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SIMULATION MODELLING OF ELECTROMAGNETIC VIBRATION POWER GENERATOR

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Summary: *The paper deals with simulation of an electromagnetic vibration power generator. The vibration power generator harvests electrical energy from ambient energy of the mechanical vibration. This generator shows an alternative for supplying wireless sensors. The construction of the vibration power generator is tuned up to the resonance frequency and acceleration of the excited vibration. The harvested power depends on the excited vibration, proof mass of the generator, quality of the resonance mechanism, coil construction and connected resistance load. This paper describes suitable non-linear model of the vibration power generator and the simulation of the generated power in time domain.*

1. Introduction

The aim of our work is a development of the vibration power generator, which generates electrical energy from an ambient mechanical vibration. This generator shows an alternative for supplying wireless sensors with energy without the use of primary batteries. The generator extends the lifetime of the wireless sensor that can be mounted without any problems inside engineering constructions or can be placed inside embedded structures. The design of the vibration generator is tuned up to the frequency and amplitude of the excited vibration. The design of the vibration power generator is tailored to the excited ambient vibration, published in (Hadaš et al., 2005, 2006b), and the appropriate designed vibration power generator can produce the required power. The simulation modelling of this mechatronic system is very useful for tuning up of optimal generator parameters. The generator model can be excited by real vibration data and the expected generated output power and voltage are simulated in time domain.

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2. Electromagnetic Vibration Power Generator

The model of electromagnetic vibration power generator consists of:

- **Resonance Mechanism** is tuned up to the frequency of excited vibration and it provides a relative movement of magnetic circuit.
- **Magnetic Circuit** provides a magnetic flux through the coil. The magnetic circuit is a part and major mass of the resonance mechanism.
- **Coil** is usually fixed to the frame of the generator. The coil is placed inside the moving magnetic circuit.
- **Electrical Load and Power management** – The Power Management is used for rectification and stabilization of generated alternate voltage to the required value. The power management can determine the connected electric load. The power management can accumulate generated energy for non-excited time of the vibration power generator too.

The construction of all parts must be designed optimally against parameters of the whole vibration power generator. The individual parameters of mechanical and electromagnetic parts of the generator are in interaction. The resonance mechanism is tuned up to main frequency of vibration, but the parameters of resonance mechanism must be set up with dependence on required output power (Singule et al., 2006). The electromagnetic parameters affect behaviour of the resonance mechanism due to dissipating of electrical energy from this mechatronics system. The simulating modelling of this generator is used for optimal set up of all parameters in dependence on required output power, overall size, weight etc.

As the generator is excited by ambient vibration, the resonance mechanism produces a relative movement of the magnetic circuit against fixed coil. This relative movement induces voltage in coil turns due to Faraday's law.

3. Vibration generator model in state space

On the base of verified non-linear model published in (Hadaš et al., 2006a) the complex model of the vibration power generator was created. The state vector $\mathbf{x}^{\mathrm{T}} = \begin{bmatrix} x & \dot{x} \end{bmatrix}$, state matrix $\mathbf{A}$, $\mathbf{A_1}$, excitation matrix $\mathbf{B}$, output matrix $\mathbf{C}$, input vector $\mathbf{u}$ (excited vibration) and output vector $\mathbf{y} = \begin{bmatrix} u \end{bmatrix}$ are defined. The output u describes generated output voltage.

The state model of system is defined:

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{A}_1 + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} \end{aligned} \quad . \tag{1}$$

The dynamic model assumes the same design as is published in (Hadaš et al., 2006b). The resonance mechanism consists of lever, with inertia moment I, with arms r_1, r_2 and the stiffness k. The differential motion equation and voltage model (Hadaš et al., 2006b) are used. Thus, the state model of the vibration generator is:

$$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 \\ -\dfrac{k}{I} r_2^2 & -\dfrac{b_e}{I} r_1^2 - F_2 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ -\operatorname{sgn}(\dot{x}) \cdot F_0 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \mathbf{u} \tag{2}$$

where b_e is electromagnetic damping caused by generating electrical power and parameters F_0 and F_2 are coefficients of the friction force in the resonance mechanism. The coefficient F_0 is used in state matrix $\mathbf{A_1}$**,** because the model is non-linear and the direction of the friction force is against the state variable velocity $\dot{x}$, but the coefficient F_0 is independent of velocity, it only depends on the sign of velocity.

