Using a Dual Vibration Absorber to Suppress Rest Hand Tremor of Elderly

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Abstract—**Human tremor is a public health problem that can lead to social and physical deterioration. Parkinson disease (PD) is a slowly progressive degenerative disorder of the central nervous system. It is more significant in elderly patients. Its signs start to appear at the age of 59 years. Levodopa is the most commonly used medication to reduce tremor in PD patients, but has serious side effects. Vibration absorbers can be used as a mechanical treatment that can counter-act the involuntary tremor caused by difficulties to give certain commands to the muscles. The hand is modeled at the musculoskeletal level as a three degree-of-freedom (DOF) system in the horizontal plane. The vibration absorbers are designed to reduce the flexion angle at the shoulder, elbow and wrist joints when the muscles are operating at the resonance frequencies that belong to the range of resting tremor. Single and dual series absorbers are designed to satisfy the tuning conditions. The system's behavior is analyzed in the frequency and time domains. The suggested dual absorber is composed of a series combination between the elastic absorber and the viscous damper absorber. It is more efficient than a single absorber of the same total mass and causes 85.7–86.6%, 88.4–91.3% and 58.29–59.9% amplitude reduction at the shoulder, elbow and wrist joints, respectively.**

Keywords-Parkinson disease; elderly; tremor reduction; mechanical treatment; dual vibration absorber.

I. INTRODUCTION

Parkinson disease (PD) is a multi-system neurodegenerative disorder caused by a deficiency of neurotransmitter dopamine within the brain and affects the brain's control of the muscles. It leads to shaking (tremor), increased muscle tone (stiffness), slowed movements and balance problems. Parkinson tremor is usually a resting tremor characterized by adduction-abduction or flexion-extension motion with frequency 3–7 Hz [1]. PD incidence increases with aging. It is difficult to specify the exact number of young patients affected by PD, but we know that they are rarely affected by this illness. It is more significant in elderly patients and its average onset age is 59 years [2]. Initial symptoms may start early in life, but tremor progresses over time and becomes significant to a physician when the patient is elderly.

Dopaminergic drugs are medications which aim to temporarily restore correct dopamine level in the substantia nigra and striatum. This treatment reduces the motor symptoms and signs of PD, without, however, curing the disease or stopping its progression. Levodopa is the most effective dopaminergic medication for elderly patients which is converted in the brain into dopamine. The recommended drug dose increases with the increased symptom severity, but high doses can produce involuntary tremor and can lead to serious side effects. In addition, about 25% of PD patients can have a low quality of life since they do not respond to drugs or neurosurgery treatments [3][4].

Vibration absorbers can be used as a mechanical treatment to reduce the tremor of elderly Parkinson patients by supplying certain commands to muscles to counter-act the vibration. Hand's involuntary tremor is transmitted to the absorber, which causes the vibration of its proof mass. Mechanical oscillations are considered as the main source for the tremor, in which joints and muscle movements satisfy the laws of physics. Therefore, a dynamic model of the human hand can describe its response and can be used for the numerical testing of absorber's performance.

A method of biodynamic response has recently been used to describe the motion of human hand and solve problems related to tremor. Jackson et al. [5] modeled human upper limbs as two pivoted straight rods (the upper arm, and the forearm together with the hand) with concentrated mass at centroid of each segment. The hand was modeled in vertical plane during locomotion where flexion-extension planar motion at the joints was considered. The described model shows similar results to the available data on the movement of the upper limb during locomotion. Raikova [6] described the real anatomy of the muscle functions by modeling the human upper limb as a seven degree-of-freedom (DOF) system. The biomechanical model consists of the upper arm, forearm and palm modeled as rigid bodies connected by the shoulder joint (three-DOF spherical joint-connected to immobile trunk), elbow joint (two one-DOF pin joints) and wrist joint (two-DOF Hook's joint).

Hashemi et al. [7] designed a single DOF vibration absorber that is and attached to the forearm. It was able to reduce tremor amplitude numerically for the model hand and experimentally for the fabricated model. Igusa and Xu [8] studied the multiple mass dampers tuned within a frequency range. They found that it is more robust than the tuned mass damper with same the total mass. Gebai et al. [9] have designed a single dynamic vibration absorber (DVA) capable to suppress the steady state response of the hand system excited at its fundamental frequency. Moreover, they proposed a single DVA which was able to help elderly patients suffering from neurodegenerative disorder by reducing the homogenous as well as the steady state response of the involuntary tremor at the hand joints [10]. They have also suggested a dual parallel DVA to reduce the pathological tremor in the hands of Parkinson patients when excited at the dual harmonic resonance frequencies [11][12]. The study reveals that the dual DVA was more effective than the single DVA with the same total mass.

