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# Modelling of Electromagnetic Coupling in Micro-scale Electromagnetic Energy Harvester

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***Abstract*—Kinetic energy harvesters as systems which convert kinetic energy of the oscillations to electric power has different transduction mechanisms. One of the most common transduction mechanisms in such systems is electromagnetic generation, when a voltage is generated according to the Faraday law. Despite the clear physical nature of the electromechanical coupling, the development of the close lumped model for electromotive force and electromagnetic force is challenging problem. The algorithm for estimation of these values and criteria of self-consistency for the model is presented in this paper. In addition, suggested algorithm is applied to the real microscopic electromagnetic energy harvester and predicted signal was compared to the experimental data.**

***Index Terms*—Energy harvesting, electromagnetic, modelling, multiphysics**

## I. INTRODUCTION

Micro-scale electromechanical energy harvesters are the rapidly developing area of the engineering knowledge [1], [2]. Recently it became possible to build micro electromechanical (MEMS) energy harvesters based on the Faraday law [3]–[6]. These harvesters traditionally consist of moving magnetic mass and coil (Fig. 1). Although such kinetic energy harvesters (KEH) are based on well-known physical principles, the modelling of the real system is challenging. The electromotive force (e.m.f.) induced in the real coil has a complicated non-linear structure, the same as the electromagnetic force acting on the magnetic load. Traditionally [7], [8], simplified expression was used for the e.m.f $\mathcal{E} = Blu_z$ and the electromagnetic force $F_{\text{EM}} = Bli$, where $B$ is the average magnet flux density, $l$ is some characteristic length of the coil, $u_z$ is the relative velocity of the magnet load and $i$ is the current in the coil. Unfortunately, this approach does not describe the correct behaviour of the system because in the region of coil vibration the magnetic field is significantly changing from point to point. Thus, it is necessary to build a lumped, physically-based model for electromagnetic interactions in the emKEH.

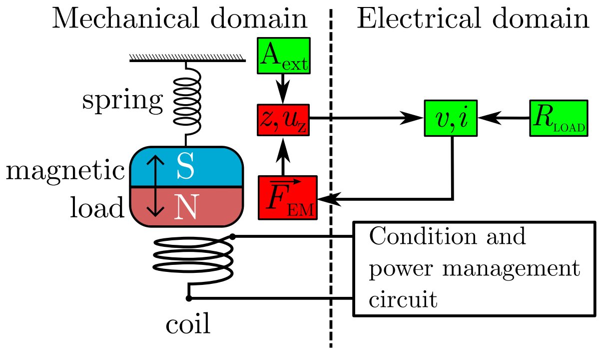

Fig. 1. The schematic diagram which shows the processes in the electromagnetic energy harvester.

## II. MODELLING OF THE ELECTROMECHANICAL COUPLING

The starting point for the model is the magnetic flux density produced by the magnet (Fig. 2). The common method for

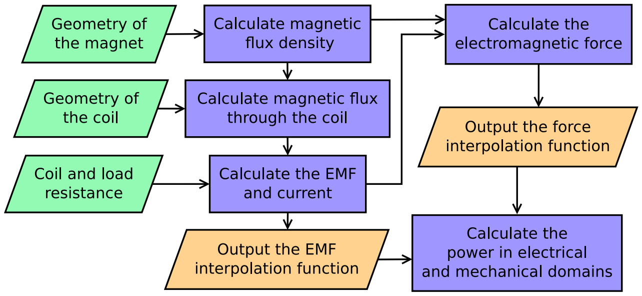

Fig. 2. Algorithm describes the approach for the developing of self-consistent model for the e.m.f, and the electromagnetic force.

evaluating the magnetic induction is the finite element method (FEM) [9]. There also exist a number of integration methods which are based of different representations of the magnet: as an array of magnetic dipoles, and as an equivalent coil [10]. Thus, criteria for the self-consistency for the methods should be developed. The self-consistency could be checked using the algorithm in figure 2. To do this it is possible to build the testing model assuming uniform motion of the coil relative to the magnet. According to the energy conservation law, the power induced in the electrical domain ($P_{\text{electr}} = v^2/R_{\text{load}}$) in this case should be equal to the power induced in the mechanical domain ($P_{\text{mech}} = F_{\text{EM}} u_z$).

To calculate the power in the mechanical and in the electrical domains, one should follow the physically based algorithm described in figure 2. After calculating of the magnetic induction, one should find the magnetic flux $\Phi_i$ through each loop of the coil for each spatial configuration which is implied by the relative motion of the magnet. For the translational oscillations of the magnet:

$$\Phi_i(z) = \iint_{\text{loop}} (\vec{B}\cdot\vec{n})\mathrm{d}A, \tag{1}$$

where $\vec{n}$ is the vector, perpendicular to the element of area $\mathrm{d}A$ of the surface, and limited by the coil loop.

The next step is the calculation of the e.m.f. induced in the coil as the sum of the voltages induced in each coil. According to Faraday's law applied to the progressive motion along the $z$-axis:

$$\mathcal{E}_i = \frac{\mathrm{d}\Phi_i}{\mathrm{d}t} = \frac{\mathrm{d}\Phi_i}{\mathrm{d}z}\cdot\frac{\mathrm{d}z}{\mathrm{d}t} = \frac{\mathrm{d}\Phi_i}{\mathrm{d}z}u_z, \tag{2}$$

and the total e.m.f. is:

$$\mathcal{E} = \sum_{i=1}^{N_{\text{loops}}} \mathcal{E}_i. \tag{3}$$

Usually, the calculation of the electromotive force for each combination of the relative speed $u_z$ and position of the magnet is extremely time consuming. Thus, it is necessary to use the interpolation function $\mathcal{E}(z, u_z)$ for further calculations.

