



Tremor Control in the Arm of a Parkinson's Disease Patient Using Piezoelectric Beam Meta-structure

Braion B. de Moura¹, Marcela R. Machado¹

¹ Department of Mechanical Engineering, University of Brasília, 70910-900, Brasília, Brazil.

Abstract: Some physiological conditions or neurodegenerative diseases, such as Parkinson's disease, often cause tremors in the wearer's limbs. This tremor is almost always associated with social discomfort and difficulty performing some movements. This work aims to establish an analysis of the efficiency of vibration control in an arm of a patient with Parkinson's disease. However, the operating logic of the control used is extracted from the technology reported in the patent document Moura and Machado (2022). This technology is capable of promoting programmable attenuation and band gaps using a piezoelectric beam meta-structure connected to a resonant shunt circuit. In resume, the present work intends to use this technology to compare and elucidate the best amount of coupling of shunt circuits to be able to attenuate a vibration mode of the arm, emphasizing a possible control saturation limit.

Keywords: Tremor, Parkinson Disease, Piezoelectric, Meta-structure

INTRODUCTION

Vibration control in human limbs is an increasingly present need in individuals who have neurodegenerative diseases such as Parkinson's Disease, White Hand Syndrome, Essential Tremor, Induced Tremor and others (Chou, 2004). Generally, these diseases have a series of unpleasant symptoms, but one of the most prominent is tremors in the upper limbs, occurring more frequently in the individual's fingers, hands and arms.

In the context of these diseases, tremors are defined by repetitive and involuntary oscillations in the limbs, and may occur, in a lasting way, in postural conditions (limb in a resting or static position), kinetic (limb in movement) or both (Crawford and Zirmmerman, 2018). In addition, tremors can also be classified by frequency (high, intermediate and low) and amplitude of oscillations (coarse, medium and fine).

Some alternatives to treat these neurodegenerative diseases or to control the corresponding tremors are already being explored through drugs, surgery, electrical stimulation, light therapy, transcranial magnetic stimulation, orthoses and vibration attenuating devices. However, each alternative may present negative or impeding points, varying from individual to individual (Diaz and Louis, 2020). Thus, when taking into account the possibility of drug allergy, the degree of invasion of the treatment and the efficiency of the treatment, it is understood that the vibration attenuating devices stand out from the others in terms of combating tremors in the limbs (Fromme et al., 2019).

In this context of attenuating devices, some patents such as Prochazka et al. (1995), Cohen et al. (2001) and Robert and Tiffany (2018) address technologies based on gyroscopes and electro-stimulation to promote attenuation of tremors in the limbs of individuals with Parkinson's disease. Other patents such as Koller et al. (2005) and Siores and Swallow (2008) also presents devices to attenuate vibrations in human limbs, but these devices are based on the use of piezoelectric materials that convert mechanical energy (tremor) into electrical energy (electric field).

In the literature, Swallow and Siores (2009) have shown that the use of piezoelectric materials associated with a specific electrical supply can attenuate vibrations in a hand of a patient with Parkinson's disease. In Kazi and Muza (2014), something similar is demonstrated, but the piezoelectric materials are arranged in a glove-shaped device. Subsequently, Lekshmi and Ramachandran (2019) demonstrated that the feeding of piezoelectric materials associated with a Proportional-Integral-Derivative (PID) controller can optimize the vibration control of patients with Parkinson's disease.

As explained above, some patents and works have addressed the use of piezoelectric power to control tremors in human limbs, since the justification for this type of control is not as invasive as in the case of mechanical orthotics controls that promote increased mass and damping in the limb (Kazi and Muza, 2014). However, recently, patent document Moura and Machado (2022), a technology was reported capable of promoting vibration control even better than other existing technologies, since it can attenuate or stop limb tremor in one or several frequency bands at the same time, without the need for external electrical energy. The operating logic of this technology is based on the use of intelligent metamaterials formed by arrangements of piezoelectric materials coupled periodically along the member, where each piezoelectric is connected to a resistive-inductive circuit in series, known as a resonant shunt circuit.

In this perspective, the objective of this work is to demonstrate the effect of vibration control of the technology reported in the patent document Moura and Machado (2022), emphasizing the effect of attenuation and band gap generation resulting from the addition of meta-material in an arm in the postural condition with tremor due to Parkinson's disease. As the technology is wearable, we intend to explore the vibration effect that the device can promote when it is attached to

the hand region, from hand to elbow and from hand to shoulder. For this, a bio-mechanical model was created based on the dimensions and properties of a real human arm and later implemented with the Spectral Elements Method.

NUMERICAL MODELING OF THE DEVICE

Numerical modeling of the arm was developed based on the model by Gebai et al. (2016) and Hosseini et al. (2021), however, three Euler Bernoulli beam elements were used to represent the parts of the human arm related to the hand, forearm and upper arm, as shown in Figure 1. All properties were chosen in order to express the first natural frequencies close to that of a real arm with Parkinson's disease tremor.