The output vector $\mathbf{y} = [u]$, which represents output voltage, is defined:

$$\mathbf{y} = \begin{bmatrix} 0 & N \cdot l \cdot B_x \dfrac{R_Z}{R_Z + R_c} \end{bmatrix} \mathbf{x}, \tag{3}$$

where parameter N is number of coil turns, l is active length of the coil turn, B_x is magnetic flux through the coil, R_c is inner resistance of coil and R_z represents resistance of electric load.

4. Model of Vibration Power Generator

Parameters of the vibration power generator published in PhD. Thesis Hadaš (2007) are used for simulating modelling. The CAD model of this generator is shown in Fig. 2. The resonance mechanics of the vibration power generator is tuned up to the stable resonance frequency 34 Hz of the ambient vibration. The generator is excited by vibration with the amplitude range of 50 – 150 μm; i.e. the level of vibration 0.2 – 0.7 G. The generator is capable to generate electrical energy with output power around 5 mW and output voltage of 2.5 V for average vibration level 0.4 G. The generator dimensions are 50 x 32 x 28 mm and the generator uses self-bonded air coil for harvesting of electrical power.

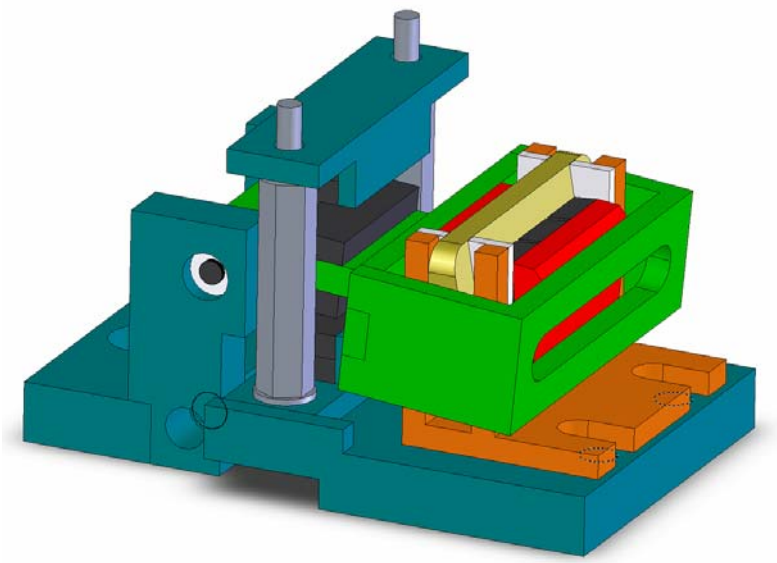

Fig. 1 CAD model of the vibration power generator

5. Simulation of Electromagnetic Vibration Power Generator

The Simulink environment was used for modelling of this complex system. The model consists of the resonance mechanism, electromagnetic circuit (magnetic circuit and coil) and electrical load. The model is excited by sinusoidal vibration or real vibration data and the response of system is analysed.

On the base of verified non-linear model published in (Hadaš et al., 2006a) the friction coefficients are estimated for the new design of the generator. The complex model of the whole generator was created in SIMULINK and it is shown in Fig. 2.

