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MODEL OF AN ADAPTIVE ENERGY HARVESTER WITH ELECTRO-RHEOLOGICAL FLUID

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The aim of this paper is to propose and analyse an energy harvester able to adapt to the external vibration frequency and to the load impedance in order to maximize the harvested energy. The design problem consists in determining the applied electric filed to a rheological fluid, for gathering the maximal power from an energy harvesting device based on an inertial mass consisting of a magnetic core in an energy harvesting coil. The optimization regards the adjustment of the damping for achieving the matching between the resonance frequency of the energy harvester moving element (inertial mass) and the tremor frequency of the patient or the matching to the load. A design configuration for an energy harvester specifically conceived for FES in Parkinson disease is presented. In the subsidiary, we specify the processing steps for the tremor signal.

Key words: energy harvesting, active control, adaptive device, optimization, electro-rheological fluid, model, design equation.

1. INTRODUCTION

Energy harvesting has seen a tremendous development during the last 10 years, with numerous proposals for devices and with an even larger number of proposed applications. In this introductory section, we provide justification of this study showing the reasons for designing adaptive energy harvesters in a set of applications related chiefly to medical engineering. For a solid justification and a comprehensive understanding of the details, we need to briefly review the state of the art of energy harvesting, moreover the basics of the limb movements producing the harvested energy and the use of the harvested energy in medical applications.

One of the fields that can much benefit from energy harvesting devices (EHDs) is the one of prostheses and wearable and implantable medical devices, see for example the papers by Chandrakasan et al. (2008) [8], Paradiso et al. (2008) [20] and Olivo et al. (2011) [19]. Tremor is the result of several pathologies and affects a large number of people, especially of the third age, see Abdo et al. [3], Benito-León et al. [6], Grimaldi & Manto (2008) [12]. Various researchers have designed prosthetic devices for controlling the tremor using functional electrical stimulation (FES), for example Smith et al. (1999) [27], Widjaja et al. [33], Popovic et al. [21], Grimaldi et al. (2011) [14], Taheri et al. [28], Yu et al. [35]. Several patents have also been issued, e.g. Smith et al. (1999) [27]. Modelling tremor in view of control and diagnostic has also been a topic largely investigated. Recently, Bó et al. (2011) [7] proposed methods for modelling and online estimation for active compensation of the pathological tremor and voluntary motion. Other models were proposed in the frame of fuzzy logic [29, 30], of nonlinear dynamics [10], or of wavelet theory [11]. The signal acquisition and processing issues for neural, electromyographic and accelerometric signals were dealt with extensively, using different tools [7, 11, 13, 25], [33] etc. In this paper, the aspects related to FES are not of direct interest, therefore the signal processing needed for the proposed energy harvester (EH) refers to acceleration signals only, specifically to the extraction of the frequency of the main spectral component. The interest in this component is that, for achieving maximal power harvest, the EHD resonant frequency must be equal to that of the external vibration (tremor), see [23, 24].

For easily grasping the relevant details of the proposed design and the practical significance of the application in FES of the EHD proposal, we recall a few tremor signals characteristics. For an overview of the causes and types of pathologic tremors, see Abdo et al. (2010) [3]. These authors reviewed numerous types of tremor that are due to various medical conditions (Parkinson disease, endocrine disorders or intoxications, essential tremor, cerebellar ataxia, atypical parkinsonism, dystonic tremor, rubral / Holmes tremor, Wilson disease) and situations of combined movement disorders, e.g. dystonia plus tremor, or combinations of Parkinsonism, ataxia, autonomic dysfunction, and spasticity. Tremor, together with dystonia, is one of the two main types of "non-jerky hyperkinetic syndromes" [3]. As Abdo et al. emphasize, "*the keyword in identifying tremor is 'rhythmicity'; that is, the oscillations occur at a regular frequency*" [3]. On the other hand, the amplitude of the tremor is variable in time, "despite having a fixed frequency, tremors often have a variable amplitude", while the frequency remains unchanged ("despite the amplitude change, tremor frequency remains unchanged", ibidem). The basic frequency (the frequency of the dominant component in the tremor spectrum) varies with the types of tremor, yet "the frequency spectrum between different tremor types overlaps considerably" [3]. Essential tremor was found to have the main component at 5.79 ± 1.32 Hz (see Elble [9]). Interestingly, the same author finds that there is a "decrement in tremor frequency over 4 years of 0.332 Hz", for aged people, on average, which poses the problem of adaptation of the EHD in time. For Parkinson disease, the tremor is produced by neurons from *globus pallidus* and has the main frequency in the range 3–6 Hz (Lemstra et al. [16]). Timmerman et al. [31] consider that "*typical Parkinson's disease resting tremor* (4–6 Hz)." On the other hand, "*Holmes tremor (also known as midbrain or rubral tremor), which typically has resting, postural and intention components*," has "*an unusually low frequency of around* 2–3 Hz" [3]. Therefore, a fixed parameter EHD cannot fit all patients and tremor cases.