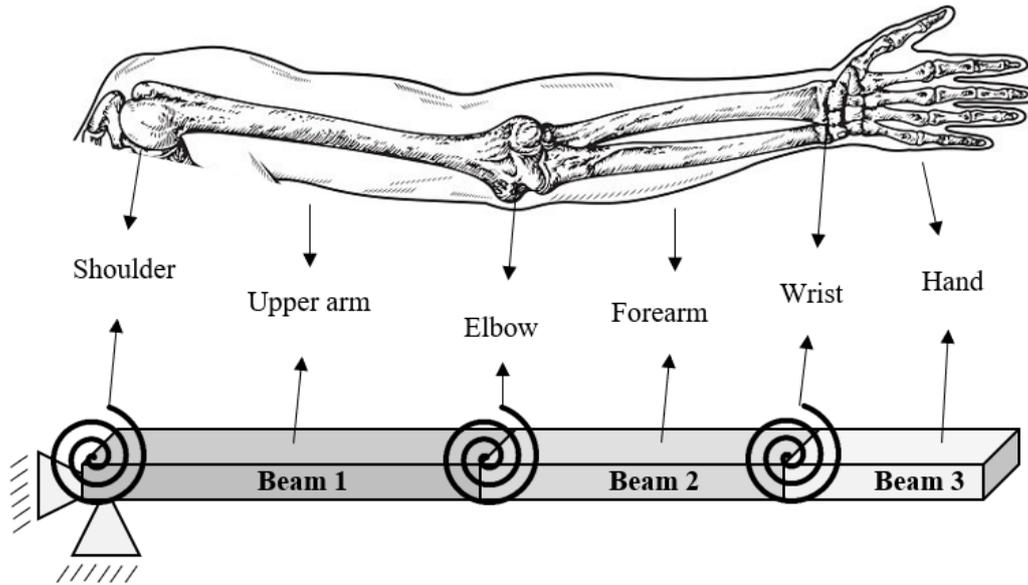


Figure 1 – Relation of the bio-mechanical model with a real human arm.

The model represented in Fig. 1 presents the extremity, referring to the shoulder, in a boundary condition supported in the axial displacement directions u and transversal displacement w . The dynamic properties arising from the wrist, elbow and shoulder joints were implemented in the corresponding degrees of freedom, by adding stiffness of 10, 150 and 170 $N.m/rd$, respectively. The other dimensions and properties of the model are reported in Tab. 1.

Table 1 – Bio-mechanical model properties.

| Properties | BEAM 1 | BEAM 2 | BEAM 3 |
|---------------------------|--------|--------|--------|
| Elastic Modulus (GPa) | 2 | 2 | 2 |
| Density (kg/m^3) | 1112.6 | 1108.6 | 1088 |
| Length (m) | 0.204 | 0.306 | 0.357 |
| Thickness (m) | 0.0022 | 0.0024 | 0.003 |
| Width (m) | 0.07 | 0.04 | 0.06 |

In the model of this work, 17 piezoelectric elements were coupled throughout the arm, and for this it was necessary to divide the entire structure into 34 elements, resulting in 4 piezoelectric elements in the hand, 6 in the forearm and 7 in the upper arm. In this distribution, each element is arranged periodically, fixed to a length of 25.5 mm .

Spectral Element of the Device

The Spectral Element Method (SEM) is used to implement the model, given its low need for the discretization to represent an element. Each element can be represented by two nodes, where each node has 3 GDL, axial u , transverse w and rotational θ displacement, as shown in Fig 2(a). In turn, the model is constructed by two distinct elements: the beam element (**B**) and the beam element with coupled piezoelectric layer (**BPS**). In the BPS element there is a resistive-inductive shunt circuit (Antonou circuit, shown in Fig. 2(b)) that determines the frequency to be attenuated.

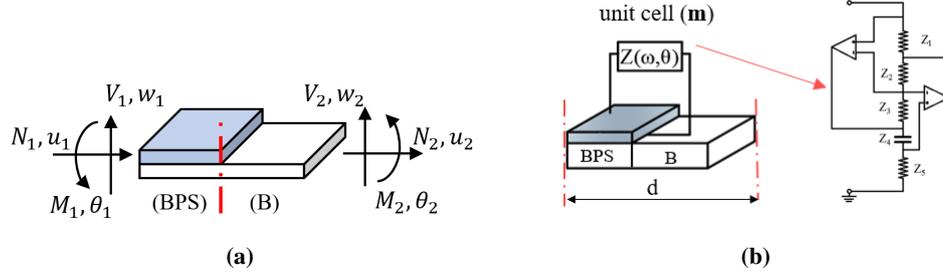


Figure 2 – Elementary representation: a) Free body diagram; b) Connection of the resonant shunt circuit.

In SEM, when relating the forces with the nodal displacements, it is possible to obtain a spectral rigidity matrix that represents the vibration dynamics of the element (Lee, 2009). Therefore, for this model, six different spectral stiffness matrices are considered: $\mathbf{S}_{B1}(\omega)$, $\mathbf{S}_{B2}(\omega)$ and $\mathbf{S}_{B3}(\omega)$ for beam 1, 2 and 3 in **B** setting, in that order, and $\mathbf{S}_{BPS1}(\omega)$, $\mathbf{S}_{BPS2}(\omega)$ and $\mathbf{S}_{BPS3}(\omega)$ for beams 1, 2 and 3 in **BPS** setting, respectively. The methodology to arrive at the dynamic stiffness matrix of both **B** and **BPS** configurations can be found in the work of Moura et al. (2022).

