Advanced Numerical Modeling of an Electromagnetic Vibration Transducer

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Abstract: The first analytical model to describe the electromechanical coupled dynamics of resonant vibration scavengers has been introduced 1996 by Williams and Yates. This model is well known in the energy–harvesting society and was continuously extended to promote a more in–depth understanding of the basic bahaviour and characteristics of resonant vibration converters. However, to design an optimal electromagnetic vibration converter for a given vibration–spectra the analytical model reach its limits. This paper presents results of a numerical model to simulate a vibration converter under realistic conditions and to find optimal parameters. Finally a virtual operation will be performed and discussed for excitation with a given measured acceleration profile.

Keywords: Energy harvesting, Electromagnetic, Micro-generator, Optimization

1. INTRODUCTION

The intention of a kinetic energy–harvesting device is to convert ambient vibration into electrical energy to power a wireless sensor node. For the development of such systems there has been a growing interest during the last few years and a lot of excellent research activities are in progress. In a large number of publications the design–flow is described to first build up a vibration converter and afterwards to adjust the vibration condition in such a manner that it is suitable for the given generator. But for application oriented developments one often needs to go the other way round. Here the vibration spectrum is given and the question is how to build up a preferably optimal generator? If the excitation is harmonic and the frequency constant the analytical model may be used for a specific design. Unfortunately in reality the vibration source is often nondeterministic in nature contains impulses and other irregularities. Moreover, a couple of nonlinear effects that take place in real devices make it even more complicated. The answer for an optimal generator can therefore not be given immediately. This paper describes a numerical modeling approach for the simulation and optimization of an electromagnetic kinetic energy harvesting device under realistic condition.

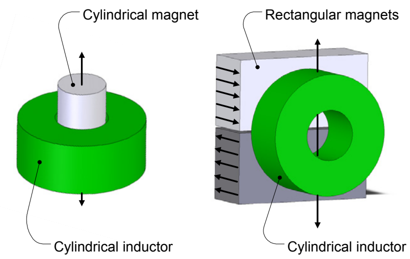

Figure 1: Device concepts for electromagnetically coupling

2. ELECTROMAGNETIC COUPLING

On the basis of Faraday's law of induction an emf (electromotive force) will be induced in every closed loop if the magnetic flux through this loop changes. This is basically the effect used in electromagnetic energy harvesting converters. The engineering design on how to produce such magnetic flux changes can be very different. Therefore a coupling coefficient can be defined which links the induced voltage U_{ind} with the velocity $\dot{z}$ and the force F with the current i in the coil:

$$U_{ind} = k_t \dot{z}, \qquad F = k_t i \,. \qquad (1)$$

In linear model analysis k_t is often defined by $k_t = NBl$ which is easy to handle and acceptably fits the arrangement in Figure 1 (right). For the popular arrangement in Figure 1 (left) this expression cannot be used. Consequently the gradient of magnetic flux has to be calculated which can be

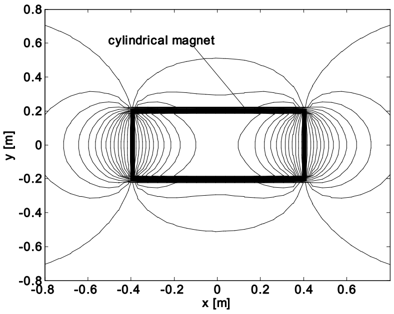

Figure 2: Residual magnetism in x-direction of a cylindrical NdFeB Magnet using the vector–potential of a solenoid

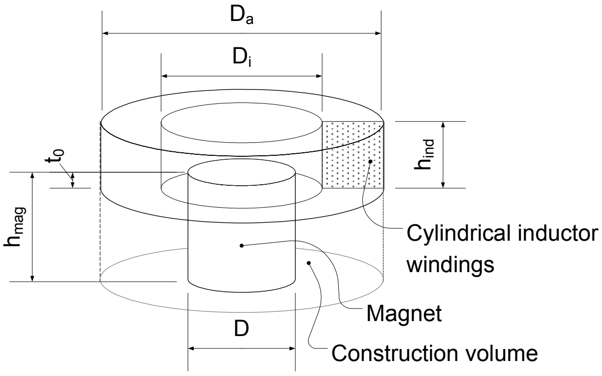

Figure 3: Principal measurement setup for the model verification with its parameters

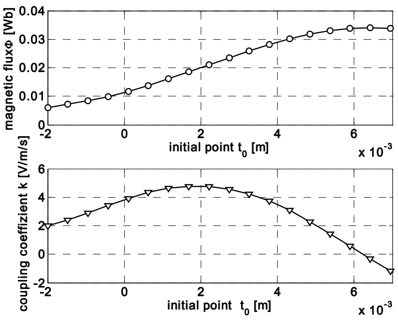

Figure 4: Magnetic flux in the solenoid for different initial positions t_0 (above) and resulting coupling factor (beyond)

