25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0015
DESIGN AND EXPERIMENTAL ANALYSIS OF A TUNED ELECTROMAGNETIC VIBRATION ABSORBER WITH ENERGY HARVESTING FOR LINEAR FIELD

Rafael de Carvalho Puglisi
Agenor de Toledo Fleury
Escola Politécnica da USP
rfpuglisi@usp.br; agenorfleury@usp.br

Abstract. *In engineering, energy transfer is revealed as an undesirable or desirable vibrational phenomenon. In mechanical systems, dynamic control to mitigate undesirable vibrations is accomplished through several techniques, among the most usual, the tunable mass damper (TMD). In electrical systems, ambient vibrations may be desirable and converted into useful electrical energy. In order to combine these phenomena and reduce operating costs, it is necessary to design robust tunable devices capable of operating efficiently over a wide frequency band. This work aims to design and experimentally analyze a tunable (semi-active) electromagnetic vibration absorber with energy harvesting (TEMVAEH) through the deliberate introduction of non-linearities. TEMVAEH consists of a non-linear mass-spring-damper system with a central oscillating magnet oriented under magnetic repulsive forces and a coil installed. Analytical methods and numerical simulations are developed to analyze the vibrational behavior of the system when induced by harmonic based excitation. The electromagnetic transduction factor that couples the mechanical to electrical system is identified. It is shown that the variation of the distance between magnets provides adjustable resonance to the system and that the resulting magnetic restoring force has a linear operating range. It is verified that the field of maximum energy harvesting is contained in this band, confirming its relevance. The results show that there is a relation of importance of the induced voltage and the electrical damping through the variation of the load resistance, affecting attenuation and power generation of the system. Finally, the aim is to present the best models and results of damping parameters in order to obtain information as a design guide to optimization and future semi-active control strategies*.

Keywords: *Dynamic vibration control. Tunable Electromagnetic Absorber. Energy harvesting. Semi-active device.*

1. INTRODUCTION

In nature, the transfer of energy is revealed through the vibratory behavior of its events, in such a way that these phenomena reach the most varied structures and systems. In many cases, this vibration is unwanted and its effects are detrimental to the system mainly at resonance, causing improper machine operations, ruptures in civil structures, instabilities, discomforts and noises. Excitations near the resonant frequencies can cause high oscillation amplitudes and lead to system failure. In this way, it is necessary to perform the dynamic vibration control and monitoring (Inman, 2008). The dynamic control is classified as: passive, active, hybrid and semi-active. The control provides changes in the stiffness and damping properties in the system, either by the increase of auxiliary devices or by the action of external forces. Passive control, e.g., tunable mass damper (TMD), is commonly employed because it presents low running and maintenance costs. However, its performance is susceptible to the nature of the excitations and to changes in the operating frequencies. Therefore, in order to increase mitigating efficiency, reduce operation cost and improve its robustness, it is necessary to design tunable devices and develop optimization techniques (Hartog, 1956) so that they can be efficiently used over a wide range of frequencies, operating either passively or actively, or the combination of both, semi-active (Liu and Liu, 2006). The semi-active control has the reliability of the passive control and the adaptability of the active control, with lower energy consumptions.

On the other hand, the vibration may be desirable and beneficial to the system. According to the major scientific and economic issues is the relationship among energy consumption, technological challenges in the power generation and the diversity of renewable generating sources. For example, decentralized generating sources reduce the loss of energy associated with the transmission network and the environmental impacts of its operation. Based on this scenario, the development of autonomous intelligent devices and wireless sensor network (WSN) has gained interest in engineering in last decades from industrial, civil and hospital applications (Challa et al., 2011). Embedded autonomous power generation vehicles tend to be more versatile and flexible in remote areas as far as maintenance is concerned. However, WSN's feeding brings some disadvantages: batteries with energy limitations, expensive battery replacement and disposal of chemical waste resulting in severe environmental problems. As an alternative to solving these questions, energy harvesting is introduced through vibration transducers, i.e., it converts energy from the vibrational environment (Pereyma, 2007) into useful electrical energy. Vibrational transducers are generally; piezoelectric, electromagnetic and MEMS. A general approach for comparing the different conversion mechanisms is presented in (Arnold, 2007) and (Roundy, 2005). In recent years, a multiplicity of electromagnetic vibration transducers has been developed for different installations, industrial applications and structural monitoring, and it is in this sense that this work performs an experimental investigation.