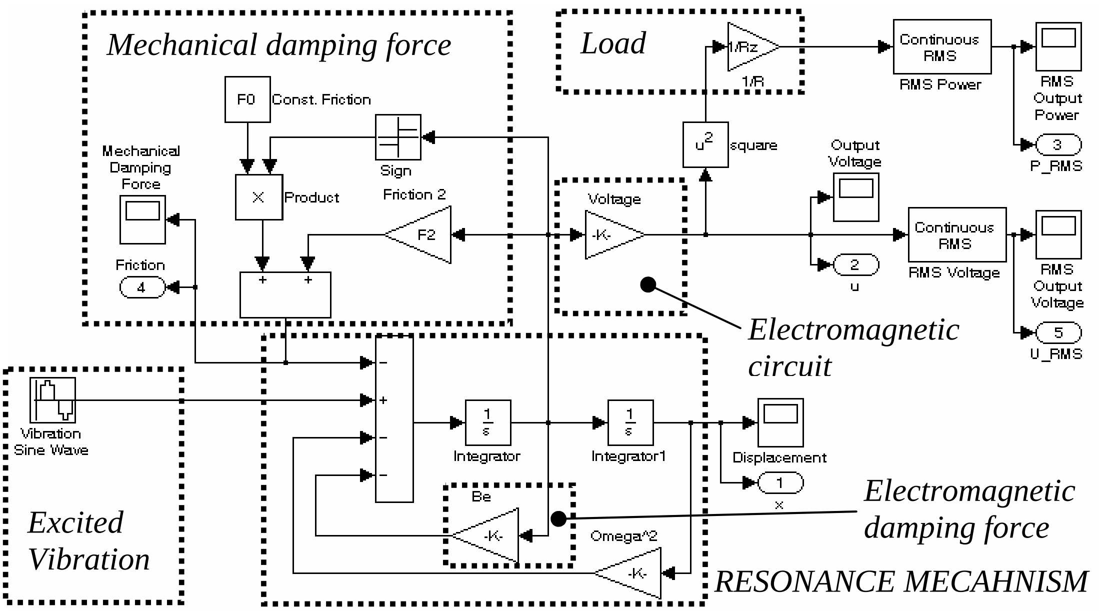

Fig. 2. Simulation Modelling of Vibration Power Generator

This model was used for optimization study of the vibration power generator. The generated power depends on the quality of resonance mechanism. This parameter is represented by friction forces in resonance mechanism F_0 and F_2. If the electromagnetic damping force in the generator, which generates useful electrical power, and the friction force in the resonance mechanism are equal the generator harvests the maximal electrical power. The electromagnetic damping depends on magnetic circuit (B_x), coil parameters (l, N, R_c) and resistance of electrical load R_z. The magnetic flux and active length of the coil depends on the generator design. Others parameters are chosen optimally for generating of required output power and voltage. The number of coil turns and resistance of connected electrical load affect electromagnetic damping force and the number of coil turns is optimized to appointed electrical load.

Fig. 3 shows the amplitude of magnetic circuit relative movement, output voltage and output power dependent on the number of coil turns for several magnitudes of connected resistance load. The number of coil turns, i.e. inner resistance of the coil, and connected resistance affect the generator behaviour as an electromagnetic force. The peak of output power corresponds to optimal coil turns for connected resistance load. Fig. 3 shows inner resistance of the coil dependent on coil turns too.

