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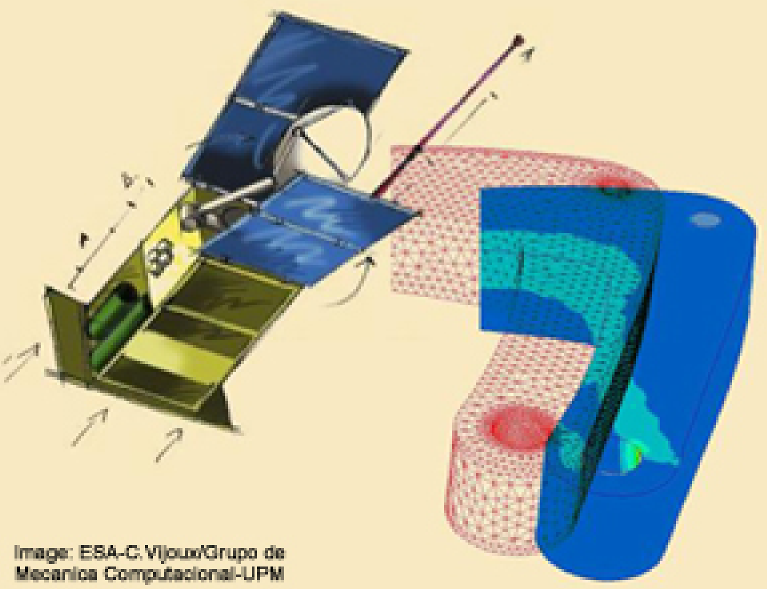

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CONTROLLED MULTIBODY SYSTEMS WITH MAGNETOSTRICTIVE ELECTRIC GENERATORS

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Abstract. *In the last few years, there has been a surge of research in the area of power harvesting for developing the alternative power sources for different micro-electromechanical devices and intelligent sensor systems. The proposed paper addresses the problem of modeling and analysis of controlled multibody systems with embedded magnetostrictive transducers. Main emphasis is put on the modeling of the considered mechatronic systems for applications in the field of power harvesting from vibrations, namely vibration-to-electric energy conversion, using novel giant magnetostrictive materials. Mathematical model of the considered mechatronic system has been developed. It comprises the constitutive equations of magnetoelastic behavior of magnetostrictive rod (active element of transducers), standard formulae of electromagnetism for induced voltage and current in the pick-up coil due to variation of magnetic field intensity, and finally the equations of motion of multibody system itself. The last one can be derived using one of the well-known multibody dynamics formalism. Assuming that massinertia parameters of magnetostrictive transducers are negligible small the inverse dynamics based algorithm has been proposed for modeling the controlled motion of multibody systems with embedded transducers. This algorithm is also suitable to evaluate electrical power output of magnetostrictive electric generators for different controlled motions of the system and to optimize the generators' design. The inverse dynamics based algorithm was implemented in Matlab/Simulink with user friendly interface. Its efficiency has been confirmed by simulation of performance of different magnetostrictive electric generators under the periodic excitations exerted by the "hosting" multibody system.*

1 INTRODUCTION

As technical systems (e.g. MEMS) and smart material technologies mature, embedded and remote systems are becoming more attractive. This is not only reason why a deep study of mechatronics and its interactions with multibody systems is important and necessary. Recently, giant magnetostrictive material technology has drawn a lot of attention both in academia and in industry. Over the last years, there can be seen many interesting applications of magnetostrictive actuators and sensors, e.g. in active vibration and noise control, structural monitoring, direct and indirect motional control, etc. [1-4]. Existing and potential applications for magnetostrictive transducers are numerous because the newer magnetostrictive materials, fabricated both in crystalline and amorphous form, can exhibit comparatively large coupling coefficients in the conversion of energy between magnetic and elastic states. Most of these applications make use of the so-called *Joule effect,* which is an anisotropic change of magnetostrictive elements in length due to application of magnetic field. *Joule effect* can also be determined as a transduction from electrical energy to mechanical energy. There is a reverse transduction which is called *Villari effect* [1, 4]. That is, by applying a mechanical stress (e.g. vibration field) to a magnetostrictive material, the magnetization along the direction of the applied stress of the material varies due to the magnetostrictive effect. The flux variation obtained in the material induces an *emf* in coil surrounding the material. Direct and inverse magnetostrictive effects applicable to actuator and sensor modes of operation are summarized in Table 1, while constructive details on such designs can be found in [1, 5].