Therefore, the present work proposes to combine tunable vibration control (passive and semi-active) with energy harvesting (TEMVAEH) through the transduction of electromagnetic vibration and the deliberate introduction of non-linearities. From a broad perspective, this implies that TEMVAEH can be designed and manufactured with some valuable resources. The first aspect, non-linear dynamic electromagnetic vibration absorber with nonlinear magnetic stiffness (Mann and Sims, 2009) can extend the effective band of mitigated frequencies, both in transient and forced harmonic response (Vakakis et al., 2008). Simultaneously, non-linear electromagnetic vibration transducer can increase the energy harvesting band. The second aspect focuses on the analysis of passive control and energy harvesting where the system (TEMVAEH) reveals a priori linear dynamic behavior, due to the relevance of this linear field in the system. Later, with this linear operation field under forced harmonic analysis, it is possible to apply consolidated optimization techniques for attenuation, resulting in an optimal mitigating field. Optimization methods can be also employed in vibrational transducers to potentialize energy conversion (Mitcheson et al., 2004). Once the elastic and damped properties of TEMVAEH were obtained, they could predict system responses and be tuned by semi-active control strategies.

2. TUNED ELETROMAGNETIC VIBRATION ABSORBER WITH ENERGY HARVESTING (TEMVAEH)

The apparatus illustrated in Fig. (1a) with the representative model in Fig. (1b) consists of three main systems: the primary system (x_p), the secondary system (x_a) and the oscillating base (y). The oscillating base transmits the excitation to the primary system through two lateral metal blades. The primary system consists basically of the set: sliding ball bearings, permanent magnet (NdFeB) fixed to the bearing support, coil and platform. The secondary system consists of a central permanent magnet (NdFeB) fixed to the bronze shaft which oscillates along the bearings. The central magnet is balanced in the center position due to a non-linear repulsive magnetic restoring force caused by the outer magnets. The bearing support in turn can be adjusted (distance between magnets) allowing the stiffness of the second system to vary, offering an adjustable resonance as shown in Fig. (2). For all next deductions presented, relative displacement is defined as, $z= x_a-x_p$, and system parameters for Fig. (1b) are described in Section 2.2.

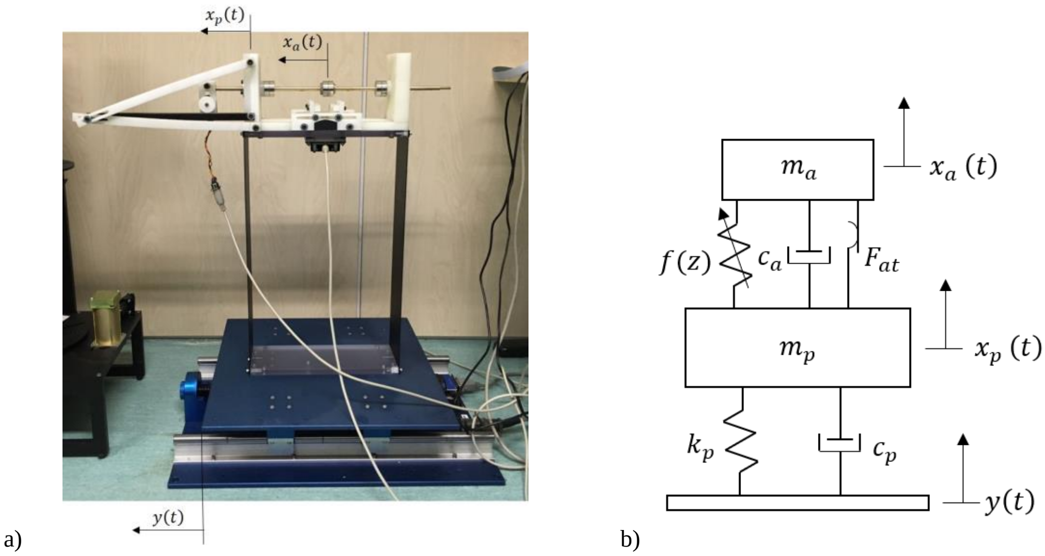

Figure 1. a) TEMVAEH device mounted on Quanser Shaker Table. b) TEMVAEH model.

