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Analysis, design and optimization of vibration minigenerator

P. Fiala, T. Jirků
Ústav teoretické a experimentální elektrotechniky,
Fakulta elektrotechniky a komunikačních technologií, VUT v Brně,
Kolejní 4, Brno
E-mail : fialap@feec.vutbr.cz, jirku@ feec.vutbr.cz

Anotace:
Článek prezentuje výsledky analýzy vibračního minigenerátoru a pojednává o postupu jeho návrhu. Vibrační minigenerátoru je použit jako zdroj energie pro nezávislé elektronické obvody. Může být použit v různých oblastech, jako například doprava, elektronika, speciální stroje a robotika. Uvedená koncepce minigenerátoru obsahuje magnetické tlumení pohybu jádra. Generátor byl numericky analyzován a bylo ukázáno, že je možné dosáhnout významně většího výstupního výkonu a napětí, než tomu bylo u experimentálních sestav dříve [1].

Abstract:
The paper presents results of the analysis of the vibration generator. The paper deals with the design of a vibration generator that is used as a power supply for independent electric circuits. The vibration generator can be used in the various areas, e.g. traffic, electronics, special-purpose machines, and robotics. The proposed design employs magnetic damping of the core movement. It was numerically evaluated and it was shown that it was possible to obtain significantly larger output voltage and output power than in experimental settings used previously [1].

INTRODUCTION

The development of any new device always lays strong requirements on its reliability. The areas where reliability demands are of particular importance are transport, robotic and automotive applications. One of the ways to increase the sensor reliability is their supplying from autonomous power sources. Sensors used in industry and automotive systems can be placed at critical points, without supply and data transmission systems. These sensors monitor important quantities during the system operation. In the course of the revision, the operator just scans the device under test, and by using wireless transmission the needed data are retrieved from all sensors. These data can be then compared with those from a previous system operation and all other data available. This paper presents the results of a vibration mini-generator (MG) analysis. The MG is intended to provide power for the above sensors. The principle of its operation is based on the utilization of changes of the external mechanical forces, which can be described by Faraday´s law [1], [2]. The required output parameters are: output voltage between 3–5 V in the ideal case, output power 200–1000 µW. The value of output power depends on the type of the sensor used. The basic arrangement of the vibration generator is in Fig. 1. The red arrows have the meaning of the magnetization orientation. The MG body is tightly connected with the source of vibration – the fuselage, and thanks to the oscillation of the whole system the MG core starts moving with respect to the fuselage. The mechanical part of the MG is designed such that the MG core driven by external vibrations performs non-damped oscillations. The design of the MG allows oscillations of the MG core within quite a wide spectrum of external oscillation frequencies. The operation of the MG is based on Faraday´s law as follows from Fig. 2. The core containing ferromagnetic parts and permanent magnets (with high density of the stored energy, e.g. FeNdB, SmCo) that moves with respect to the winding connected to the shell induces in it a voltage and the external current connected to it starts carrying a current. Both the induced voltage and current in the external circuit are generally complex functions of time.

According to the research report [4] is possible to formulate the mathematical model of the generator in relation

$$m\ddot{z} + l_c\,\dot{z} + k\,z = \left(m_m + m_p\right)g(t) - \int_{V_J}\left(\boldsymbol{J}_v \times \boldsymbol{B}\right)\cdot \boldsymbol{n}\,dV - \int_{V_{Jc}}\left(\boldsymbol{J}_{circ} \times \boldsymbol{B}\right)\cdot \boldsymbol{n}\,dV \tag{1}$$

where m is total mass of the MG moving elements, m_m the magnet mass, m_P the spring mass,

$\ddot{z} = \frac{d^2 z}{d t^2}$ is the acceleration of the MG moving parts,

$\dot{z} = \frac{d z}{d t}$ is the velocity of the MG moving parts – v,

z is the Cartesian coordinate, t time, l_c the coefficient of damping, k the stiffness coefficient of the flexible MG parts, $\boldsymbol{B}$ the magnetic flux density vector, $\boldsymbol{J}_v$ the current density of the electrically conductive parts incurred by the influence of the eddy currents, $\boldsymbol{J}_{circ}$ the current density in the coil winding, i the instantaneous coil current value and g is the gravity constant.