The use of resonant EHDs in Parkinson subjects and other tremor type subjects is limited because of the various frequencies of the limb movements, as described above. The movement changes not only from subject to subject, but also for the same subject, depending on momentary conditions, type of tremor, and age. Therefore, fitting an EHD to a specific subject, based on her prevalent tremor frequency is not only time consuming, but also virtually impossible, because of the patient-dependent tremor frequency. It would be inconvenient to design and manufacture several types of EH devices, one per type of tremor, moreover to operate EHDs in a far from optimal regime for subjects with variable frequency tremor. These considerations indicate the need of adaptive EHDs. We propose subsequently an electro-rheological fluid (ERF) based device able to optimize its performance, according to the tremor type and frequency.

2. BASIC DESIGN

2.1. Equations of the standard EH device

The proposed EH device if of electromagnetic type and consists in a standard configuration for magnetic energy harvesting [4, 5, 24], with two exceptions: (i) that the moving magnet is maintained in a rheological fluid, and that (ii) the assembly includes two electrodes that allow the application of a voltage $u(t)$ that controls the rheological properties of the fluid. The proposed device is, according to the terminology in [19], a "*kinetic harvester, aimed to collect the energy related to human motions and transform it into electrical energy*", which, "*because of the employed transduction method*" is electromagnetic.

Various types of kinetic EHDs, including the electromagnetic ones, are reviewed in several papers, for example [5], and the essential equations are presented in them. The typical magnetic EH consists of an inertial (also named "seismic") mass and an elastic element (spring) opposing the movement of the mass. Damping, i.e., energy dissipation occurs due to the transfer of the harvested energy to the load and to frictions (internal energy losses to the system, for example in the spring and in the gas or fluid surrounding the mass). The basic equation of the systems is, in case of the integral (energy) variant, $L_{ext} = E_{kin} + E_{pot} + E_{trans} + E_{loss}$, where L_{ext} is the work of external forces in the considered time lapse, E_{kin} is the variation in the kinetic energy of the mass (the spring is assumed to have negligible mass), E_{pot} is the potential energy transferred, essentially the variation of the elastic energy stored in the spring, E_{trans} is the energy transferred to the external environment – in this case to the load, that is, the energy transfer by the mechanical-electrical coupling, and E_{loss} is the total work of loss forces. In differential form, the above equation is $ma_{ext} = mx'' +$

$+ k\Delta x + F_{trans} + F_{loss}$, where we assumed that the movement is along the Ox axis, a_{ext} is the acceleration due to external vibrations, m is the inertial mass, k is the elastic constant, assuming the spring is ideal, Δx is the variation in position with respect to the equilibrium ($\Delta x = x$ for equilibrium position at the origin), F_{loss} depends on all loss processes in the system, and F_{trans} is the equivalent force transmitted to the load and depends on the system configuration. The usual hypothesis is that the internal losses depend on the velocity, $F_{loss}= \lambda x'$. While apparently elementary, this model has difficulties in its details, because of the potential complexity of the terms F_{loss} and F_{trans} in the context of optimizing the transferred energy. The presented research is in line with the discussion in [5], who puts it rightly, "*it may be useful to be able to vary damping levels. … increased damping effects will result in a broader bandwidth response and a generator that is less sensitive to frequency. …Both the frequency of the generator and the level of damping should be designed to match a particular application in order to maximize the power output*."