In the **BPS** element, in addition to the normal coupling relationship between the beam and the piezoelectric elements, there is also the connection of the resonant shunt circuit through the following relationship,

$$[\mathbf{S}_{BP}(\omega) + \omega_n^2 \mathbf{S}_{SH}^2(\omega) \left(\frac{1}{i\omega_n + 1/Z_{EL}} \right)] \mathbf{d}(\omega) = \mathbf{f}(\omega) \quad (1)$$

where $\mathbf{S}_{BP}(\omega)$ and $\mathbf{S}_{SH}(\omega)$ are the dynamic stiffness matrix of beam with piezoelectric and resonant shunt circuit, respectively. $\mathbf{d}(\omega)$ and $\mathbf{f}(\omega)$ are the nodal displacements and forces acting on the element, in this order. The Z_{EL} is the electrical impedance associated with each shunt circuit, where in this series resistive-inductive circuit it has the following form,

$$Z_{EL} = \frac{R + i\omega L}{1 - \omega^2 LC_p^T + i\omega RC_p^T} \quad (2)$$

where R is the resistor, L is the inductor and C_p^T is the capacitance of the piezoelectric.

RESULTS

In this analysis, it is considered that 17 piezoelectrics are coupled periodically along the human arm model, and that it is excited in the same frequency range as Parkinson's disease, $\omega_1 \cong 3$, $\omega_2 \cong 5$ and $\omega_3 \cong 12$ Hz. The resonant shunt circuits used are tuned to a frequency of 5 Hz. For the saturation comparison, three arrangements are considered: resonant shunt circuits connected only in the hand region (Fig. 3(a)); resonant shunt circuits connected from the hand to the elbow (Fig. 3(b)); and resonant shunt circuits connected from the hand to the shoulder region (Fig. 3(c)).

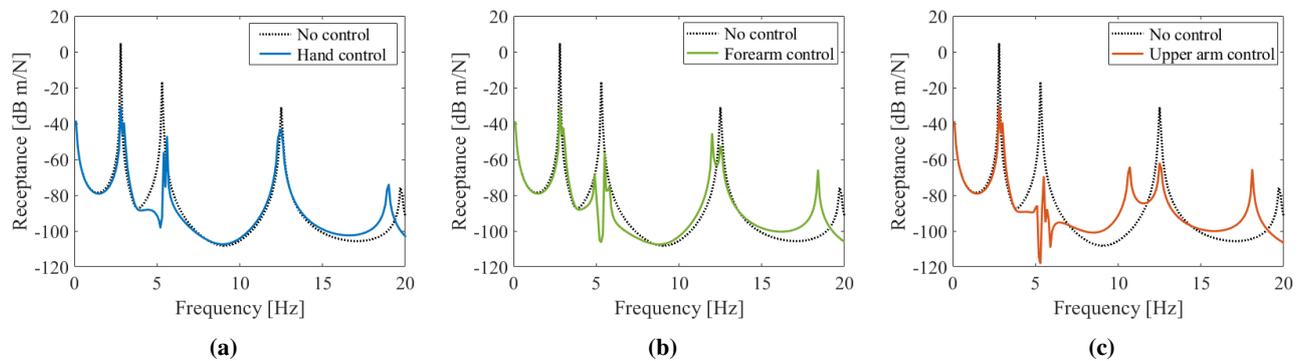


Figure 3 – Magnitude of the bio-mechanical model comparing vibration control applied only to: a) Hand; b) Forearm; c) Upper arm.

Analyzing the vibration controls in Fig. 3, it can be seen that the attenuation happens differently for the three configurations. Looking at Fig. 3(a) a small attenuation can be observed in the first and third modes of vibration, but only in the second mode, located in the tuning frequency of the shunt circuit, is a large attenuation noticeable. In Fig. 3(b), this attenuation is even greater in the second mode, appearing as a vibration stop (band gap) with a width of approximately 2 Hz. For the configuration of Fig. 3(c), in addition to the band gap in the second mode, it can be seen that the third mode suffered a greater attenuation than in the other configurations, presenting an attenuation effect similar to that of a vibration absorbed spring-mass.

CONCLUSION

In this paper, it is demonstrated that the technology reported in the patent document by Moura and Machado (2022) presents different vibration control efficiencies for tremors in a human arm with tremors from Parkinson's disease. The control configurations in the hand region, in the hand to the elbow region and in the hand to the shoulder region present satisfactory attenuation effects, it being clear that the configuration with more shunt circuits presents greater attenuation. However, as the purpose of the circuit programming was to control only the second mode of vibration, it is clear that the control from the hand to the elbow would already be efficient. Furthermore, this paper demonstrates a bio-mechanical model capable of representing the dynamic behavior of a human arm.

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