Analytical solution of the instantaneous current value $i(t)$ of the MG loaded by the impedance Z is according to [4]

$$i(t)=\frac{U_i}{(R_v+\mathrm{Re}\{Z\})}\left[\frac{4}{\pi}\sum_{k_o=1,3,5,\ldots}^{\infty}\frac{\boldsymbol{sin}(k_o\,\omega t)-k_o\,\omega\tau\,\boldsymbol{cos}(k_o\,\omega t)}{k_o\left[1+(k_o\omega\tau)^2\right]}+\left[\boldsymbol{tanh}\left(\frac{T}{4\tau}\right)-1\right]e^{-\frac{t}{\tau}}\right] \tag{2}$$

where T is the signal period length, R_v is the resistance of the real coil winding, L_v is the induktance of the real coil winding, U_i is the voltage induced in the conductor, ω is the angle velocity $\omega = 2\pi/T$, and τ is the time konstant $\tau = (L_v+Im\{Z\})/(R_v+ Re\{Z\})$.

The exciting vibrations spectrum is possible to be wider in the operating mode of the MG. The instantaneous current value $i(t)$ will be of the periodic character and the solution aim is to set such conditions, which will cause the minimal damping l_c for the whole exciting frequency spectrum.

Typical oscillation frequencies of the vibration source that were measured at two places of one investigated device (aircraft) are, for an illustration, shown in Fig. 3. The graphs express the square of amplitude of the movable parts on external oscillation frequencies (the amplitudes are, moreover, related to quantity g=9.81 m/s^2).

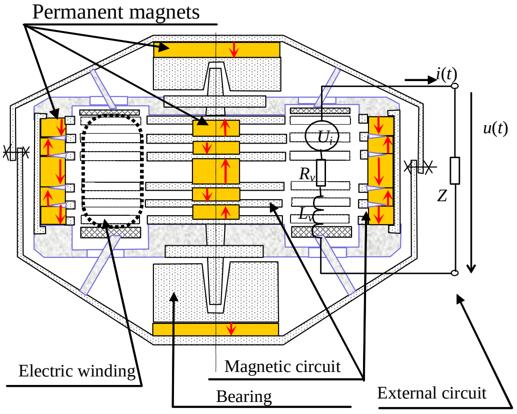

Fig. 1: The basic arrangement of the investigated device

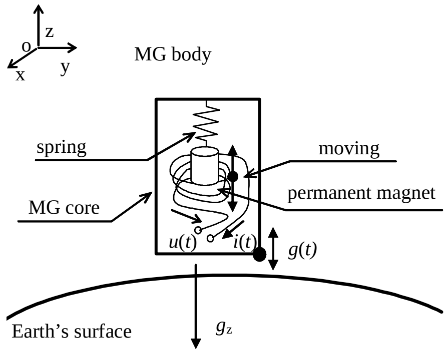

Fig. 2: The principle of a vibration minigenerator

MATHEMATICAL MODEL

The mathematical model of the problem consists of a partial differential equation describing the distribution of electromagnetic field in the device and two ordinary nonlinear differential equations describing the behavior of external electric circuit and mechanical movement the movable parts of the generator. The electromagnetic and mechanical phenomena strongly influence one another. The generator (Fig. 4) whose volume is denoted by letter Ω contains several important sub-domains (Fig. 5) of different physical parameters. These sub-domains are denoted as Ω_Fe - ferromagnetic parts of the magnetic circuit, Ω_p - permanent magnets, Ω_W - windings. Other sub-domains are, for example, spring, shell and air. The electromagnetic part of this coupled model may be described by the reduced Maxwell equations:

$$\mathrm{curl}\,\boldsymbol{H}=\boldsymbol{J}\ \text{ in }\Omega,\ \mathrm{div}\,\boldsymbol{B}=0\ \text{ in }\Omega,\qquad \mathrm{curl}\,\boldsymbol{E}=-\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\ \text{ in },\Omega_\mathrm{w} \tag{3}$$

where $\boldsymbol{H}$ is the magnetic field intensity vector, $\boldsymbol{E}$ the electric field intensity vector and $\boldsymbol{J}$ the current density vector. Material relations are represented by relations

$$\mathrm{div}\,\boldsymbol{J}=0\ \text{ in }\Omega_\mathrm{w},\ \boldsymbol{B}=\mu_0\mu_\mathrm{r}\boldsymbol{H}\ \text{ in }\Omega_\mathrm{Fe},\qquad \boldsymbol{B}=\mu_0\mu_\mathrm{r}\boldsymbol{H}+\mu_0\boldsymbol{M}\ \text{ in }\Omega_\mathrm{p},\ \boldsymbol{J}=\gamma\boldsymbol{E}\ \text{ in }\Omega_\gamma \tag{4}$$

where μ_0 is the permeability of vacuum, μ_r the relative permeability, $\boldsymbol{M}$ the remnant intrinsic magnetization vector of permanent magnet, γ the specific electric conductivity and Ω_γ any from the above sub-regions with nonzero electrical conductivity. After introducing magnetic vector potential by equations

$$\mathrm{curl}\,\boldsymbol{A}=\boldsymbol{B},\ \mathrm{div}\,\boldsymbol{A}=0,\ \boldsymbol{E}=-\mathrm{grad}\,\varphi-\frac{\mathrm{d}\boldsymbol{A}}{\mathrm{d}t}. \tag{5}$$

The symbol $\boldsymbol{A}$ means the magnetic vector potential and the symbol φ is the electric scalar potential.

Eddy currents in the electrically conductive parts (that are not connected to external sources) of density $\boldsymbol{J}_\mathrm{t}$ generally consist of two components: current density due to temporal ($\boldsymbol{J}_\mathrm{eddy}$) and spatial ($\boldsymbol{J}_\mathrm{m}$) changes of magnetic field. Similarly, the voltage induced at the terminals of the winding consists also of two components due to temporal and spatial variation of magnetic field. The total current passing through the external circuit is then given from solution of the corresponding circuit equation whose form depends on the character of the load (consisting mostly of a resistance and inductance). The electromagnetic model together with the circuit equation has to be supplemented with another nonlinear ordinary differential equation for the mechanical circuit. Considering that the movement is realized in the direction of axis *z*, this equation may be written in form

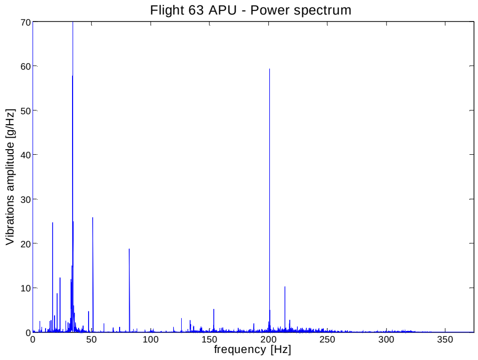

Fig. 3: Squared relative amplitudes of vibrations versus external frequency of oscillations (measured at two different places of an aircraft)