When the inertial mass is a magnet placed in a coil (or vice versa, a coil between fixed magnets) and the energy is harvested from the variation of the magnetic field, the equivalent electromagnetic damping force , that is, F_{trans}, created by the energy transfer is, according to Saha et al. [24]

$$F_{em} = \frac{1}{Z}\cdot\left(\frac{N\mathrm{d}\Phi}{\mathrm{d}x}\right)^2 x', \tag{1}$$

where $Z= R_C + R_l + \mathrm{j}\omega L$ is the impedance of the overall load circuit, R_C is the coil resistance, N is the number of turns, L is the coil inductance, Φ is the magnetic flux, R_l is the load resistance, and x' denotes time derivative. It is usual to put into evidence the electromagnetic (transfer) damping factor in the above expression, as $D_{em} = \frac{1}{Z}\cdot\left(\frac{N\mathrm{d}\Phi}{\mathrm{d}x}\right)^2$, with the damping depending on the geometry of the system, including the shape and the number of turns of the coil and the geometric distribution of the magnetic flux, and on the external load. The coil output voltage is $e= - \mathrm{d}\Phi/\mathrm{d}t$. Using the above expressions in the damped movement equation, with $\Delta x = x$, assuming that the internal losses are $F_{loss}= \lambda x'$, we obtain

$$ma_{ext} = mx'' + kx + \frac{1}{Z}\cdot\left(\frac{N\mathrm{d}\Phi}{\mathrm{d}x}\right)^2 x' + \lambda x'. \tag{2}$$

The analysis in [24] and in [18] for internal losses depending on the velocity, $F_{loss}= \lambda x'$, shows that there is an optimal value of the coefficient λ for the optimal energy transfer to the load, under resonant conditions. The optimality criterion is based on the maximal energy transfer to the load, which is typically a circuit charging a battery. For the optimality criterion, see [24].

2.2. Electro-rheological fluids – models

Electrorheological fluids (ERFs) are described by Martin et al. [18] as a liquid with "*…suspending particles … whose dielectric constant or conductivity is mismatched in order to create dipolar particle interactions in the presence of an … electric field. ER fluids … increase their viscosity dramatically, in response to an electric field …*." For details, see the reviews by [18] and the newer one by [26, 32]. For the EH application, the rheological fluid should be a good dielectric, for reduced electric losses, and should have low viscosity when no field is applied, for reduced friction losses due to the moving parts in the EHD. Rheological fluids based on silicone oils with dielectric micro-grains, such as $BaTiO_3$, satisfy both conditions.

There are numerous models of rheological fluids, see [15, 22, 26, 32]. These models fall into two categories: purely empirical and theoretical-empirical ones. The purely empirical models start from the hypothesis that the viscosity depends on several parameters, such as temperature and strain, and develop essentially statistical relationships based on nonlinear regressions to fit the data for a specified fluid. The models in the second category start with sets of hypothetical equations relating stress, σ, its time derivative, σ', elasticity (elastic constant E of the rheological fluid) and viscosity η to the strain ε and its derivative ε' and determine which set of equations best fits a specified set of empirical data for a class of rheological fluids. The reader is referred to [22] mainly for empirical models and to [15] for theoretical and empirical models. Several models in the second class are well known. Starting from the models of the ideal spring, $\sigma = E\varepsilon$, and of the elementary damper (dash-pot), $\sigma = \eta\varepsilon'$, Maxwell model (Fig. 1) corresponds to the two elements connected in series, with the equation $\sigma+\eta\sigma'/E = \eta\varepsilon'$. Kelvin-Voigt model (Fig. 2) connects the spring and the damper elements in parallel, with the equation $\sigma = E\,\varepsilon + \eta\varepsilon'$ [15].

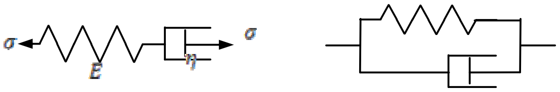

Fig. 1 – Basic models of the rheological fluid: Maxwell (left) and Kelvin-Voigt [15, p. 294].