Direct Effects	Inverse Effects
Joule Effect Change in sample dimensions in the direction of the applied field	**Villari Effect** Change in magnetization due to applied stress
Δ*E* effect Magnetoelastic contribution to magnetocrystilline anisotropy	Magnetically induced changes in the elasticity
Wiedemann effect Torque induced by helical anisotropy	**Matteuci effect** Helical anisotropy and emf induced by a torque
Magnetovolume effect Volume change due to magnetization (most evident near the Curie temperature)	**Nagaoka-Honda effect** Change in the magnetic state due to a change in the volume

Table 1: Magnetostrictive effects and their inverse.

In the last few years, there has been a surge of research in the area of power harvesting for developing the alternative power sources for different micro-electromechanical devices, intelligent sensor systems, etc. [6-20]. The term “power harvesting” is used for process of acquiring the energy surrounding a system and converting it into usable electrical energy. Solar power is one alternative power source that has been used to power wireless sensor devices. While solar power is abundant in some applications, it is unsatisfactory in many others. Mechanical vibrations have received attention from various researchers as a potential source of power for sensors and wireless electronics in a wide variety of applications [6-20]. One method is to use piezoelectric materials to obtain energy lost due to vibrations of the host structure. While piezoelectric materials are now major method of harvesting energy [6], other methods do exist; for example, methods based on *Villari effect* of magnetostrictive materials [1, 4]. Novel magnetostrictive materials are probably most prospective materials for vibration-to-electric energy conversion since they have high energy density and very high electromechanical coupling effect.

In Fig.1 the schematic representation of *Villari effect* is depicted. In this way the magnetostrictive electric generator (MEG) that utilizes vibrations to produce power can be designed. Three different sketches of MEG are shown in Fig. 2-4. Being incorporated into the structure of controlled multibody system, a MEG can also be used at the same time as a sensor for identification of the parameters of vibration and as a damper for attenuation of the vibration.

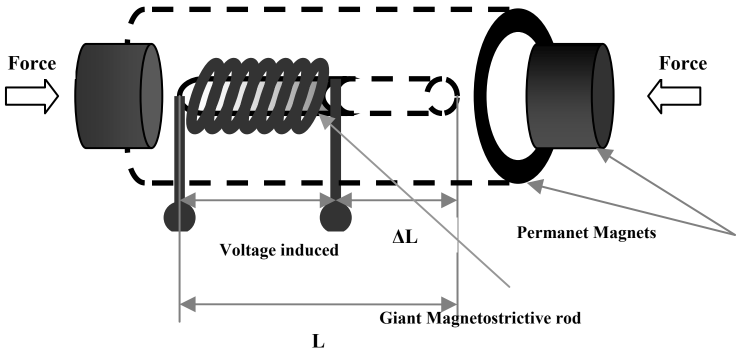

Fig. 1 Schematic of Villari effect.

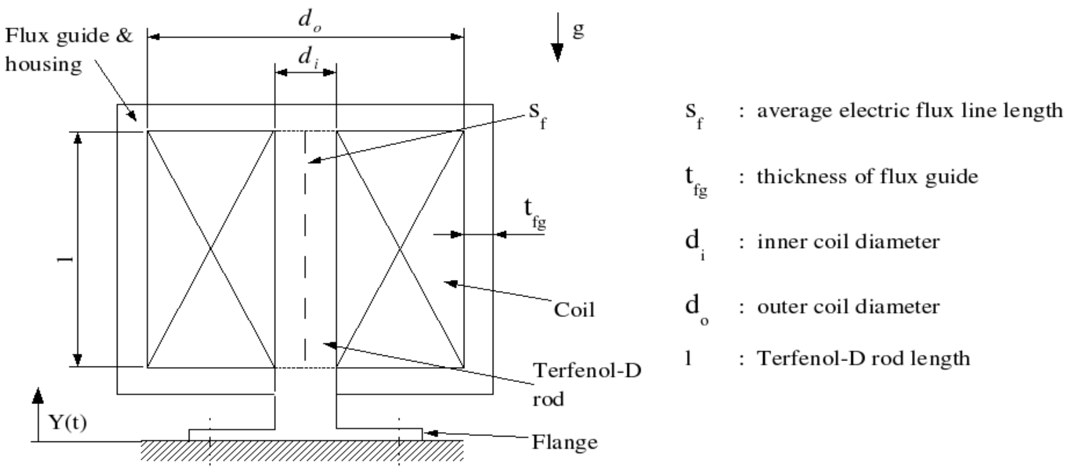

Fig. 2 Schematic diagram of MEG integrated into multibody system by flange.