In this study, a new three-DOF hand system is used to describe the biodynamic response of the hand of a PD Patient. The system is operating at the first two natural frequencies due to the shoulder, elbow and wrist muscles activation. The dynamic model of the hand is used to study the performance of a dual DVA in suppressing the rest tremor of a PD patient. This absorber is formed from an elastic absorber connected in series to a viscous damper absorber; we will call it the dual series elastic-viscous damper (SEVD) absorber. This absorber is connected to the forearm of the hand and compared to the single TVA of the same total mass. Both absorbers are designed to satisfy the tuning condition. The equation of motion for the system is derived using the non-Lagrangian formulation and solved using system's transfer function. The flexion angle at the hand joints are shown in the frequency and time domains.

The paper is organized as follows: Section 2 presents the dynamic structure of the model hand system, its sized segments and the derived equations of motion. Section 3 describes the designing steps for tuning the absorbers. Section 4 presents the frequency and time domain response at hand's proximal joints. Section 5 provides a comparison with the previous studies done. Section 6 includes the conclusions and recommendation for future work.

II. BIODYNAMIC HAND MODELING

The human hand shown in Fig. 1 is modeled in the horizontal plane as a three-DOF system reflecting the biodynamic response of a Parkinson Patient. Most researchers agreed on modeling the bones and corresponding soft tissues as rigid bodies connected by frictionless joints with fixed axes or centers of rotation [13]. So, the hand segments are described as rigid bodies where the upper arm and forearm (ulna and radius) are modeled as truncated cones and the palm as rectangular plates to specify their volume (*V*). The three segments are connected by one-DOF frictionless kinematic pairs to permit the flexion-extension planar motion at the proximal joints. The upper arm is pinned by the shoulder joint, which is fixed to the trunk in order to reflect the resting condition of the hand. The length (*l*), position of centroid from proximal joints ($\bar{r}$) and density (*D*) used for each segment are provided experimentally by Drillis et al. [14] and shown in Table 1. Then, the mass (*m*) and the mass moment (*I*) of each sized segment are calculated using the following equation:

$$m = D.V, \quad \bar{r} = \frac{\int r^2 dm}{\int dm} \quad and \quad I = \int \bar{r}^2 dm \qquad (1)$$

and the obtained results are listed in Table 2. The four muscles modeled to produce a movement are: the single joint shoulder, elbow and wrist joint muscles and the Biceps brachii muscle. Theoretically, muscles can be assumed to be regulated independently [7]. The modeled stiffness and damping coefficients of the considered muscles are provided in Table 3. Damping and stiffness coefficients of the muscles are assumed to be linearly proportional [15]. The active inputs can be described as muscular activity [16] and can be considered as sinusoidal function(s) [17].

Equation of motion for the hand system with a single DVA attached to the forearm is provided by Gebai et al. [9][12] and derived using the non-Lagrangian formulation. A similar strategy is used for the hand controlled by the dual SEVD DVA, where the general equation of motion is:

$$[M]\{\ddot{\theta}\} + [C]\{\dot{\theta}\} + [K]\{\theta\} = \{f\} \qquad (2)$$

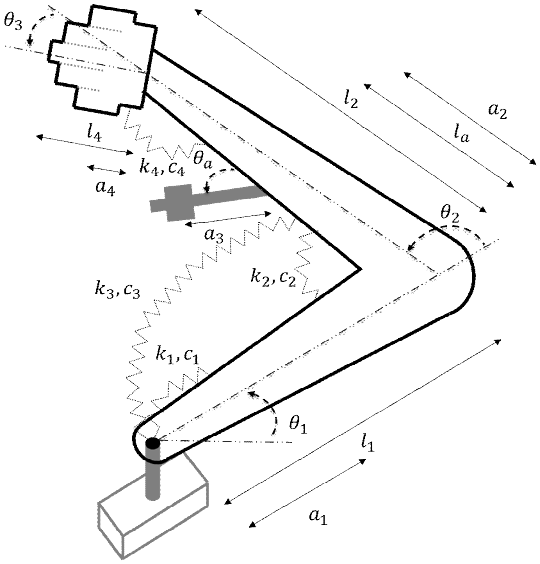


Figure 1. Dynamic model of human hand at the musculoskeletal level.