Characterization of the TEMVAEH focuses on determination of the variable range of the stiffness and the electromagnetic transduction factor. In what follows a detailed characterization procedure is presented. It is expected that the developed approach is useful for the design of similar devices. Total magnetic restoring force *f(z)* for the symmetrical spacing of the magnet can be expressed by the vector sum of the restoring forces F_m related to the separated distances d_0 between magnets. Section 4 describes more accurately this experimental procedure and results.

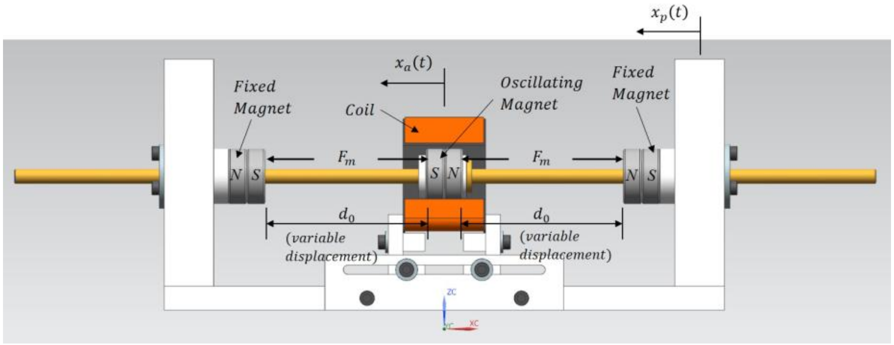

Figure 2. Schematic diagram of the TEMVAEH device (maximum distance set).

2.1 Eletromagnetic transductor factor

The presence of an oscillating magnets and the coil open the possibility of energy conversion. During disturbances, the magnets will generate a variation of the magnetic field. The addition of a fixed coil within the variable field will allow a voltage to be induced in the coil by respecting the Maxwell-Faraday equations for electromagnetism derived in Eq. (1). Magnet motion is illustrated in Fig. (3a) with a coil and the coordinates used to describe the magnetic field, *B*, around the magnet. Magnetic dipole moment vector M indicating the orientation and intensity of the magnetic field, V_c is the coil volume, l_w is the wire length and μ_0 is the permeability of free space. The coil radius is *a*, and the distance separating the center of the magnet from the coil is *z* (*z*=*c*-*d*), where *c* is the coil height and *d* is a reference fixed in the device as shown in Fig. (3b). The unit vectors, *z*, *a*, and angle *β*, are pointed in the positive direction. Due to the symmetry of the cylindrical magnet, the field of flux density has only components B_a in the direction *a* (radial component) and B_z in the *z* direction (axial component).