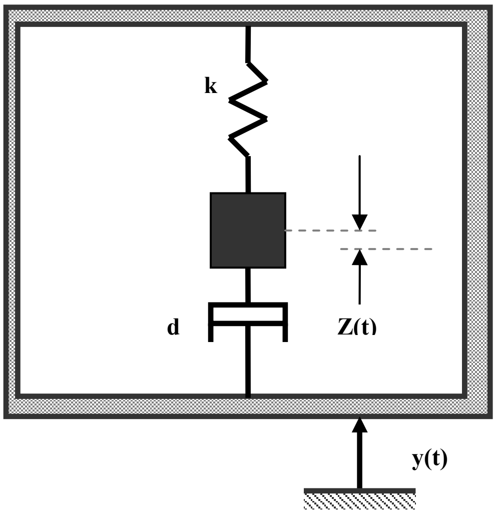

Fig. 3 Schematic diagram of the generator in micro level.

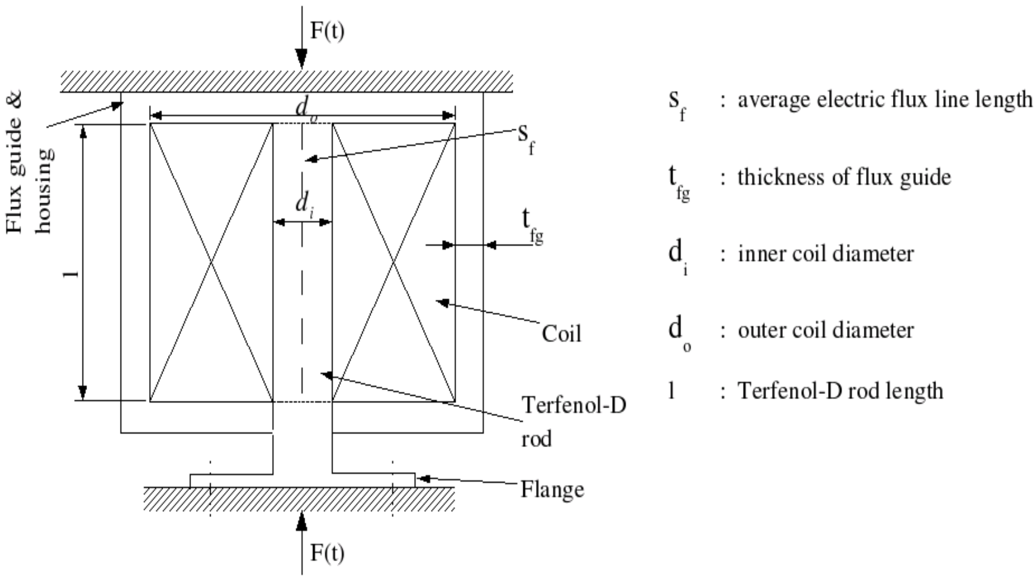

Fig. 4 Schematic diagram of clamped arranged MEG.

Operation of power harvesting devices that use magnetostrictive materials is based on dynamic interaction between magnetic and electric fields, inherent elastic properties of active material and mechanical vibration. To be able to analyze the energy transduction processes, to design and to optimize the performance of a magnetostrictive power harvesting device, it must be considered as a complex *magnetoelastic electromechanical system.*

The proposed paper addresses the problem of modeling and analysis of controlled multibody systems with embedded magnetostrictive transducers. Main emphasis is put on the modeling of the considered mechatronic systems for applications in the field of power harvesting from vibrations, namely vibration-to-electric energy conversion, using novel giant magnetostrictive materials.

2 MATHEMATICAL MODEL OF CONTROLLED MULTIBODY SYSTEM INTEGRATED WITH MAGNETOSTRICTIVE TRANSDUCER

Consider a multibody system having *n* degrees-of-freedom. Let the equations of controlled motion are as follows:

$$\mathbf{A}(\mathbf{y})\ddot{\mathbf{y}} + \mathbf{C}(\mathbf{y}, \dot{\mathbf{y}}) = \mathbf{u} \tag{1}$$

Here $\mathbf{y} = (y_1, y_2, ..., y_n)$ is a vector of generalized coordinates, $\mathbf{u} = (u_1, u_2, ..., u_n)$ is a vector of the controlling stimuli (forces, torques), $\mathbf{A}, \mathbf{C}$ are given matrices.