TABLE I. COLLECTED HAND ARM PARAMETERS [14]

Right Hand	Length (cm)		Centroid (m)		Density (kg/m^3)	
Upper arm	l_1	36.4	a_1	0.427 l_1	D_1	2.070
Forearm	l_2	29.9	a_2	0.417 l_2	D_2	1.160
Palm	l_4	20.3	a_4	0.361 l_4	D_4	0.540

TABLE II. CALCULATED HAND ARM PARAMETERS

Right Hand	Upper arm		Forearm		Palm	
Mass (kg)	m_1	2.070	m_2	1.160	m_4	0.540
Inertia $(kg.m^2/rd)$	I_1	0.0228	I_2	0.0082	I_4	0.0012

TABLE III. DESIGNED PARAMETERS OF JOINT'S MUSCLES

Muscle	Shoulder	Elbow	Biceps	Wrist
$k\,(N.m/rd)$	180	70	40	10
$c\,(N.m.s/rd)$	0.002 k_1	0.002 k_2	0.002 k_3	0.002 k_4

$$\theta = \{\theta_1 \quad \theta_2 \quad \theta_2 \quad \theta_{a_1} \quad \theta_{a_2}\}^T \tag{3}$$

Where,
$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & M_{15} \\ M_{21} & M_{22} & M_{23} & M_{24} & M_{25} \\ M_{31} & M_{32} & M_{33} & M_{34} & M_{35} \\ M_{41} & M_{42} & M_{43} & M_{44} & M_{45} \\ M_{51} & M_{52} & M_{53} & M_{54} & M_{55} \end{bmatrix} \tag{4}$$

$$M_{11} = \left(I_1 + m_1 a_1^2\right) + \left(I_2 + m_2 a_2^2\right) + m_2 l_1^2 + m_4\left(l_1^2 + (l_2 + a_4)^2\right) + m_{a_1}\left(l_1^2 + (l_a + a_3)^2\right) + m_{a_2}\left(l_1^2 + (l_a + a_3 + a_5)^2\right)$$

$$M_{12} = \left(I_2 + m_2 a_2^2\right) + m_4 (l_2 + a_4)^2 + m_{a_1}\left(l_a^2 + a_3^2 + 2 l_a a_3\right) + m_{a_2}(l_a + a_3 + a_5)^2, \quad M_{13} = m_4\left(a_4^2 + l_2 a_4\right)$$

$$M_{14} = m_{a_1}\left(a_3^2 + 2 l_a a_3\right) + m_{a_2}(l_a + a_3 + a_5)(a_3 + a_5)$$

$$M_{15} = m_{a_2}\left(l_a a_5 + a_3 a_5 + a_5^2\right),\ M_{21} = M_{12}\ ,\ M_{22} = M_{12}$$

$$M_{23} = M_{13},\ M_{24} = M_{14},\ M_{25} = M_{15},\ M_{31} = M_{13}$$

$$M_{32} = M_{23},\ M_{33} = I_4 + m_4 a_4^2,\ M_{34} = 0,\ M_{35} = 0$$

$$M_{41} = M_{14},\ M_{42} = M_{24},\ M_{43} = 0$$

$$M_{44} = m_{a_1} a_3^2 + m_{a_2}(a_3 + a_5)^2$$

$$M_{45} = m_{a_2}\left(a_3 a_5 + a_5^2\right),\ M_{51} = M_{15},\ M_{52} = M_{25}$$

$$M_{53} = 0, M_{54} = M_{45},\ M_{55} = m_{a_2} a_5^2$$

$$K = \begin{bmatrix} k_1 + k_3 & k_3 & 0 & 0 & 0 \\ k_3 & k_2 + k_3 & 0 & 0 & 0 \\ 0 & 0 & k_4 & 0 & 0 \\ 0 & 0 & 0 & k_a & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

$$C = \begin{bmatrix} c_1 + c_3 & c_3 & 0 & 0 & 0 \\ c_3 & c_2 + c_3 & 0 & 0 & 0 \\ 0 & 0 & c_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & c_a \end{bmatrix} \tag{6}$$