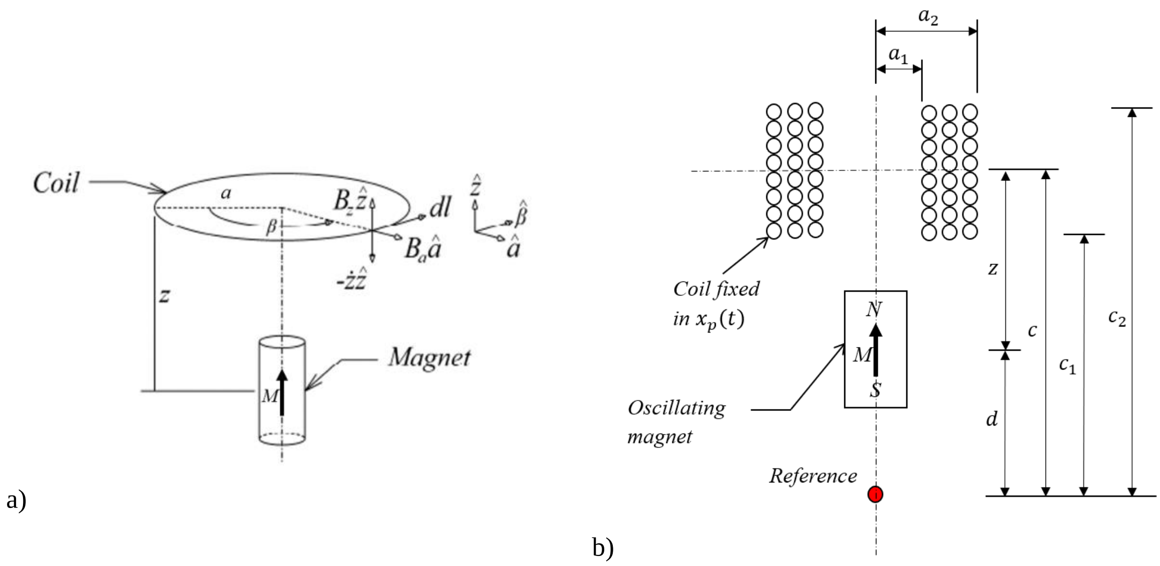

Figure 3. a) Schematic diagram of the magnet motion under the action of a coil; b) Relation among distances z, d and c.

By applying Kirchoff's law the electric circuit equation is obtained. For the simplification, the inductance of the coil will be neglected by fitting $L_{coil} = 0$, as shown in Eq. (3). The energy produced is restricted to the load resistor (R_{load}), which is not capable of storing any energy. Details of the electric circuit and simplifications will be presented in the final paper. The mechanical domain (relative mass velocity, *z*, and input force) and the electric domain (FEM, *ε*, and induced current, *i*) are coupled by the electromagnetic transduction factor $k_t(z)$ defined by Eq. (2).

$$\varepsilon = \oint_{l_w} (-\dot{z}\hat{z}) \times (B_z\hat{z} + B_a\hat{a})\, d\vec{l}\beta = -\dot{z} \oint_{l_w} B_a\, d\vec{l} \tag{1}$$

$$k_t(z) = -\frac{l_w}{V_c} \int_0^{2\pi} \int_{c_1}^{c_2} \int_{a_1}^{a_2} \frac{3\mu_0}{4\pi} M \frac{a(c-d)}{\left(a^2+(c-d)^2\right)^{5/2}} a da.dc.d\beta \tag{2}$$

Through energy conservation and Lenz's law, the value of the induced voltage (V_{load}) and the electric damping coefficient (c_e) can be determined by Eq. (3) and Eq. (4), respectively.

$$V_{load} = iR_{load} = \frac{k_t R_{load}}{(R_{coil}+R_{load})}\dot{z} \quad (3)$$

$$c_e = \frac{k_t^{\,2}}{(R_{coil}+R_{load})} \quad (4)$$

2.2 Final equations of motion

By applying Newton's second law of dynamics in Fig. (1b), Eq. (6) and Eq. (7) can be defined for the combined system under base acceleration ($\ddot{y}$). The term $F_{at}(\dot{z})$ represents the frictional force and may contain non-linearities and the elastic restoring force $f(z)$ determined by the magnetic interaction as mentioned before. All parameters were identified, either analytically or experimentally. Here, m represents mass, k represents the stiffness, c_m represents the mechanical viscous damping ($c_a=c_m+c_e$), indices p and a denote the primary system and secondary system, respectively.

$$m_p\ddot{x}_p+c_p\dot{x}_p+k_p x_p-(c_m+c_e)\dot{z}-F_{at}(\dot{z})-f(z)=-m_p\ddot{y} \quad (6)$$

$$m_a\ddot{x}_a+(c_m+c_e)\dot{z}+F_{at}(\dot{z})+f(z)=-m_a\ddot{y} \quad (7)$$

3. FREE FALL TEST – INDUCED VOLTAGE AND ELECTRICAL DAMPING

In order to determine and validate experimentally the electromagnetic transduction factor $k_t(z)$, the free fall test approach is used as shown in Fig. (4a). The energy conversion model can be validated by releasing the oscillating magnet through a coil. This work focuses on analyzing the influence of the load resistors on the induced voltage and on the electrical damping which affect the attenuation and energy harvesting. The terminals of the different coils are connected in series with different load resistors to an oscilloscope. The voltage measured in each coil, varying the load resistance, was compared to the voltage predicted by the model as presented in Fig. (3b). The center of the coil is positioned at z = 83mm relative to the resting position of the oscillating magnet. It is observed that the maximum amplitudes of the $k_t(z)$ occur in the vicinity of the coil and aligned to its faces.