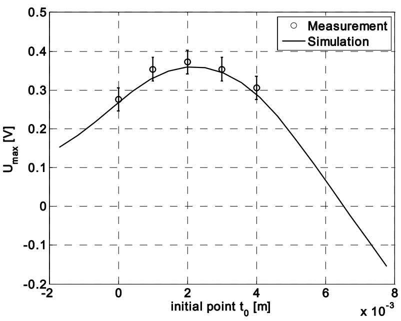

Figure 5: Measured voltage at different initial positions compared to the simulation result

Table 1: Parameter values for the verification of the electromagnetic coupling calculations

Magnet

Parameter	*Value*	*Meaning*
D	4 mm	Diameter Magnet
h_{mag}	8 mm	Length Magnet
B	1,25 T	Residual magnetism

Solenoid

Parameter	*Value*	*Meaning*
D_a	11,8 mm	Outer inductor diameter
D_i	5 mm	Inner inductor diameter
h_{ind}	5 mm	Height of the inductor
d_{wire}	40 µm	Diameter of the wire
R_i	530 Ω	Resistance

done using Finite Element Analysis (FEA) method [1]. Here the vector potential of a cylindrical inductor is used to determine the magnetic field of a cylindrical magnet [2] (Figure 2). The solution contains elliptic integrals which must be solved numerically. Once implemented for example in a Matlab environment the calculation of magnetic flux gradients for any cylindrical magnet to solenoid arrangement can be performed. The results can be verified on measurements with a sample magnet to coil arrangement (Figure 3). The dimensions are listed in Table 1. For different initial points t_0 the magnetic flux in the coil was calculated (Figure 4 above). The coupling factor is simply the derivative of the magnetic flux function (Figure 4 beyond):

$$U_{ind} = -\frac{d\phi}{dt} = -\left(\frac{d\phi}{dz}\cdot\frac{dz}{dt}\right) = -\frac{d\phi}{dz}\cdot\dot{z}\,. \qquad (2)$$

The coupling factor can be assumed to be constant for little elongations and it gets maximal for an initial point of 2 mm which is around 40% of h_{ind}. This is an important result and holds for any device with the considered concept. For the verification the magnet was exited with a lab shaker and swings with a harmonic motion (75 µm amplitude at 160 Hz) around different initial positions. The measured output voltage compared to the simulation is shown in Figure 5. Since the exact magnetic flux function and coupling factor can now be computed for any geometry, optimization calculations can now be performed. The procedure is briefly demonstrated for a simple example. We assume a given cylindrical construction volume of 1 cm³ with *Da=1.2 mm* and an excitation of 5 m/s² at 80 Hz. For the optimization two parameters have to be considered. The first one is the coupling factor which should be maximal to produce a preferably high voltage and the second one is the mass which should also be as high as possible to produce high inner velocity. However, these two parameters evoke a trade–off with respect to the mass. Maximum k_t results for a rather small magnet whereas a maximum velocity is obtained for the biggest possible magnet. The optimum results for a superposition of both parameters (Figure 6). For the given volume and excitation the best possible generator will contain a magnet with *D=8mm* and h_{mag}*=6mm*.

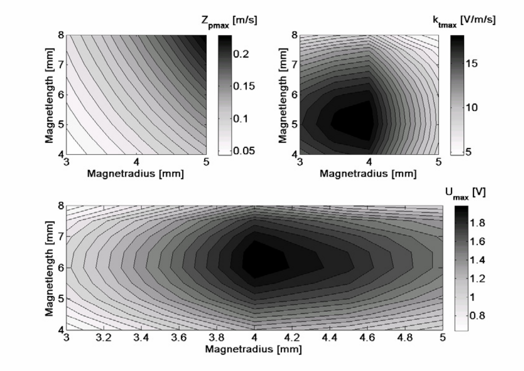

Figure 6: Resulting maximal values of mass velocity, coupling factor and induced voltage

3. GENERATOR MODEL

To predict the behaviour of an energy harvesting device under realistic condition it is necessary to build up a model containing also realistic effects. Therefore the well known resonant spring–mass–damper model [3] has been enhanced and implemented in Matlab/Simulink. In this model the effects of nondeterministic excitation, nonlinear spring and damper, inelastic collision of mechanical stop and load circuit containing full wave rectifier with forward voltage drop of the diodes can be investigated (Figure 7). Also here the procedure should be discussed for an example excitation profile (Figure 8).