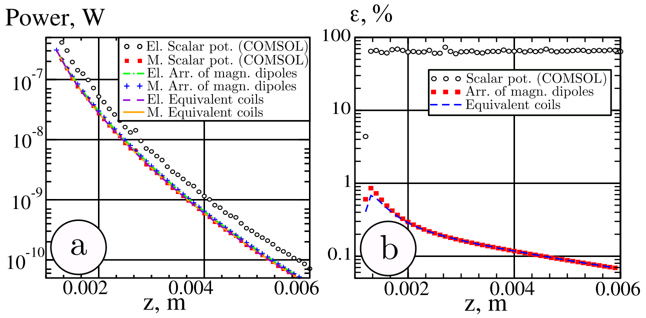

Fig. 3. Comparing of self-consistency of the different models of the permanent magnet. a) the power in mechanical and electrical domains for different approaches; b) the relative error $\varepsilon = 2|P_{\text{mech}} - P_{\text{electr}}|/(P_{\text{mech}} + P_{\text{electr}})$ obtained in different approaches.

Finally, according to the algorithm one needs to find the electromagnetic force acting on the magnet (which is equal to the force acting on the coil loop due to Newton's second law). It is much easier to calculate the force which is acting on the coil because it is equal to the sum of the elementary forces acting on the elements of the wire $\mathrm{d}\vec{l}$ with current:

$$(\vec{F}_{\text{EM}})_i = \oint_{\text{loop}} i[\vec{B}\times\mathrm{d}\vec{l}]. \tag{4}$$

For developing the model of the progressive vibrations of the harvester, the $z$-component of the force is useful. The calculation of the force is also time-consuming, so the interpolation function $(F_{\text{EM}})_z(z, u_z)$ is also very valuable. Two interpolation functions allow one to define the power in the electrical and the mechanical domains, and determine the self-consistency of the method. Note that for the coil with a high inductance $L$, part of the energy is dissipated as electromagnetic waves, but for MEMS devices this effect is rather negligible. It is easy to see that the resulting expression for the force is proportional to $u_z$; this simplifies the final expression for the resultant electromagnetic force.

The self-consistency shows that the standard FEM gives rather small reliability with high execution time (Fig. 3). The representation of the magnet as an array of the magnetic dipoles gives much lower uncertainty. However, it could not be applicable for the definition of the magnetic induction inside of the magnet, because it gives a singularities near these points, described by the dipoles. Thus the most accurate and fast approach to represent the magnet as an equivalent coil. It is significantly more effective in the case of the magnet with the form of a block, because it can be reduced to the calculation of a linear integral. Moreover, the expression for

TABLE I
PARAMETERS OF THE SYSTEM [8]

| Parameter | Value |
|---|---|
| Magnet dimensions | $2.5 \times 2.5 \times 2.0 \quad \mathrm{mm}^3$ |
| Magnetization | $7.6 \times 10^5 \quad \mathrm{A/m}$ |
| Wire loop dimensions | $2.8 \times 2.8 \quad \mathrm{mm}^2$ |
| Number of loops in the coil | 144 |
| Resistance of the coil | $192 \quad \Omega$ |
| Magnet relative speed for the testing problem | $0.5 \quad \mathrm{m/s}$ |
| Wire loop resistance for the testing problem | $10.0 \quad \Omega$ |

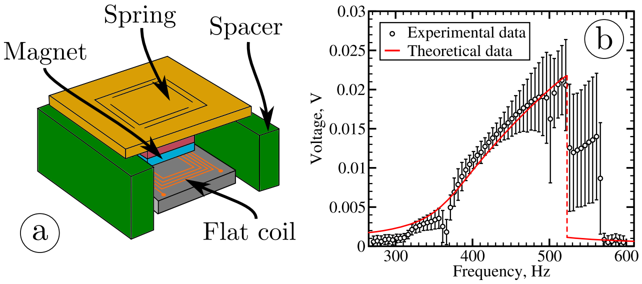

Fig. 4. a) The MEMS electromagnetic energy harvester; b) Comparison of the theoretical and experimental e.m.f.

the electromagnetic force and e.m.f. is proportional to the current in the equivalent coil which allows one to transform the approach for the properties of the real magnetic material.

## III. EXPERIMENTAL VERIFICATION

The methods described above were implemented for the translation vibration mode of a real [8] MEMS electromagnetic energy harvester (Fig. 4 a). It consists of a block magnet which is vibrating on the non-linear spring near a flat square coil. This device actually has not only the progressive mode, but also the rotational one [11]. However, these methods could also be implemented for the rotational motion. For the progressive mode, one can use a second order differential equation for the mechanical domain:

$$m\ddot{z} = -c\dot{z} - k(z)z + F_{\mathrm{EM}}(z,\dot{z}) + mA_{\mathrm{ext}}\cos(\omega_{\mathrm{ext}}t), \qquad (5)$$

where $m$ is the mass of the device, $c$ is the air damping coefficient, $k(z)$ is non-linear spring coefficient, $A_{\mathrm{ext}}$ and $\omega_{\mathrm{ext}}$ are the excitation acceleration and external frequency respectively.

This expression can define the displacement and velocity of the magnet, and therefore the e.m.f. of the harvester. The modelling shows rather good correlation (Fig. 4 b) between the model and experimental data (with the open circuit). The analysis of the given device shows that it is far away from the optimum, because the electromagnetic force acting on the magnet is negligible compared to the air damping coefficient. However, the correct model of electromagnetic interactions in the device allows to design a much more efficient harvester, and to predict it's power spectrum.

Our further investigations will be focused on developing the model for the rotational modes for the device, and the application of the approach to electromechanical systems with various geometries.

## IV. ACKNOWLEDGEMENT

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