Let assume that the multibody system is integrated with a magnetostrictive transducer. In what follows it will also be assumed that the massinertial parameters of the magnetostrictive transducer are negligible small and the inherent dynamics of the transducer does not affect the dynamics of the multibody system.

A characteristic property of magnetostrictive materials (active material in magnetostrictive transducers) is that a mechanical strain will occur if they are subjected to a magnetic field in addition to strains originated from pure applied stresses. Also, their magnetization changes due to changes in applied mechanical stresses in addition to the changes caused by changes of the applied magnetic field. These dependencies can be described by mathematical functions [1]:

$$\varepsilon = \varepsilon(\sigma, H) \tag{2}$$

$$B = B(\sigma, H) \tag{3}$$

Here ε, σ, H be strain, stress and applied magnetic field strength, respectively, B be magnetic flux density.

Taking into account all above mentioned and the fact that the most important mode of operation of magnetostrictive materials is the longitudinal one, the linearization of the differential response of strain and magnetization (relations (2) and (3)) leads to the following equations of magnetomechanical coupling:

$$\varepsilon = S^H \sigma(\mathbf{y}, \dot{\mathbf{y}}) + d_{33} H \tag{4}$$

$$B = d_{33}^* \sigma(\mathbf{y}, \dot{\mathbf{y}}) + \mu^\sigma H \tag{5}$$

Here:

$S^H = \frac{\partial \varepsilon}{\partial \sigma}_{|H=const} = \frac{1}{E^H}$, where E^H be Young's modulus at constant applied magnetic field strength;

$d_{33} = \frac{\partial \varepsilon}{\partial H}_{|\sigma=const}$ be the magnetostrictive strain derivative (linear coupling coefficient);

$d_{33}^* = \frac{\partial B}{\partial \sigma}_{|H=const}$ be magnetomechanical effect;

$\mu^{\sigma} = \frac{\partial B}{\partial H}_{|\sigma=const}$ be magnetic permeability at a constant stress.

In equations (4), (5) the stress $\sigma(\mathbf{y},\dot{\mathbf{y}})$ characterizes the interaction between dynamics of multibody system (hosting system) and dynamics of magnetostrictive transducer. Below it will be assumed the following

$$\sigma(\mathbf{y},\dot{\mathbf{y}}) = f(\mathbf{y},\dot{\mathbf{y}},\mathbf{c}) \tag{6}$$

where function $f(\mathbf{y},\dot{\mathbf{y}},\mathbf{c})$ and vector parameter $\mathbf{c}$ are determined by the given magnetic design of a magnetostrictive transducer and by the design of adaptive structure that needed to integrate the transducer into hosting multibody system.

It's not necessary to assume the coefficients $E^{H}, \mu^{\sigma}, d_{33}, d_{33}^{*}$ are single valued or linear, however this is generally approach taken in many investigations of performance of magnetostrictive transducers [21].

Several important assumptions are built into the magnetostrictive model (equations (4), (5)). First, linear operation of active material (Terfenol-D [1]) in the magnetostrictive transducer is assumed. Although the magnetostrictive effect is nonlinear, for low signal levels, less than approximately one-third the maximum strain capability, the linear equations of magnetostriction provide a good first approximation [21]. Second, the magnetostriction process is assumed to be reversible according to

$$d_{33} = \frac{\partial \varepsilon}{\partial H}_{|\sigma=const} = \frac{\partial B}{\partial \sigma}_{|H=const} = d_{33}^{*} \tag{7}$$

Finally, strain, stress, *H,* and *B* are assumed to be uniform throughout the active material.

Equations (1) - (7) constitute the mathematical model of magnetoelastic mechanical system modeled the controlled multibody system integrated with magnetostrictive transducer. As indicated in (4)-(6), it is assumed that the stress σ depends on phase state of the multibody system $(\mathbf{y},\dot{\mathbf{y}})$, i.e. the dynamics of hosting system affects the performance of the magnetostrictive transducer.

3 INVERSE DYNAMICS OF CONTROLLED MULTIBODY SYSTEM INTEGRATED WITH MAGNETOSTRICTIVE TRANSDUCER

The developed mathematical model of controlled magnetoelastic mechanical system can be used for many applications. For instance, to solve the inverse dynamics problems for controlled multibody systems integrated with magnetostrictive transducers (actuators, sensors, MEG).

Consider the following problem.

Problem A. Let the motion of controlled multibody system (1) integrated with magnetostrictive transducer (4)-(7) is given, that is the time history of generalized coordinates are prescribed:

$$\mathbf{y} = \mathbf{y}_a(t), \qquad t \in [0,T] \tag{8}$$

where T is the duration of controlled motion of the system in question.