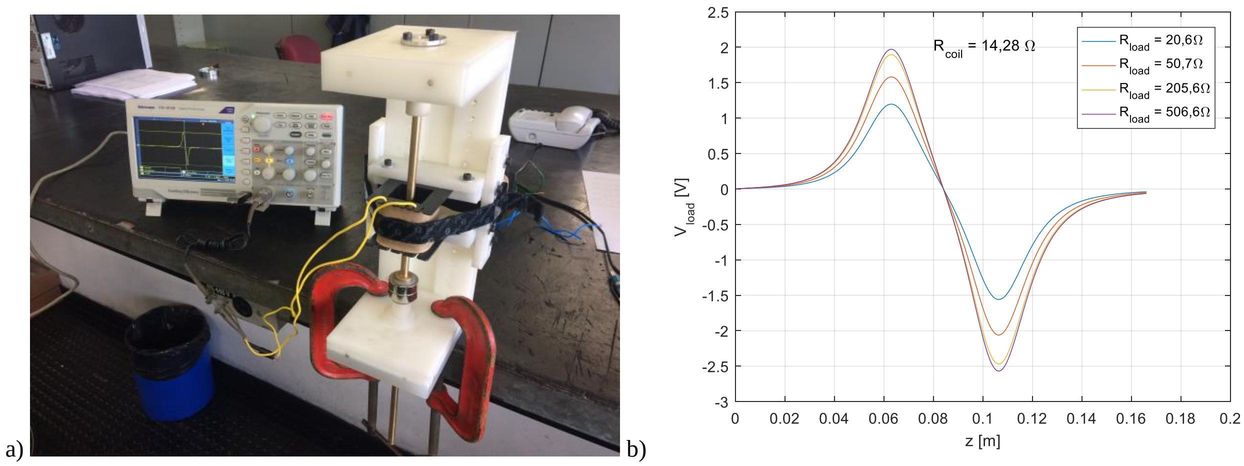

Figure 4. a) Free fall test. b) Voltage of the resistor vs. load resistance.

According to the Fig. (4b), it is verified that the maximum energy harvesting occurs when the oscillating magnet induces the maximum voltage values, i.e., close to the coil. Note that between the two maximum peaks, the voltage variation is approximately linear and the value of k_t remains constant in this field, causing alternating current in the coil. This analysis makes an assumption which is in contradiction with the nonlinear k_t presented in Eq. (2), where the Lorentz force applied to the system is linear. The displacement and velocity are 90 ° out of phase with each other. This implies that when the displacement is maximum, the velocity is minimal. The lower values of k_t corresponding to large displacements will pursue little influence due to the low velocity component. The damping will be defined by the highest values of k_t where the velocity is high but displacement is small. Therefore, transduction factor can be described linearly and approximately the maximum value of k_t. This gives the device an intriguing feature, where the maximum energy harvesting may occur in small amplitudes of oscillation. Figure (4b) shows that there is a relationship of the load resistance to the induced voltage and the electrical damping. It is demonstrated that for higher load resistances, higher voltages generated and higher damping levels set by optimal values.

3.1 Electrical damping effects

The damping coefficient is defined by Eq. (4). In Fig. (5), it is shown that higher electromagnetic transduction factor, higher will be the electrical damping coefficients. It is possible to confirm again that, for lower load resistance in the resistor, higher values of electrical damping coefficient obtained, until a critical value. The variation in the electrical damping allows TEMVAEH the ability to obtain an adjustable damping, which favors the mitigation of vibrations and energy harvesting.

This work focuses on presenting the influence of electrical damping on the dynamics of the system. Although these variations were done manually, it is worth emphasizing the possibility of making these adjustments through semi-active control strategies.