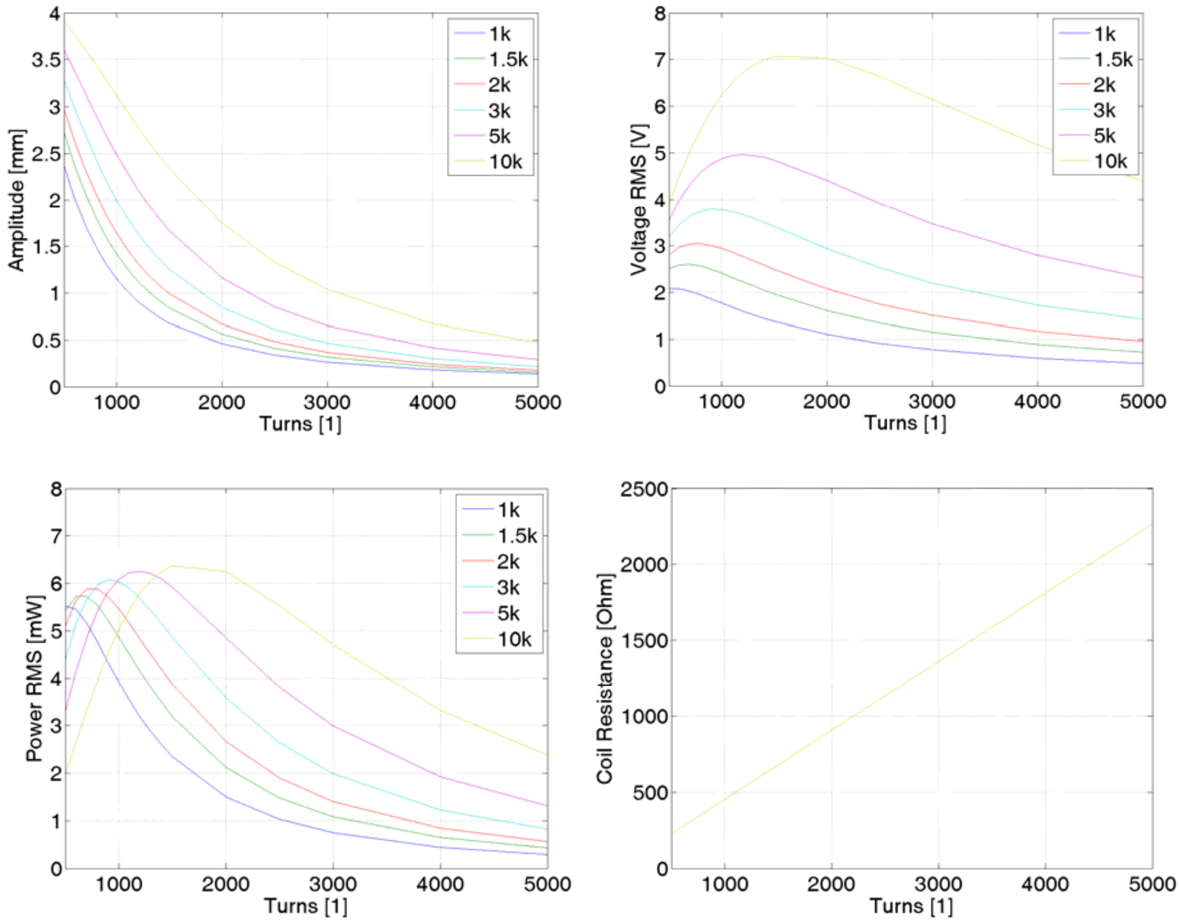

Fig. 3. Optimal coil turns vs. resistance load [Ω]

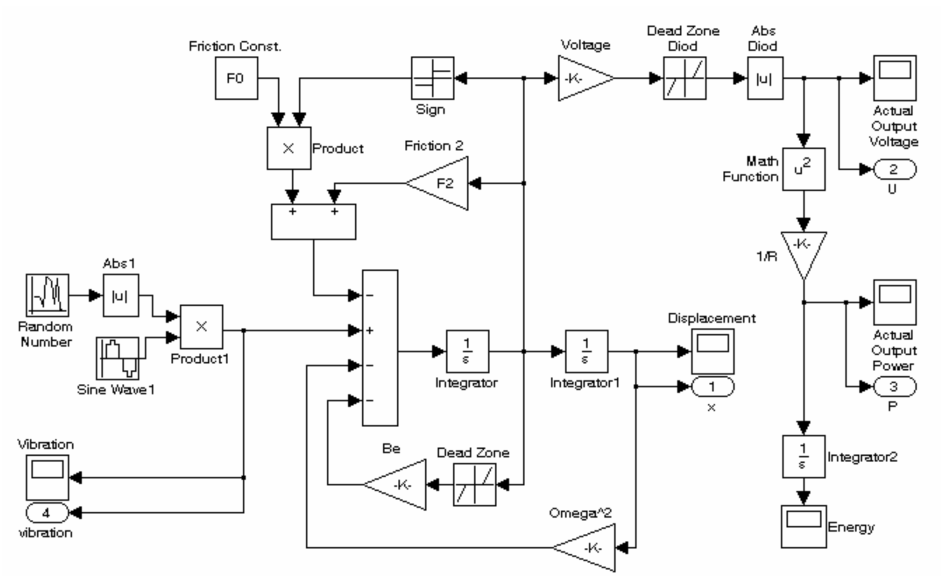

Fig. 4. Model of Vibration Power Generator with Diode Rectifier;
Excited by Random Vibration

Fig. 4 shows model of the vibration power generator excited by random vibration. The coil parameters for resistance load 5 kΩ are chosen from the analysis results in Fig. 3. The model of Grätz bridge (diode rectifier) is included too. This model can simulate exciting by random vibration and monitor amplitude of the relative movement, rectified output voltage and actual output power during all time of exciting by an ambient vibration. This simulation is shown in Fig. 5. The waveform of a random vibration is very similar to the real vibration. The real vibration has varied amplitude of deflection during excited time. The advantage of this model is exciting by the real vibration and monitoring of assumed output voltage and power. This process is very useful for design of optimal generator parameters.