It is required to determine the control stimuli **u**(t) that is necessary to perform the prescribe motion (8), the voltage *U(t)* induced in coil surrounding the Terfenol-D sample, and the strain *ε(t)* in the active material of the magnetostrictive transducer.

The solution of the *Problem A* can be obtained by the following procedure.

Using equations of motion (1) the control stimuli **u**(t) needed for prescribed motion (8) can be calculated by the formula

$$\mathbf{u}_a(t) = \mathbf{A}(\mathbf{y}_a(t))\ddot{\mathbf{y}}_a(t) + \mathbf{C}(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t)) \tag{9}$$

For given magnetic design and adaptive structure of the magnetostrictive transducer (function $f(\mathbf{y}, \dot{\mathbf{y}}, \mathbf{c})$), the stress applied to active material during the prescribe motion $\mathbf{y} = \mathbf{y}_a(t), \quad t \in [0, T]$ of the hosting system is determined by expression:

$$\sigma(\mathbf{y}, \dot{\mathbf{y}}) = \sigma(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t)) = f(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t), \mathbf{c}) \tag{10}$$

From equations (5) and (10) it follows

$$B = d_{33}^{*} f(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t), \mathbf{c}) + \mu^{\sigma} H \tag{11}$$

The action of the applied stress produces a changing flux density *B* which according to Faraday's law induces a voltage, *U(t),* in a coil surrounding the Terfenol-D sample such that:

$$U(t) = -NA\frac{dB}{dt} \tag{12}$$

where *N* and *A* are the number of turns and the cross section area of coil.

This voltage will generate a current, *I*, in the coil, that according to Lenz's law will give rise to an opposing field, H_r :

$$H_r = \frac{NI}{l} \tag{13}$$

where *l* is the length of coil.

Using the equations (12), (13) and Ohm's law

$$I = U / R \tag{14}$$

the total applied field, *H,* will be given by formula

$$H = H_0 + H_r = H_0 - \frac{N^2 A}{Rl}\frac{dB}{dt} \tag{15}$$

where H_0 is a steady magnetic field, $R = R_0 + r$, R_0 is the electric circuit load, and r is the coil resistance.

Substituting expression (15) into equation (11) the following differential equation for magnetic flux will be obtained:

$$\frac{dB(t)}{dt} + cB(t) = f_a(t) \tag{16}$$

Here

$$\begin{aligned} & c = Rl/(\mu^\sigma N^2 A) \\ & f_a(t) = c(\mu^\sigma H_0 + d_{33}^* f(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t), \mathbf{c})) \end{aligned} \tag{17}$$

The solution to equation (16) be of the form

$$B(t) = e^{-ct}(B_0 + \int_0^t f_a(\tau) e^{c\tau} d\tau) \tag{18}$$

where $B_0 = B(0)$ is initial magnetic flux.

Using (12), (14), (16)-(18), and (4) the induced voltage, $U(t)$, and strain, $\varepsilon(t)$, in the magnetostrictive transducer are determined by the following expressions:

$$U(t) = -NAf_a(t) + cNAe^{-ct}[B_0 + \int_0^t f_a(\tau) e^{c\tau} d\tau] \tag{19}$$

$$\varepsilon(t) = \frac{1}{E^H} f(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t), \mathbf{c}) + d_{33}(H_0 - \frac{1}{c\mu^\sigma}(f_a(t) - cB(t)) \tag{20}$$

Here c, $f_a(t)$, $B(t)$ are determined by formulae (17) and (18), respectively.

If the magnetostrictive transducer is MEG, having the induced voltage (19) the electrical power can be evaluated as follows

$$P(t) = U^2(t)/R \tag{21}$$

So, the inverse dynamics problem for the controlled multibody system integrated with magnetostrictive transducer has solved.

4 EXPERIMENTAL DATA BASED SOLUTION OF INVERSE DYNAMICS PROBLEM FOR MAGNETOSTRICTIVE ELECTRIC GENERATOR WITH PERIODIC EXTERNAL EXCITATION

The developed algorithm for solving inverse dynamics problem *(Problem A)* can be used for many applications. This algorithm is based on linearized relations (4), (5) and can predict performance of magnetostrictive transducers within the frame of above listed assumptions.

From the other side there are a lot of experimental data on behavior of magnetostrictive materials. For instance, for a representative single Terfenol-D rod the magnetostriction and the magnetic flux density curves as the function of magnetic field intensity for various prestress levels are well-known [1]. This information can be used for modeling and design of magnetostrictive transducers for different applications.