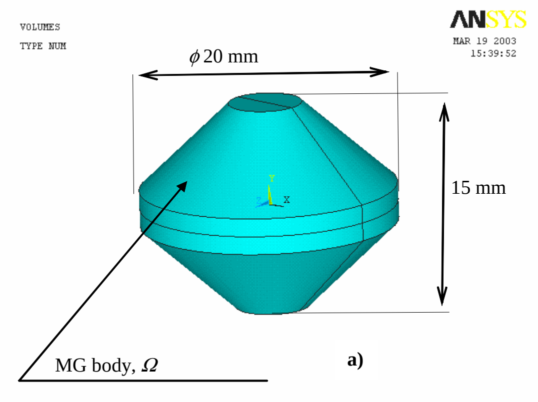

Fig. 4: Overall view of the device

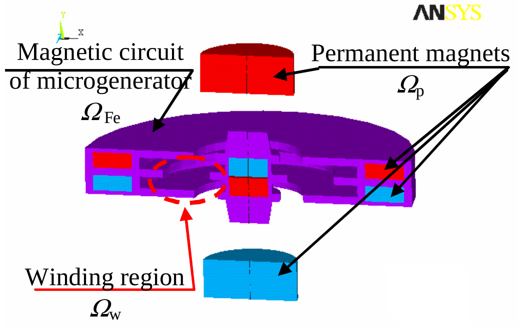

Fig. 5: Particular subregions in the device

$$m\ddot{z} + l_c\,\dot{z} + k\,z = \sum F \qquad (6)$$

Symbols used on the left side of this relation are described below the relation (1) and Σ***F*** is the total external force acting on the movable parts that consists of their weight and forces of magnetic origin. After applying of the Galerkin method the continuous model is transformed to a finite-element model.

The model for basic geometry solution was created and analysed as quasistationary. It has been solved using ANSYS supplemented with a number of own scripts and macros. Fully dynamic model respecting the time dependency of the source and the load of the MG according to relations (1) and (2) was created and solved with the help of the semianalytic form of the relation (6) in the MATLAB application – closer information is described in the work [4].

MODEL OF MINI-GENERATOR IN ANSYS PROGRAM

The geometrical model was created with standard tools in the ANSYS program [5] and with the aid of automated mesh generator. The element applied is SOLID97. The ferromagnetic material is non-linear with the *B*-*H* curve of steel given by the ČSN 15670 standard. The properties of the FeNdB permanent magnet were taken over from the data sheet of the magnet manufacturer.

RESULTS OF NUMERICAL ANALYSIS

The modules of vector distribution of magnetic flux density ***B*** is shown in Fig. 6.

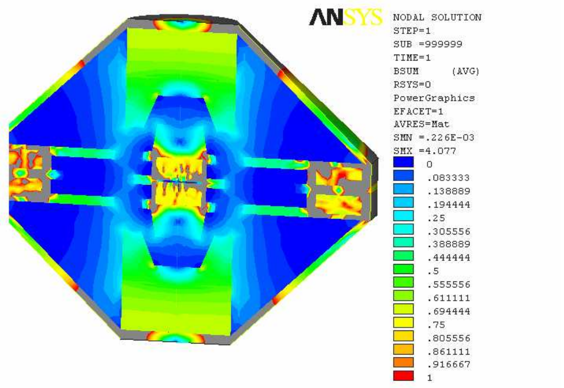

Fig. 6: Evaluation of modules of magnetic field density ***B***

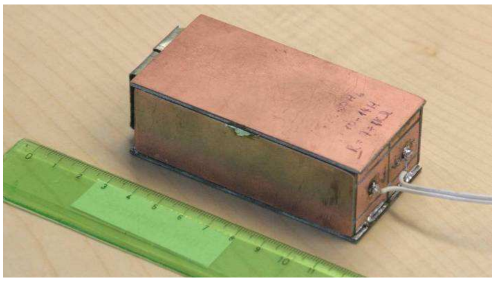

Fig. 7: Functional sample of a generator version (10÷100) mW

The model is fully 3D. No symmetries were used in the model. This is due to the convergence evaluation and error estimation [6], [7].

EXPERIEMNTAL REALIZATION OF VIBRATIONAL GENERATOR

Several prototypes of mini-generators of different constructions were realized. Fig. 7 shows the prototype of a minigenerator of output P_{out} = 10÷100 mW.