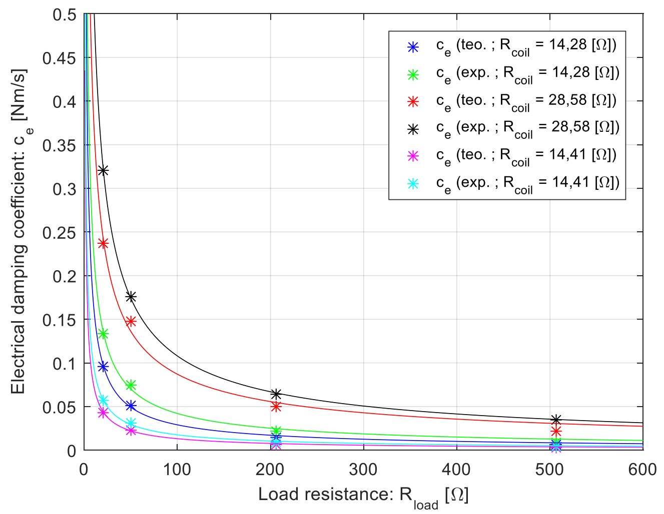

Figure 5. Electrical damping coefficient (c_e) as a function of the load resistances (R_{load}) for different coils.

4. MAGNETIC RESTORING FORCE – STIFFNESS

Through a series of static tests, the non-linear stiffness of the secondary system (oscillating magnet) due to the magnetic restorative forces is verified. A magnet was placed on a support attached to a load cell and spaced apart by varying distances d_0. A series of displacement force measurements were recorded experimentally and several curves were adjusted (least squares procedure) in order to find the best characteristic function. The total force-displacement relationships $f(z)$ were then formulated, and the separation distance as a function of the displacement of the center of magnets, z.

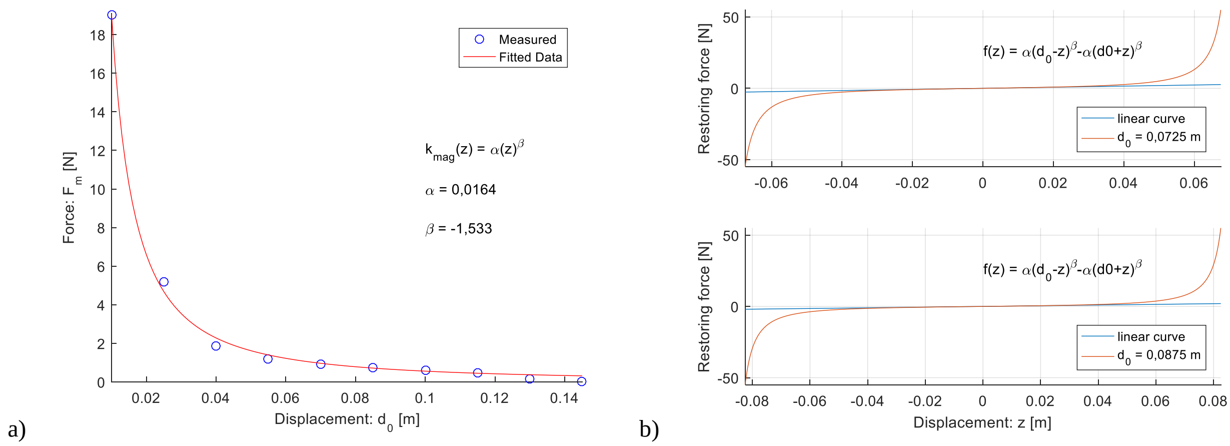

Figure 4. a) Magnetic force-displacement. b) Total force-displacement ratio for different magnet spacings.

The nonlinear force generated by the magnets can be clearly seen, becoming more evident as d_0 decreases in Fig. (4a). However, in Fig. (4b) is demonstrated, through a linearization procedure for small oscillations (Taylor Series expansion), that one of the major components of the total magnetic restoring force is linear, resulting in a significant linear stiffness component. In general, TEMVAEH analyzes of this work focus on this linear field a priori. All the curves fitted with the experimental values show a linear operating range. Note that the greater the distance d_0, lower the linear stiffness and greater the operating range. Therefore, it can be stated that the linear operating range may contain the maximum energy conversion defined by the electromagnetic transduction factor.

5. CONCLUSION

This work was dedicated to designing and experimentally analyzing a tunable (semi-active) electromagnetic vibration absorber with energy harvesting (TEMVAEH) in reference to a test apparatus consisting of a primary system (oscillator) which allows the testing of the transient and forced response. From a broad perspective, magnetic nonlinear stiffness can extend the effective band of passively mitigated frequencies as well as nonlinear electromagnetic vibration transduction can increase the energy harvesting band.