l_1, l_2, l_4 are the length of the upper arm, forearm and palm. a_1, a_2, a_4 are the distances between the centroid of the upper arm, forearm and palm to their corresponding proximal joint. a_3, a_5 are the distances from the joint of the elastic absorber and viscous damper absorber to its corresponding proof mass. m_1, m_2, m_4 are the masses of the upper arm, forearm and the palm. m_{a_1}, m_{a_2} are the masses of viscous damper absorber and the elastic absorber of the SEVD absorber. I_1, I_2, I_4 are the mass moments of inertia of the upper arm, forearm and palm. M, C, K are the mass and the damping and stiffness coefficient matrices of the system. $\theta_1, \theta_2, \theta_3, \theta_{a_1}, \theta_{a_2}$ are the flexion angles at the shoulder, elbow and wrist joints.. k_1, k_2, k_3, k_4 and c_1, c_2, c_3, c_4 are the stiffness and damping coefficient of the shoulder, elbow, biceps brachii and wrist muscles. k_a, c_a are the stiffness and damping coefficients for beams of the elastic absorber and viscous damper absorber.

$$f = \{f_1 \quad f_2 \quad f_3 \quad 0 \quad 0\}^T \tag{7}$$

$$\begin{gathered} f_k = F_{k_1} \cos(\omega_1 t) + F_{k_2} \cos(\omega_2 t),\ k = \{1,2,3\} \\ F_{k_1} = F_{k_2} = 0.5\ N.m\ and\ \omega_m = \omega_{n_m},\ m = \{1,2\} \end{gathered} \tag{8}$$

f_1, f_2, f_3 are the input moments of the hand due to the shoulder, elbow and wrist joint muscles. F is the magnitude of the input moment and ω is the driving frequency

The natural frequencies obtained using primary system's characteristic equations are:

$$\omega_{n_1} = 3.609 Hz, \omega_{n_2} = 5.348 Hz\ and\ \omega_{n_3} = 12.682 Hz \tag{9}$$

III. TUNED ABSORBER'S DESIGN

Two tuned vibration absorbers (TVAs) are designed to be attached separately to the forearm at the same position. The two absorbers have the same total mass (251.2 *g*) and the same total length (8.5 *cm*).

As demonstrated by Gebai et al. [9], as the absorber's joint approaches the position of the wrist joint, more reduction can be achieved at the palm. Taking into consideration the maximum designed length of both absorbers, the absorbers will be tested at a position l_a which is 8.5 *cm* away from the wrist joint ($l_a = l_2 - 8.5$ *cm*). Absorbers dimensions can be chosen depending on the Dunkerley's semi-empirical formulation [18] as done by Gebai et al. [9][10][12].

The single DVA is modeled as a stainless steel alloy cantilevered beam with a copper mass attached along its length. Its configuration, dimensions and equivalent linear model are shown in Fig. 2. No damper is attached to this absorber, a very little damping can be provided by the beam's material. The stiffness (k_a) and damping (c_a) coefficients are assumed to be proportional by a constant [7], such that $c_a = 0.005 k_a$. This elastic absorber is tuned to the second natural (9) frequency of the primary system to reduce the resting tremor at this frequency:

$$\omega_a = \omega_2 \text{ and } \omega_2 = \omega_{n_2} \tag{10}$$

The dual SEVD vibration absorber is designed as an elastic absorber attached in series to a viscous damper absorber. The elastic absorber is formed from a thin cantilevered beam providing its stiffness (k_a) with a zero damping coefficient and a copper mass attached along its length. It is modeled at the tuning condition of (10). At the end of the elastic absorber's beam, a purely high damping material having a zero stiffness coefficient is modeled as beam's material. A copper mass is attached along the beam's end. The appropriate dimensions and equivalent linear model of this absorber are shown in Fig. 3. The damping coefficient (c_a) in the viscous damper absorber of the SEVD absorber is designed to satisfy the tuning condition of the fundamental frequency (9) of the primary system:

$$\omega_a = \omega_1 \text{ and } \omega_1 = \omega_{n_1} \tag{11}$$

The response of the system is needed for tuning the absorber at the chosen responses. The absorbers are tuned by satisfying the root in the real part (A_{1ik}) in the numerator of the corresponding response. The response is obtained using the transfer function (H) of this dynamically coupled system to represent the frequency domain response (Θ) using the Receptance transfer function (α) as follows:

$$H(\omega)=\left\{\left(-\omega^2[M]+[K]\right)+j\omega[C]\right\}^{-1} \tag{12}$$

$$H(\omega)=\{\alpha_1 \quad \alpha_2 \quad \ldots \quad \alpha_k\} \tag{13}$$

$$\alpha_k = \frac{A_{1_{ik}} + B_{1_{ik}}}{A_2 + jB_2} \tag{14}$$

$$\Theta_{ik} = \sum_{k=1}^{2}\sum_{m=1}^{2} |\alpha_k| F_{k_m} \tag{15}$$

i, k are the i-*th* row and k-*th* column for the n×n transfer function of the n-DOF system.

The single DVA and the elastic and viscous damper absorbers of the dual SEVD DVA are tuned to the wrist joint's response (Θ_3) due to the elbow muscle activation (F_2):

$$A_{1_{32}} = 0 \tag{16}$$

Using MATLAB, the stiffness and damping coefficients of each absorber can be determined as shown in Table 4, in addition to the absorbers mass.

All absorbers parameters are evaluated satisfying the tuning condition. Then, they are ready to be attached to the forearm to test their performance in tremor suppression.

IV. SIMULATED RESULTS

A. *Frequency Domain*

The frequency domain response of (15) is represented by graphs showing the behavior at the shoulder, elbow and wrist joints over a range of driving frequencies.

Maximum flexion angles are shown in Fig. 4 at the resonance frequencies of the uncontrolled hand system and the hand controlled by the single TVA and the dual series TVA. Tuning is well shown at the second natural frequency (tuning frequency) of the uncontrolled system at hand joints due to the single TVA. It shows high reduction in the tremor amplitude at the resonance frequencies of the proximal joint's responses and a good reduction at the other frequencies. The dual SEVD TVA shows qualitatively similar behavior to the single TVA with much damped tremor's amplitude. However, the wrist joint's response is subjected to tremor amplification at 7.623 *Hz* because of the high shifting to the right in the highest resonance frequency of the primary system due to its damper. The dual SEVD TVA is a very effective absorber at system's resonance frequencies and most of the other frequencies. It can cause a very high reduction in the resting tremor's amplitude in the hand of PD patients.

The resonance frequencies of the controlled system are derived using the characteristic equation, for the hand contr-

TABLE IV. TUNED ABSORBER'S PARAMETERS

Parameters	Single TVA	Dual series TVA	
		Elastic	Viscous Damper
$k_a\,(N.m/rd)$	0.2181	0.3211	0.0000
$c_a\,(N.m.s/rd)$	0.0011	0.0000	0.0016
$m_a\,(kg)$	251.2	125.6	125.6

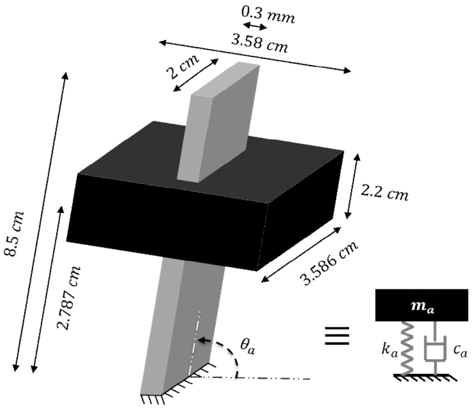


Figure 2. Single dynamic absorber.