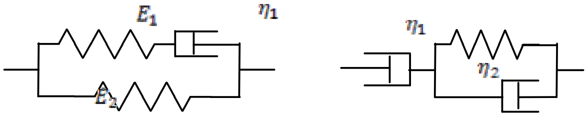

Fig. 2 – Mixt (standard solid type II, left, and standard fluid type II, right) models of the rheological fluid [15, p. 294].

The so-called standard solid type II and fluid type II models – Kelly (2014) [15, p. 294] – are combinations of three elements as in Fig. 2 and have the equations

$$\sigma+\frac{\eta}{E_2}\sigma'=E_1\,\varepsilon+\frac{\eta\,(E_1+E_2)}{E_2}\cdot\varepsilon' \tag{3}$$

for the configuration of one spring in parallel to a series spring-damper subsystem (solid type II), and

$$\sigma+\frac{\eta_1+\eta_2}{E}\sigma'=\eta_1\varepsilon'+\frac{\eta_1\eta_2}{E}\cdot\varepsilon'' \tag{4}$$

for one damper in series with a parallel spring-damper subsystem (fluid type II). The first of these equations is used in the design, which assumes the fluid in the ESD has that model.

3. DESIGN OF THE ADAPTIVE EHD

3.1. EHD configuration

The configuration of the proposed EH device corresponds to that of the kinetic electromagnetic EHD, with the main modifications consisting in (i) the use of an ERF to fill the space where the inertial mass moves and (ii) in the use of electrodes for controlling the ERF behavior. The main purpose of the design is to provide means for adaptation of the parameters of the EHD in view of maximizing the harvested energy. The inertial mass *m* of the magnet is connected to a spring of elastic constant *k* and moving in the fluid inside a coil that collects the harvested power. For the theoretical model, we assume that the dimensions of the moving mass (magnet) are much smaller than those of the container, $r << R$, $l_2 << l_1$. These conditions allow us to neglect the piston effect of the moving mass and the effect of the walls (thus preserving the hypothesis of movement in an infinite viscous space). Moreover, this allows us to use single axis geometry. The configuration in Fig. 3 has some resemblances with those studied by [1, 2, 17].

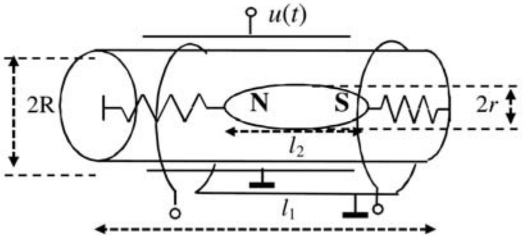

Fig. 3 – Basic configuration of the sensor. (NS) is a magnet. For details, see for example [4, 5, 24].

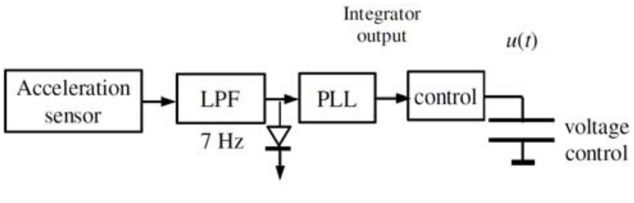

Fig. 4 – Sketch of the signal processing blocks for extracting the frequency of the main spectral component of the tremor and the output voltage proportional to the basic frequency of the tremor.

Several types of active control using the electro-rheological effect can be applied. In the first place, control can be based on the average or the peak amplitude of the signal, to limit the displacement of the inertial mass and protect the device against high accelerations in the low frequency band (output after the low-pass filter (LPF) in Fig. 4). Second, a direct current (d.c.) voltage control may be used to adjust the equivalent viscosity and adapt the EHD to the load, as explained in Section 3.2. A third type of active control detects and tracks the main frequency of the vibration and modifies the applied voltage in accordance with the difference between the difference in frequency between the vibration and the resonance of the EHD. For this purpose, the EH device also includes means for determining the frequency of the main spectral component of the external acceleration. The frequency of the main component in the acceleration signal may be found digitally, by computing the Fourier spectrum, or analogically, using a PLL and the signal at the input of the VCO in the PLL circuit (Fig. 3). In both cases, a pre-filtering of the signal with a low-pass filter with a corner frequency of 6 – 7 Hz, corresponding to the tremor band, is useful (Fig. 4).