In what follows, the MEG depicted in Fig. 2 will be considered. Performance of the generator will be predicted by solving inverse dynamics problem *(Problem A)* using experimental data available for Terfenol-D rod.

Let the input from the hosting multibody system to the MEG is given by periodic excitation:

$$Y = Y_0 \cos \omega t \tag{22}$$

where Y_0 is the amplitude and ω is the angular frequency.

The force acting on the Terfenol-D rod due to periodic excitation (22) can be calculated as follows.

$$F(t) = -\ddot{Y}(t)m + mg = m(g - Y_0 \omega^2 \cos \omega t) \tag{23}$$

where m is the mass of the generator except the Terfenol-D rod.

Using the experimental data of normalized magnetostriction for various prestress levels σ_0 as a function of an applied magnetizing field of a representative single Terfenol-D rod ([1], Fig. 3.5, page 214), the following approximation of the function $\varepsilon = \varepsilon(B, \sigma_0)$ can be found:

$$\varepsilon(t) = B^2(2900.24 + 0.799\sigma_0 - 0.253\sigma_0^2) + B^4(-1649.41 + 10.305\sigma_0 + 0.07\sigma_0^2) \tag{24}$$

The plots of function $\varepsilon = \varepsilon(B, \sigma_0)$ for different prestress levels σ_0 are depicted in Fig. 5.

The inverse of the function $\varepsilon = \varepsilon(B, \sigma_0)$ is given by the following formula:

$$B(t) = B(\varepsilon, \sigma_0) = \frac{1}{2}\left(\frac{756.899\sigma_0 b_1}{b_2 b_3} - 28.37\left(\frac{0.064 b_1^2 (105.55 + \sigma_0)^2}{b_2^2 b_3^2} + \frac{0.282\varepsilon(t)}{b_2 b_3} \right)^{\frac{1}{2}} \right)^{\frac{1}{2}} \tag{25}$$

$$b_1 = \sigma_0 - 108.711, \quad b_2 = \sigma_0 - 96.436, \quad b_3 = \sigma_0 + 242.619$$

Using the experimental data of magnetization for various prestress levels as a function of applied magnetic field ([1], Fig. 3.4, page 213), it is possible to find the approximation of the function $H(t) = H(B, \sigma_0)$. The following expression for this function can be proposed:

$$\begin{aligned} H(t) = {} & B(t)(0.014\sigma_0^2 + 4.959\sigma_0 - 9.739) + \\ & B(t)^2(-2.791\times10^{-16}\sigma_0^2 + 1.917\times10^{-14}\sigma_0 - 1.804\times10^{-13}) + \\ & B(t)^3(-0.186\sigma_0^2 + 4.724\sigma_0 - 76.467) + \\ & B(t)^4(3.941\times10^{-17}\sigma_0^2 - 4.8289\times10^{-15}\sigma_0 + 1.464\times10^{-13}) + \\ & B(t)^5(0.633\sigma_0^2 - 35.651\sigma_0 + 484.272) + \\ & B(t)^6(-5.054\times10^{-17}\sigma_0^2 + 3.149\times10^{-15}\sigma_0 - 2.005\times10^{-14}) + \\ & B(t)^7(-0.469\sigma_0^2 + 29.192\sigma_0 - 185.893) \end{aligned} \tag{26}$$

Several plots of function *H(t)* which is determined by formula (26) are depicted in Fig. 6.