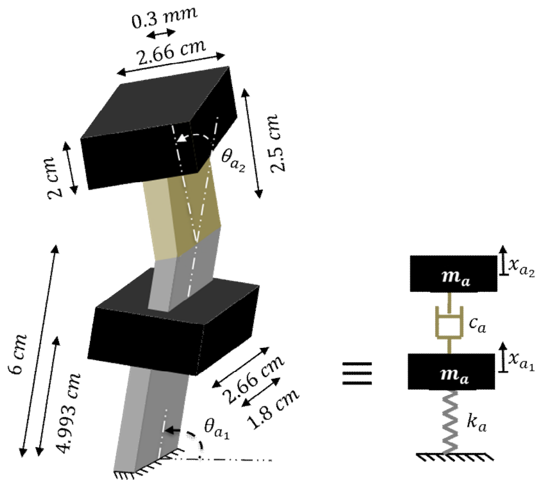
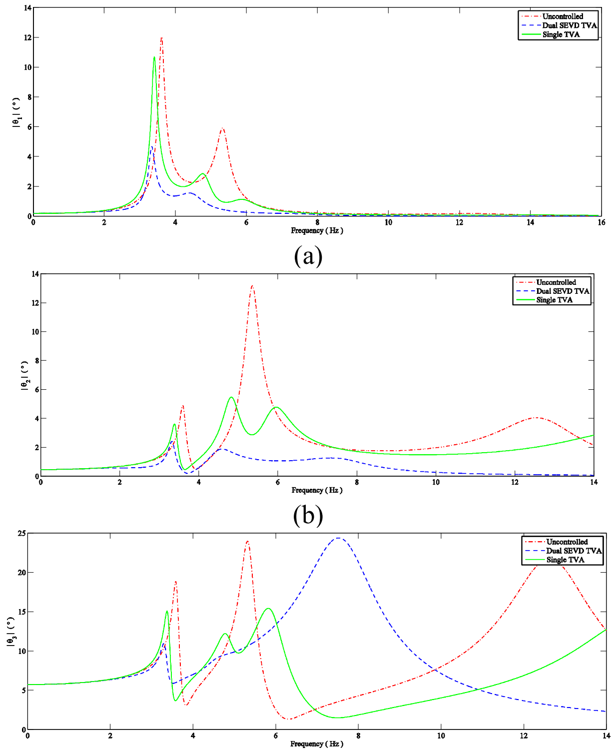


Figure 3. Dual series elastic-viscous damper absorber.



(a)

(b)

(c)

Figure 4. Frequency domain response at: shoulder (a), elbow (b) and wrist joints (c).

olled by:

- Single TVA:

$$\omega_{n_1}=3.263Hz,\omega_{n_2}=3.921Hz,\omega_{n_3}=5.383Hz,\ and\ \omega_{n_4}=13.915Hz \tag{17}$$

- Dual SEVD TVA:

$$\omega_{n_1}=0Hz,\omega_{n_2}=2.454Hz,\omega_{n_3}=3.330Hz,\ \omega_{n_4}=4.496H\ and\ \omega_{n_5}=7.623Hz \tag{18}$$

B. *Time Domain*

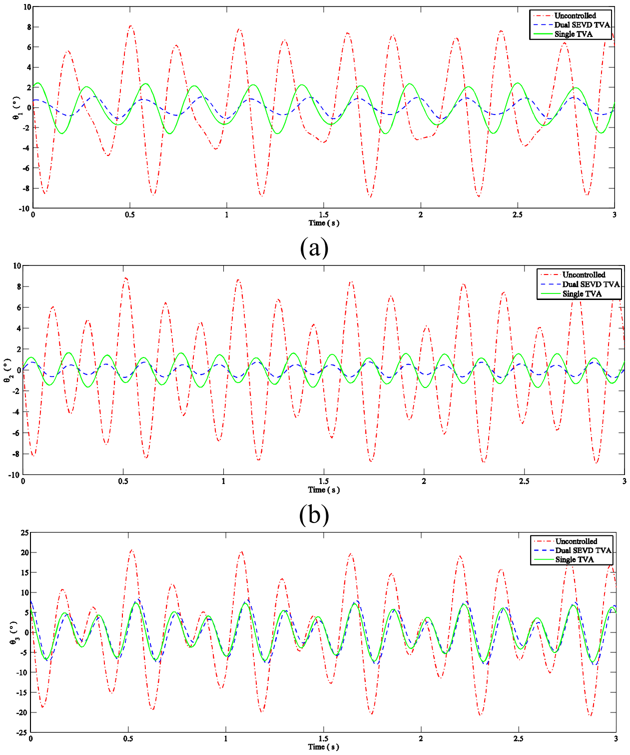
The time domain response is used to analyze the behavior of the system at the specified excitation frequencies in terms of joints angular displacement.