3.2. Basic example

As an introductory example aimed to help grasping the principle of operation of the adaptive EHDs, assume that the behavior of the fluid is pseudo-Newtonian, that is, it behaves as a fluid governed by the equation $\sigma=\eta\varepsilon'$, where, however, the value of η depends on the applied voltage, u, $\eta=\eta(u)$. The rough approximation in this toy example is acceptable for values of the voltage close to zero. According to Saha et al. [24], the optimal value of the damping coefficient λ in the term $\lambda x'$ in the movement equation is given by the condition of optimal load resistance, which in turns is ([24], equ. 6):

Thus, the optimality condition, assuming resonance, is

$$\eta(u)\times\left(\rho N^2+\frac{R_{load}}{N^2}\right)=N^2\cdot\left(\frac{N\mathrm{d}\Phi}{\mathrm{d}x}\right)^2, \tag{5}$$

which gives the required law of variation of $\eta(u)$, hence of u when R_{load} changes. If a Taylor approximation is used, $\eta(u)=\eta(0)+\eta_1 u$, the required voltage applied for optimal power transfer to the load is

$$u=\frac{1}{\eta_1}\times\left(N^2\cdot\left(\frac{\mathrm{d}\Phi}{\mathrm{d}x}\right)^2\Big/\left(\rho N^2+\frac{R_{load}}{N^2}\right)-\eta_0\right), \tag{6}$$

where η_1 is the first derivative of the viscosity of the pseudo-Newtonian fluid with respect to the applied voltage (electric field), $\eta_1=\mathrm{d}\eta/\mathrm{d}u|_0$. This model allows adaptation to the load only, not to the tremor frequency. Notice that there is so power loss due to the control circuitry and to the actual voltage control on the electro-rheological fluid. Consequently, the control is useful only when the load mismatch is large enough and the efficiency increase in the energy gathering is larger than the control loss. Therefore, the equation (6) apply only after some minimal threshold of u.

3.3. General equations

In the applications related to FES in tremor, the EHD is supposedly placed on the tremor-affected limb. In a typical magnetic EHD, the movement of the mass is governed by the second order differential equation (2), which was analysed in the papers already cited. When the mass moves in an electrorheological fluid, all terms become dependent on the applied electrical field, the equation must be re-stated because, among others, (i) The mass includes a certain contribution of the liquid displaced, which is dependent in turn on the rheological properties; (ii) The viscosity behaviour of the rheological liquid is controlled by the field, so at least the coefficients k and λ become functions of the applied voltage, u. In a general setting, the movement equation is:

$$mx''+g(\overline{\eta},l_1,l_2,R,r,x')+kx+h(\overline{\eta},l_1,l_2,R,r,x)=F_{ext}-F_{em}=ma_{ext}-F_{em}, \tag{7}$$

where $\overline{\eta}=\overline{\eta}(u,\theta)$ is the vector describing the behaviour of the fluid (elasticity and viscosity), θ is the temperature, $u(t)$ is the external control voltage applied to the rheological fluid, the functions g, h are supposed known, and the other parameters are geometric parameters given in Fig. 3. As discussed, under the hypotheses $r << R$, $l_2 << l_1$, the parameters R and l_1 are no more present in the above equation, and the geometry of the magnet (r and l_1) can be accounted for by a single parameter which also takes care of the shape of the magnet. However, such a general model as (7) is of little practical use. Subsequently, we make additional hypotheses for deriving useful equations.

To build the new model, we notice that the same deformation as sustained by the physical spring is also sustained by the fluid; therefore we will assume that the model is obtained by connecting in parallel the physical spring with the fluid. In addition, a Kelvin-Voigt model (Fig. 1) is considered. The result is a system identical to a solid type II, with the model as in Fig. 2 and with the equation (3); replacing σ by the external force and ε by x, the result is

$$F + \frac{\eta}{E_2} F' = E_1 x + \frac{\eta \cdot (E_1 + E_2)}{E_2} x' , \tag{8}$$

where F stands for F_{elast} in the general movement equation, with F_{elast} including both the term corresponding to accumulated potential energy (spring-like) and the one standing for losses (friction, viscosity-like),

