original system. The higher natural frequencies of the original system were not affected by the addition of the absorber, Figure 1. This is due to that they correspond to motion with high stiffness and the mass of the absorber, which is set as 5% of the upper arm, is not sufficient to change the characteristics in this frequency level.

At the absorption frequency 3.5Hz, the vibration absorber is effective and the coordinates amplitude show low values. The relative displacement of the absorber with respect to the forearm is high in comparison with the response of the other coordinates where they are minimum. At this point, the absorber produces a counter force to the perturbation signal in order to cancel it. This is the reason why the displacement must be high in order to produce a force sufficiently high at the spring.

The vibration absorber can only be tuned to a specific frequency and it is effective only in a narrow range around it. This range can be defined as absorption range and is limited by the natural frequencies around the absorption frequency. Near these peaks, the amplitude response highly increases and the absorber is not effective anymore. In this sense, for the simulation, the absorption frequency was tuned to 3.5Hz since this value is within the Parkinson disease range. However, it must be tuned according to the parameters of the patient, especially the experimental tremor frequency in order to maintain the absorption range effective. The absorption range also depends on the absorber mass. A higher absorber mass produces a higher absorption range. Nevertheless, it could impact to the patient comfort since it is required to have the lowest weight value. Thus, the patient can use the absorber for the daily activities.

There was a significant reduction of the oscillation during a desired trajectory with the vibration absorber and also the control over motion was improved, Figure 3. However, there is still small oscillations which could affect the daily activities of patients. Likewise, the effectiveness is not the same during different conditions of perturbation signals. The hand motion takes place in a 3D space; in this sense, there are multiple directions of motion each instant. Results show that a vibration absorber with one degree of freedom is not able to produce the counter force in every direction in despite of the vibration absorber is tuned to the tremor frequency as shown in Figure 3b where the tremor frequency is 3.5Hz. It would be required more than one vibration absorber or one with multiple degrees of freedom in order to compensate the three-dimensional behavior. It was also found that low excitation frequencies are the source of high oscillation amplitudes during motion since they produce an offset of the desired motion during more time each period. Furthermore, natural frequencies of the arm are mainly low frequencies which produces high vibrations amplitudes when the tremor is close to them. The vibration absorber is still able to reduce the tremor in spite of it is composed by different low frequencies 2…5Hz when it is tuned at 3.5Hz as shown in Figure 3e. This behavior simulates a case close to the real tremor produced by Parkinson and shows the potential of the vibration absorber as a solution if it is assisted by other mechanisms in order to compensate the three-dimensional behavior.

5. CONCLUSIONS

An analytical model of a dynamic vibration absorber attached to a human arm was developed in three dimensions. The tremor was simulated as a sinusoidal force and as a force composed by multiple frequencies within Parkinson range. The absorber was able to reduce the oscillation during a desired trajectory while its parameters are tuned to the tremor frequency even in low frequencies where the oscillation impacts highly to the desired motion. However, during a three-dimensional motion, it is not as effective as it is when the motion is produced in a plane. Since different rotation directions are involved, more than one absorber is required.

The attenuation percentage highly depends on the absorption range and the tremor frequencies The absorber is effective in a narrow range around the absorption frequency tuned. This range can increase as the absorber mass increase. However, it impacts to the patient's comfort and could result invasive. In this sense, the absorption parameters must be calculated as a balance between attenuation percentage within the Parkinson range and comfort with experimental data from patient.

Passive vibration absorber showed a potential solution for tremor attenuation. Its simple components and fabrication are significant advantages. However, it is limited to specific activities and a narrow tremor frequency range. Alternatives with a variable stiffness are explored in order to compensate this behavior and make it tunable for a higher absorption range.

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