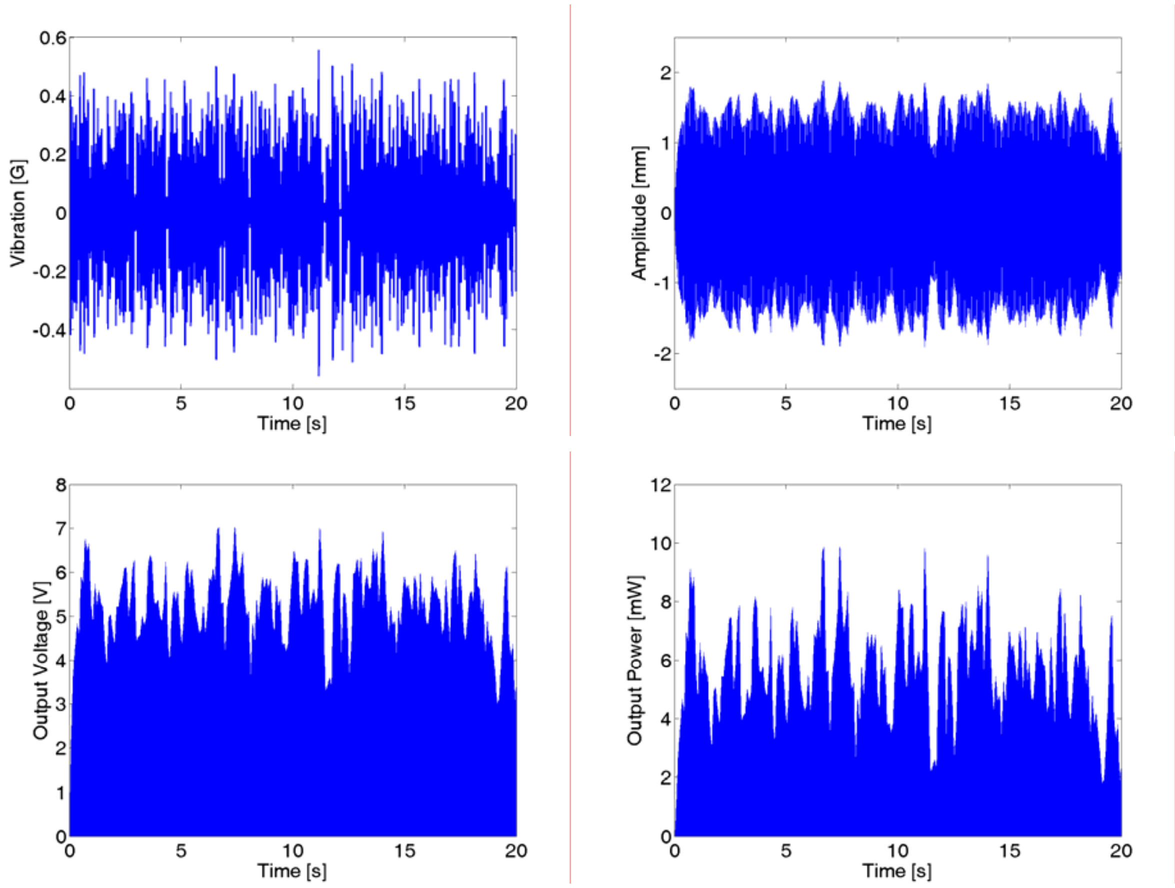

Fig. 5. Output Parameters in Time Domain; Excited by Random Vibration

6. Conclusions

The simulation of the vibration power generator is important for tuning up of the generator parameters to excited vibration. This generator model is able to be used for optimization and minimization study too. The simulating modelling of vibration power generator is useful for modelling of assumed harvested power during real vibration.

The power management for stabilization of generated voltage to the required value must be included in the real vibration power generator. The waveform of output voltage and power depends on level of the excited vibration and the amplitude of vibration is very varied in time.

Next function of the power management is accumulating of excess harvested energy for non-excited time of the vibration power generator.

The development of the vibration power generator has a great potential as an inexhaustible source of the electrical energy. The generator can provide sufficient electrical energy for wireless sensors in aeronautics applications.

7. Acknowledgement

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