$$ma_{ext} = mx'' + F_{elast} + F_{trans} \tag{9}$$

as already discussed. From (9), $F_{elast} = ma_{ext} - F_{trans} - mx''$, which replaced in (8) produces

$$ma_{ext} - mx'' - F_{trans} + \frac{\eta}{E_2}\left(ma_{ext} - mx'' - F_{trans}\right)' = E_1 x + \frac{\eta\left(E_1 + E_2\right)}{E_2} x' \tag{10}$$

and the model becomes

$$\frac{\eta}{E_2} mx''' + mx'' + \frac{\eta\left(E_1 + E_2\right)}{E_2} x' + E_1 x + F_{trans} + \frac{\eta}{E_2} F'_{trans} = ma_{ext} + \frac{\eta}{E_2} ma'_{ext} . \tag{11}$$

Finally, replacing in (11) the force F_{trans} as in (1), the equation is

$$\frac{\eta}{E_2} mx''' + mx'' + \frac{\eta\left(E_1 + E_2\right)}{E_2} x' + E_1 x + \frac{1}{Z} \cdot \left(\frac{N\mathrm{d}\Phi}{\mathrm{d}x}\right)^2 x' + \frac{\eta}{E_2}\frac{1}{Z} \cdot \left(\left(\frac{N\mathrm{d}\Phi}{\mathrm{d}x}\right)^2 x'\right)' = ma_{ext} + \frac{\eta}{E_2} ma'_{ext} , \tag{12}$$

with the derivative F'_{trans} left undeveloped, for brevity.

This type of adaptive EHDs would be useful when the external movements are variable, especially when the external vibrations significantly change their main frequency. In addition, the adaptive EHDs are useful when very large accelerations occur, that can destroy the device; in that case, a high viscosity can be induced by a large external electric filed to effectively make the assembly rigid.

4. DISCUSSION AND CONCLUSIONS

We presented the principles and general design equations of ERF-based adaptive EHDs, with the purpose of the design being the optimization of the characteristics of an energy harvesting device, with the main application in mind the functional electrical stimulation (FES) for the muscular control of subjects that present pathologic tremor. The design reflects and heavily relies on the recently knowledge on tremor signal analysis, on the magnetic energy harvesting, and on FES stimulation.

The modelled EHD is able to adapt to the frequency of the tremor, to the load, or to both, depending on the properties of the rheological fluid used. Models of the EHD incorporating the equations of the rheological fluids were determined and the corresponding design equations were derived. The equations are third order, nonlinear in the displacement (strain) and must be solved numerically for optimizing a specific EHD. Notice that other medical applications could benefit of this analysis, for example dampers for applications at MRI.

Among the advantages of the proposed ERF-based device are: (i) it is able to sustain without damage large accidental accelerations (large values of *g*s); (ii) it can adapt to the external accelerations in view of increasing the EHD efficiency; (iii) it can adapt to the load, for optimizing efficiency. The adaptive EHDs described have also several drawbacks, including higher costs and temperature dependence, also potential aging of the ERF, not well understood today. Further work is needed to simulate, build, and test the proposed EHD configuration and to validate the adaptation principle under various geometries, especially under geometries that do not respect the condition of large ratios R/r and l_1/l_2.

The adaptation principle presented in the paper for electromagnetic EHDs can easily be transposed to other types of kinetic EHDs, e.g., piezoelectric. Also, instead of using magnets in dielectric ERF one may imagine the use of ferro-fluids. Further work is also needed to optimize the efficiency of the EHD when the tremor has two or several spectral components of similar amplitudes, as in the case of tremors of chaotic aspect. The proposal may give an impetus in the study of rheological fluids in the electronic manufacturing of “intelligent” EHDs. Beyond FES for tremor control, the proposed EHDs could find applications in various prostheses and in deep brain stimulation, among others.

Concluding, the main contributions of the papers are: i) the proposal of adaptive EHDs able to modify their parameters (damping and resonant frequency) according to the parameters of the main frequency of the harvested vibrations and respectively to the load impedance, and ii) the derivation of the related equations. Future work should address vibrations with a broad spectrum, as discussed in [34], as well as simulations and tests on experimental devices.

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