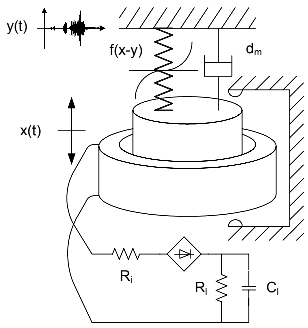

Figure 7: Overall model of the vibration transducer

How to optimize the electromagnetic coupling has already been explained. Thus the mechanical system and load circuit needs to be optimized for the sample excitation. First of all we perform a fully transient analysis with a variety of linear and nonlinear spring characteristics, where the restoring force is calculated by [4]:

$$f(z) = kz\left(1 + \mu k z^2\right). \qquad (3)$$

where k is the spring constant and μ the nonlinearity coefficient ($\mu>0$ hardening–, $\mu<0$ softening behaviour). In this simulation the mass is assumed to be 10g and the maximum inner elongation is limited to 1mm by the mechanical stop. The nonlinearity is furthermore limited for both hardening and softening behaviour. The restoring force of the softening springs are strictly increasing and the maximum restoring force of a hardening spring at 1mm is twice as much as that of the linear spring. The result is shown in Figure 9. For the given excitation the highest amount of power can be converted with a nonlinear spring. Compared

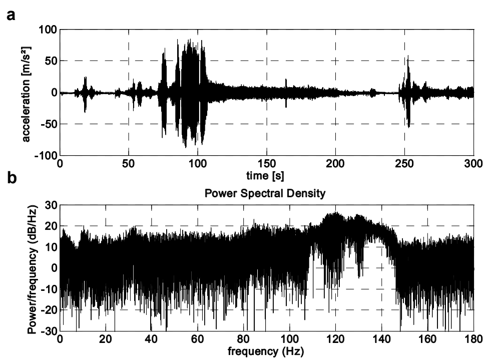

Figure 8: Example nondeterministic excitation profile (a) and the corresponding power spectral density (b)

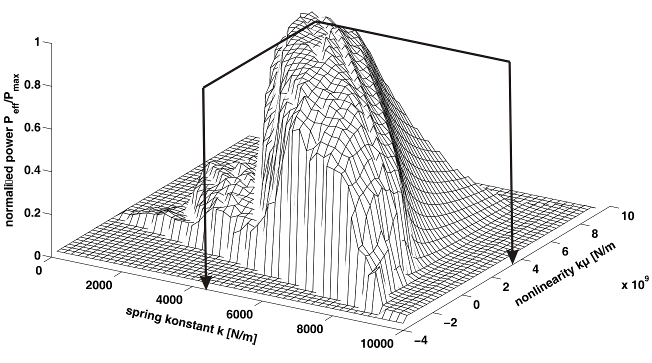

Figure 9: The most power can be extracted with a nonlinear hardening spring

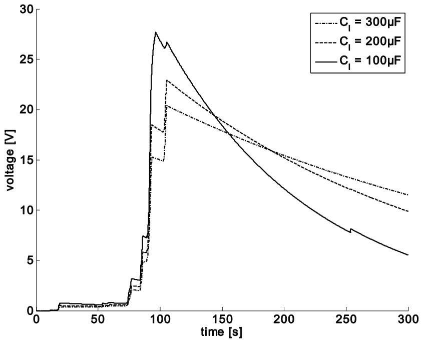

Figure 10: Transient analysis of an optimized converter with different load capacitors and 1MΩ load resistor

to a linear spring where $k\mu=0$ the power can be increased by 10 % for the given excitation profile. It must be pointed out, that nonlinear springs are not necessarily better. For a linear spring the maximum Power is in agreement with that of the PSD ($k=5500 \rightarrow \approx 120Hz$). At this point one needs to be careful, since the resonant conversion mechanism is dependent on the frequency and the highest value in the PSD is not necessarily the point where the most energy can be converted. That means that lower powerlevels in the input signal at higher frequencies can possibly be more efficient than higher powerlevels at lower frequencies. In a final step we address the electrical circuit which is implemented in a rather simple manner. Therefore we can not really talk about optimization since a real load circuit will be much more complicated. Nevertheless interesting and considerable results can be obtained. First of all we perform transient analysis with different resistors to obtain resistance matching. In this simulation the internal resistance of the coil was 3kΩ. Maximum power to electrical load will be transferred with a 20kΩ resistor which is in good agreement with the analytical predicted value of 19kΩ for the used mechanical damping of 0.1N/m/s and a coupling factor of 40V/m/s [5]. In contrast to this agreement the often asserted condition that the mechanical damping should match the electromechanical damping could not be confirmed in our investigations. However, for a factual generator operating under realistic conditions it is difficult to realize load matching as well as damping adjustment since the current is defined by a more complex load circuits and the mechanical damping should ever be as low as possible. Taking all the performed optimizations into account we can now determine the voltage stored in a load capacitor over time for the given example vibration profile (Figure 10). If the stored energy in the capacitor is much higher than the energy required for a specific application the transducer can be reduced in size and vice versa.

CONCLUSION

In this paper optimization results obtained by an advanced numerical model of an electromagnetic vibration scavenger excited by a measured example vibration profile has been presented. The results show that depending on requirements in application and the given vibration characteristic an optimal device can be designed through numerical modeling if realistic effects were taken into account.

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