The mechanical and electrical model of TEMVAEH was coupled and the final dynamic equations obtained. Experimental analyzes of the free fall test validated the electromagnetic transduction factor model by examining the influence of the variation of the load resistances on the induced voltage. It was found that the electromagnetic transduction factor acts linearly in the field of maximum energy harvesting, despite the dependence on displacement. With the transduction factor, the electric damping coefficient was analyzed. Circuit inductance and its simplifications have been examined, demonstrating that under certain conditions it can be admittedly negligible. Magnetic restoring forces were obtained and analyzed through static testing and curve fitting to describe the experimental results. It was concluded that the approaches and simplifications are valid under the defined conditions. The effects of nonlinearities on TEMVAEH stiffness, as well as the linear operating field (linear stiffness) were verified. The distance between the fixed magnets and the oscillating magnet was analyzed, giving the system adjustable resonance. Finally, the electrical damping was studied according to the spacing between magnets. It was concluded that there is a performance link in the expansion of the effective vibration mitigation band together with the maximization of the energy harvesting contained in this operating band (linear field). For all analyzes, although not presented, the resonance phenomenon is essentially considered and relevant to dynamic vibration control and energy harvesting.

Therefore, this work focused on the development and analysis of passive control and energy harvesting strategy where TEMVAEH reveals a priori linear dynamic behavior, due to the relevance and potential of this field in the system for attenuation and energy harvesting. Once the linear operating field has been identified, it is possible to apply optimization techniques to extend the linear operating field of the TEMVAEH under forced excitation, which results in an optimal attenuation field, and to develop optimization methods to maximize the energy conversion of the TEMVAEH. It is by varying the electric current of the coil that the electric damping would be adjusted in real time. This study aimed to determine the best results of damping parameters in order to obtain information for the proposition of a semi-active complementary device. Since the elastic and damped properties of TEMVAEH have been obtained experimentally and, as a way to improve TEMVAEH's robustness in future applications, they can be combined and tuned by implementing a possible semi-active controller.

6. ACKKNOWLEDGEMENTS

I thank to the Polytechnic School of USP (Brazil) and to CAPES for providing the necessary support for the development of this work. To the University Center of FEI (Brazil) for cooperating with laboratory facilities and machinery.

7. REFERENCES

Arnold, D.P., 2007. “Review of microscale magnetic power generation”. Trans. Magn. 43(11), 3940–3951.

Challa, V.R., Prasad, M.G. and Fisher, F.T., 2011. “Towards an autonomous self-tuning vibration energy harvesting device for wireless sensor network applications”. *Smart Materials and Structures*, 20(2):025004.

Den Hartog, J.P., 1956. *Mechanical Vibrations*, McGraw-Hill, New York, 4th ed.

Inman, D.J., 2008. *Engineering Vibration*, Pearson Education, 3rd ed.

Liu, J. and Liu, K., 2006. “A tunable electromagnetic vibration absorber: characterization and application”. *Journal of Sound and Vibration*, vol. 295, 708-724.

Mann, B.P. and Sims, N.D., 2009. “Energy harvesting from the nonlinear oscillations of magnetic levitation”. *Journal of Sound and Vibration*, vol. 319, pp. 515-530.

Mitcheson, P.D., Green, T.C., Yeatman, E.M. and Holmes, A.S., 2004. “Architectures for vibration-driven micropower generators”. *Journal of Microelectromechanical Systems*, 13(3):429–440.

Pereyma, M., 2007.“Overview of the modern state of the vibration energy harvesting devices”. *Proceedings of MEMSTECH*, Lviv-Polyana, pp. 107–112. ISBN: 978-966-553614-7.

Roundy, S., 2005.“On the effectiveness of vibration-based energy harvesting”. J. *Intell. Mater. Syst. Struct*. 16(10), 809–823.

Vakakis, A.F., Gendelman, O.V., Bergman, L.A., McFarland, D.M., Kerschen, G. and Lee, Y.S., 2008. “Nonlinear targeted energy transfer in mechanical and structural systems”. Nonlinear Targeted Energy Transfer in Mechanical and Structural Systems.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.