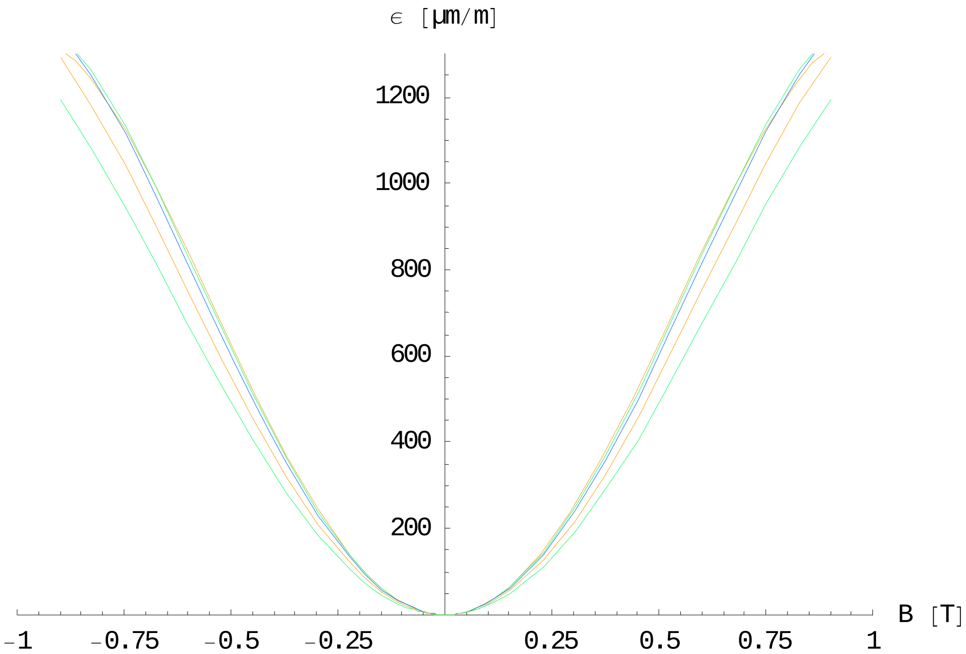

Fig. 5 Approximation of $\varepsilon = \varepsilon(B, \sigma_0)$ for different prestress values σ_0.

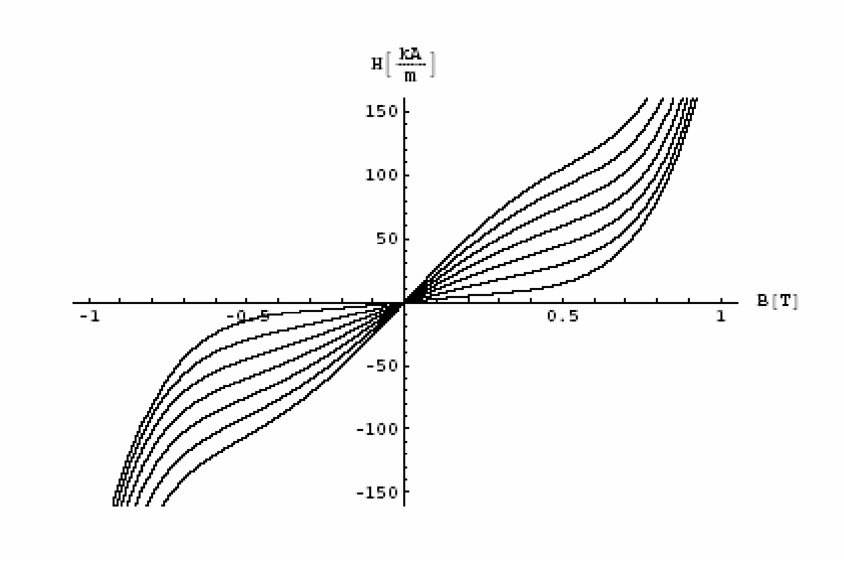

Fig. 6 Approximation of $H(t) = H(B, \sigma_0)$ for different prestress values σ_0.

Now the algorithm of solution of inverse dynamics problem is as follows.

1) Prescribe the external excitation *Y*(t) by formula (22) and define the value of all components of vector **c.**
2) Calculate excitation force *F*(t) by using formula (23).
3) Assuming that the strain in Terfenol-D rod can be determined by taking into account only mechanical stress as input to this active material the following formula will be used:

$$\varepsilon(t) = \frac{\sigma(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t))}{E^H} = \frac{f(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t), \mathbf{c})}{E^H} = \frac{F(t)}{E^H \pi r_{rod}^2} \tag{27}$$

Here r_{rod} and E^H are radius of circular cross section and Young's modulus of Terfenol-D rod.

4) Having the strain, the flux density *B*(t) and the magnetic field intensity *H*(t) can be calculated by using formulae (25) and (26), respectively.
5) Current *I*(t) generated in coil and induces voltage *U*(t) can be found by from equation (13) and Ohm's law (14).
6) Finally, electrical power *P*(t) of the considered MEG is evaluated by expression (21).

The described above algorithm was implemented in Matlab/Simulink with user friendly interface. In Fig. 7 several plots are presented to illustrate the solution of inverse dynamics problem by developed algorithm.