Tab. 1: Measured values of generator output voltage

Δx (mm)	U_{p-p} (V)	f (Hz)	U_{max-p} (V)	a $(ms^{-2})/g$	f_{cent} (Hz)
0.4	26	27-38	46	0,586149	36-37
0.2	14	27-38	36	0,293074	38
0.1	8	27-38	18	0,146537	38
0.05	4	28-38	7	0,073269	31

The prototypes were tested on a vibration bench during their development. The non-harmonic periodical voltage transients were obtained by measurement for vibration displacement within the range $\Delta x \in <0.1,0.4>$ mm. The vibration bench measurements were performed for various bench displacements (see Tab. 1). The theoretical values of generator output parameters are listed in Tab. 2. This is necessary to verify by experiment.

Tab. 2: Theoretical and experimental values of generator output voltage

Δx (mm)	U_{rms}(V) theoretical	U_{rms}(V) measured	f(Hz)	P_{rms} (mW)	Z (Ω)
0.3	0,75	0.6	34	**1**	**50**
0.3	1,09	0.890	34	**3**	**100**
0.3	1,87	1.5	34	**5**	**500**
0.3	3,17	1.82	34	**11**	**1000**
0.3	3,52	1.934	34	**5,39**	**1200**
0.3	3,47	1.85	34	**6**	**2000**
0.3	3,31	1.72	34	**4**	**5000**
0.3	2,35	1.52	34	**3**	**10000**

Experimental generator with the maximal output power P_{out}=10mW, dimensions 25x27x50 mm, winding with N=10000 turns , electric wire ϕ=0.05 mm Fig.8. was tested on the vibration , Fig.9.

Fig. 8: Functional sample of a generator version P_{out}=10 mW

The prototypes 10mW version of generator was tested without impedance on the output and output voltage was U_{p-p} = 4-5V P-P . Therefore output power was evaluated like a minimal 1.3 mW , g=0.65 G. After the design changing was test repeated and appended the electronic power management and the parameters was: output current I_{rms}=4.409mA, U_{p-p}=13,01V, P_{out}=14,946mW. The example of output values is on the Fig.10.

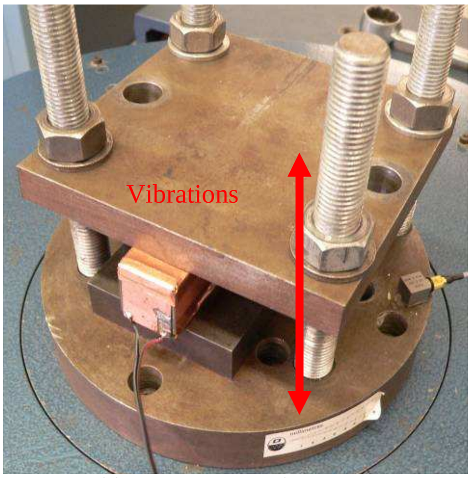

Fig. 9: Testing of functional sample of a generator version P_{out}=10 mW

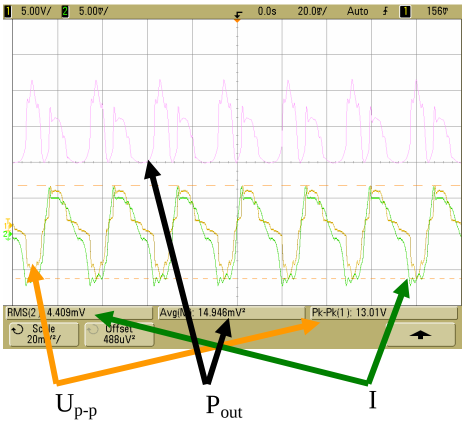

Fig. 10: Testing of functional sample of a generator version P_{out}=10 mW with electronic power management

CONCLUSIONS

The paper represents a part of an introductory study of the vibration MG design. It is intended as a preparation for a proposal of the 6th General European Project. The paper presents results of the distribution of magnetic and electric field strengths and flux densities. In order to get voltage of required time dependence it is possible to suitably modify the shape of the winding (the details are discussed in [4]). The time domain simulations were performed using the lumped equivalent circuit in the MATLAB program. This approach is not very accurate in comparison with FEM capabilities. However, this approach is substantially faster. The results of the analysis serve as a foundation for the design of the minigenerator.

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