The time domain response is determined using (15) and derived as follows:

$$\theta_{ik}=\Theta_{ik}e^{j(\omega_m t-\varphi)}$$

$$\left|\Theta_{ik}\right|=F_{k_m}\sqrt{\frac{A_{1_{ik}}^2+B_{1_{ik}}^2}{A_2^2+B_2^2}}\quad and\quad \varphi=\tan^{-1}\left(\frac{B_{1_{ik}}}{A_{1_{ik}}}\right) \tag{19}$$

φ is the phase angle resulting from the damping coefficient. In Fig. 5a-c, the time domain response (19) at the shoulder, elbow and wrist joints responses of the hand excited at the first two resonance frequencies is shown due to the single joint muscles activation (8). The single TVA and dual SEVD TVA causes high reduction in tremor's flexion angle.



(a)

(b)

(c)

Figure 5. Time domain response at: shoulder, elbow and wrist joints.

The percentage of reduction in the tremor's amplitude between the uncontrolled ($\Theta_{\text{unc.}}$) and controlled ($\Theta_{\text{c.}}$) systems in the time domain is calculated using this equation:

$$\%\text{ Reduction}=\frac{\Theta_{\text{unc.}}-\Theta_{\text{c.}}}{\Theta_{\text{unc.}}}\times 100 \tag{20}$$

The percentage of reduction at the shoulder, elbow and wrist joints due to attaching both absorbers to the forearm is summarized in Table 5. It is shown that the dual SEVD TVA is an important absorber to be considered. It causes 85.7–86.6%, 88.4–91.3% and 58.29–59.9% reduction in the involuntary tremor's amplitude transmitted to the shoulder, elbow and wrist joints due to the activated muscles.

TABLE V. PERCENTAGE REDUCTION IN TREMOR'S AMPLITUDE

% Reduction	**Shoulder joint**	**Elbow joint**	**Wrist joint**
Single TVA	61.4–69.9	72.5–81.2	54.4–64.3
Dual TVA	85.7–86.6	88.4–91.3	58.29–59.9

The SEVD and single TVAs have the same total mass and length and are tested at the same design conditions. However, the DEVD dual TVA is more effective than the single TVA in reducing the flexion angular displacements.

V. DISCUSSION

Several studies [7][9]–[12][19] have been done to mechanically reduce the involuntary tremor in hands of PD patients. The main challenges are referred to the dynamic hand modeling that can best reflect Parkinsonism and that takes into account the tremor displacement at most allowed angular displacements. In addition, developments in the absorbers design are of high importance. Changing in the configuration of the passive absorber aiming to increase its performance attracted many researchers [8][12].

In a previous study, Hashemi *et al.* [7] have modeled the human hand as two uniform rigid rods to describe the flexion-extension motion of the elbow and shoulder joints. The system was excited due to the elbow muscle activation driven at a single frequency. In our study, the hand system is modified considering an additional DOF to describe the angular displacement at the wrist joint of a system actuated with several muscles. In [7], a one-DOF absorber was attached to the forearm but it was not designed at the tuning condition. The resonance frequency was 2.24 *Hz* while the absorber's natural frequency was 2.755 *Hz*. So, the absorber was not designed to operate at its maximum performance.

Rahnavard et al. [19] used the same hand model designed by Hashemi et al. [7]. However, the single DOF absorber's parameters were designed using the H_2 optimization method. The proposed system leads to a 20 *cm* long absorber providing high percentage of reduction at the shoulder and elbow joints. In our study, very effective single and dual TVAs are designed with an optimum length of 8.5 *cm* at all the hand joints.

VI. CONCLUSION

The three-DOF dynamic model of the human hand is designed to reflect the biodynamic response at the proximal joints of an elderly PD patient. The model describes the flexion-extension motion for the system operating at resting tremor's resonance frequencies in the horizontal plane. Two absorbers having the same total mass and length are tuned to reduce the involuntary tremor transmitted to the hand joints due to the single joint muscles activation. Both absorbers are tested when attached at the same position on the forearm. The one-DOF absorber causes 61.4–69.9%, 72.5–81.2% and 54.4–64.3% reduction in tremor amplitude at the shoulder, elbow and wrist joints in the time domain. A very effective two-DOF SEVD TVA is used for tremor reduction. The SEVD is formed from a series combination between the elastic absorber and the viscous damper absorber. It causes 85.7–86.6%, 88.4–91.3% and 58.29–59.9% reduction at the shoulder, elbow and wrist joints.

As future work, the molded hand system can be sized depending on the hand dimensions of a real Parkinson patient. Then, the suggested passive controllers can be manufactured and tested when attached to the forearm of the real hand. In addition, a comparison can be done between the numerical and experimental studies.

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