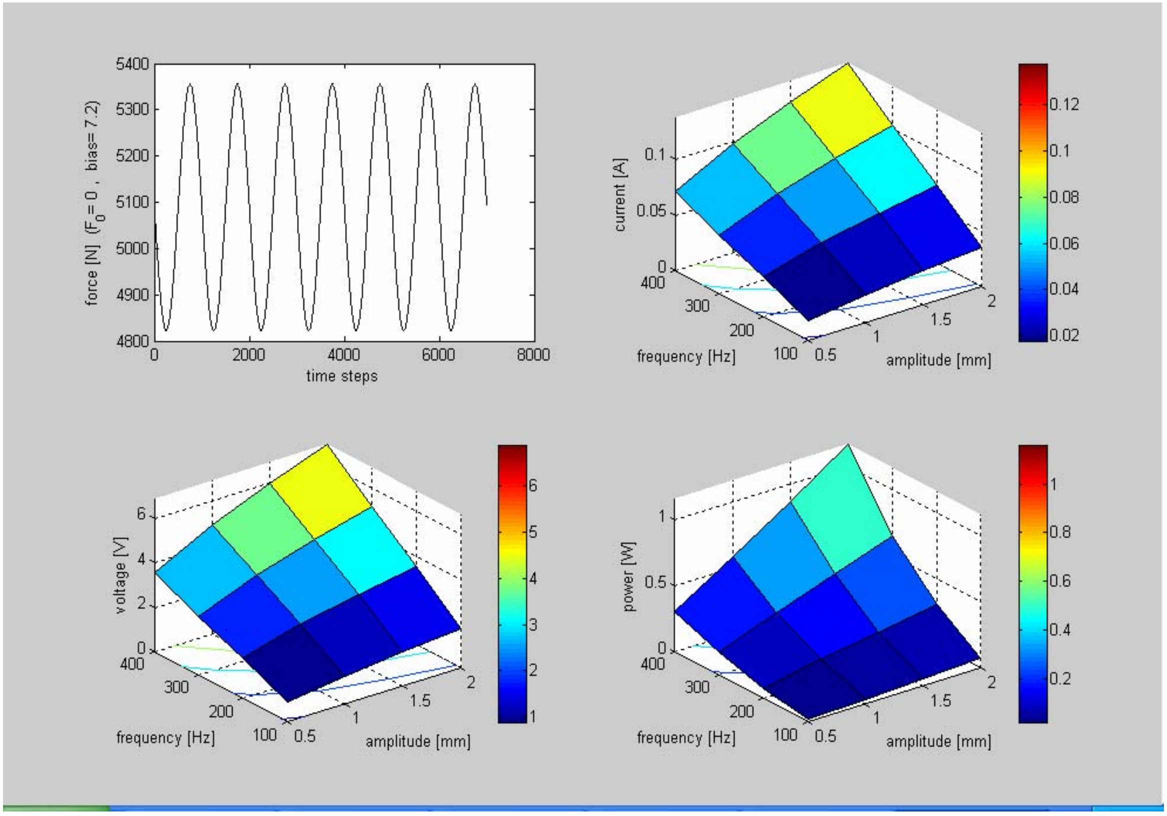

Fig. 7 Solution of inverse dynamics problem for MEG.

These plots correspond to performance of the MEG which is depicted in Fig. 2. The following data were used as input to the calculations: amplitude of excitation – 0.002m, frequency – 400Hz, rod radius – 0.015m, rod length – 0.050m, Young's modulus – 70000MPa, coupling factor – 0.75, coil diameter – 0.04m, number of coil turns – 600, resistance – 50 Ohm, prestress – 7.2MPa, coil efficiency – 0.3, and mass *m* – 0.6kg.

5 CONCLUSIONS

The mathematical model has been developed for modeling the controlled multibody systems with embedded magnetostrictive transducers (actuators, sensors, power harvesting devises). It comprises the constitutive equations of magnetoelastic behavior of magnetostrictive rod (active element of magnetostrictive transducer), standard formulae of electromagnetism for induced voltage and current in the pick-up coil due to variation of magnetic field intensity, and finally the equations of motion of multibody system itself. The last one can be derived using one of the well-known multibody dynamics formalism [22]. Assuming that massinertia parameters of magnetostrictive transducers are negligible small the inverse dynamics based algorithm is proposed for modeling the controlled motion of multibody system integrated with MEG or sensor. This algorithm is also suitable to evaluate electrical power output of MEG for different controlled motions of the system and to optimize the generator's design. The inverse dynamics based algorithm has been implemented in Matlab/Simulink. Its efficiency has been confirmed by simulation of performance of different MEG under the periodic excitations exerted by the "hosting" multibody system. The results obtained can be used for development of self-powered systems, active suspensions, power generators for MEMS applications, others.

6 ACKNOWLEDGMENTS

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