PRACTICAL AND THEORETICAL LIMITS OF THE OUTPUT POWER OF ELECTROMAGNETIC ENERGY HARVESTERS AT MINIATURIZATION

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Abstract: This paper analyses and discusses the limits of the output power of miniaturized resonant linear electromagnetic micro energy harvesters based on an analytic description containing essential geometric parameters and practical examples. It addresses drawbacks as low flux conduction, low volume utilization, low aspect ratios and high damping of large flat structures that especially occur when microtechnologies are used. Suggestions to further optimize electromagnetic harvesters are given.

Keywords: electromagnetic energy harvesting, optimization, miniaturization, output power limitations

INTRODUCTION

During the past 10 years many authors have investigated electromagnetic energy harvesters at milli- and microscale [1, 2] The basic principle is to use the relative motion between an oscillator and the casing or foundation to induce a voltage and transform mechanical into electrical energy. The focus of the previous research was mainly on developing a variety of designs that can be fabricated in microtechnologies. One can find different approaches based on beams or laser machined springs. The harvesters were optimized by changing different geometrical parameters. However, the normalized output power of these harvesters is often below one microwatt per ms^{-2} and cm^3 even at volumes of up to more than 100 cm^3. In [3] we briefly introduced an energy harvester that was designed with respect to a maximum normalized power. Its value of 3.6 $\mu W(ms^{-2}cm^3)^{-2}$ at a volume of 10.8 cm^3 proves that a systematic optimization can enable to achieve high output power at small excitations and volumes. But in contrast to many other authors, no microtechnologies but precision mechanics have been used. For harvesters with a significantly smaller volume microtechnologies are required to realize mass production with low tolerances and at low costs. However, microtechnologies constraint the optimization of harvesters. We will discuss some limiting factors when linear resonant harvesters are miniaturized and microtechnologies are used.

BASIC MODEL

The simple model of an electromagnetic harvester comprising one single oscillator mounted to a spring and damped according to the damping constant d_m was derived in several publications, e.g., [4, 5]. The output power of such a device at resonance when attached to a resistive load R_l can be calculated from

$$P = l^2 B^2 \frac{R_l}{(R_l + R_c)^2} \frac{\omega^4 m^2 Y^2}{d_m + \frac{l^2 B^2}{R_l + R_c}} \tag{1}$$

where B is the magnetic flux density perpendicular to the coil wire and the direction of oscillation, l is the coil wire length perpendicular to the direction of oscillation, ω the angular excitation frequency, Y the excitation displacement amplitude and m the oscillator mass. Rewriting the $R_l = \rho_c l/A$ and $lA = V_c k_c$ one can find a practicable equation for the output power

$$P = \frac{k_c V_c B^2}{4 d_m \left(k_c V_c B^2 + \rho_c d_m\right)} \omega^4 m^2 Y^2 \tag{2}$$

with k_c the copper filling factor, V_c the volume of the coil and ρ_c the electrical resistivity of the coil wire material [3]. The theoretical maximum of the peak output power of a resonant harvester is given by

$$P = \frac{\omega^4 m^2 Y^2}{4 d_m} . \tag{3}$$

PERFORMANCE

Equation (3) gives the dependence of the output power on the oscillator volume that is proportional to m. However, when an electromagnetic harvester is assumed as a black box just its total volume V_{sum}, its shape, its aspect ratio as well as the excitation acceleration $\omega^2 Y$ are defining the scopes for design. For evaluating the performance and respectively its limitations one can apply the normalized output power P_n as primarily proposed by Arnold [2].

$$P_n = \frac{P}{V_{sum}^2 \left(\omega^2 Y\right)^2} \tag{4}$$

Comparing equations (3) and (4) micro energy harvester should reach the maximum normalized output power, because their small volume enables to reduce d_m.

Figure 1 pictures the huge differences of P_n of recently published generators. Alternative benchmark parameters as P/V_{sum}, $P/(V_{sum}\omega^4 Y^2)$ or $P/(m^2\omega^4 Y^2)$ that might be of importance for different applications draw a similar picture. Many microharvesters have low performances. The reason is rather not a disadvantageous generator shape or aspect ratio. Moreover, harvesters are often designed with respect to fabrication possibilities that are typically restricted in microtechnologies.

LIMITATIONS

For analyzing the limitations quantitatively the two magnetic circuits shown in figure 2 are simulated with Maxwell and compared. The first one (a) is a cylindrical magnet (NdFeB, N35) with two coils leveled with the bottom and top surface area of the magnet, the second circuit (b) is a cylindrical magnet (N35) combined with back iron (steel 1008) and coils leveled to the center of the back iron parts below and on top of the magnet. The volumes of (a) and (b) are equal and kept constant at different aspect ratios. For the aspect ratio of 1 height and diameter are 5 mm. If not stated differently the resolution of the geometric parameters is 0.1 mm.

Back iron is used to control the magnetic flux and maximize the squared magnetic flux density B^2 orthogonal to the wire and the direction of motion. In fact, the back iron might reduce the available volume for the coil and the magnet. However, V_cB^2 can significantly be increased by the usage of back iron. Assuming the same outer dimensions figure 3 gives the maximum V_cB^2 of setup (a) and (b) after optimizing the geometric parameters for different ratios of the height h and the diameter d. Although the design of the back iron in (b) is not completely optimized but just varied in thickness it gives an enhancement to up to more than 250 %. Only at the aspect ratio 1:2 and small airgaps the results with back iron are below those without. In setup (a) two coils are implemented, but in many publications just one coil is used [6-16]. Thus V_c reduces by appr. 50 %.
From both setups as well as from literature it can be concluded that typically the magnet or the magnetic circuit have a much bigger volume than the coil and should therefore be used as oscillator to maximize m. For the higher B^2 and the lower V_c in the optimized setup (b) the volume of the magnetic circuit is even larger than in (a). Back iron can therefore add to a higher oscillator mass.

Air gaps are required to realize the relative motion between the coil and the magnetic circuit or the magnet. For miniaturized harvesters they often become large compared to the other dimensions. Reasons are high relative tolerances when movable parts are fabricated by precision mechanics [6, 13, 16-19] or, in case of microstructuring, are patterned by isotropic etching through thick substrates [13, 14]. According to figure 3 an airgap g that is increased from 1 % to 2 % of the smaller outer dimension reduces V_cB^2 by up to more than 45 %.

Planar coils are used by many authors [6-10, 13-16, 20, 21]. Their low wire aspect ratio causes low filling factors k_c as shown in figure 4. Here the insulation or gap is kept constant while the copper cross section and the wire aspect ratio are varied.
Figure 5 illustrates the distribution of B^2 of permanent magnets with different aspect ratios in case no back iron is used. The small and nearly circular area of high

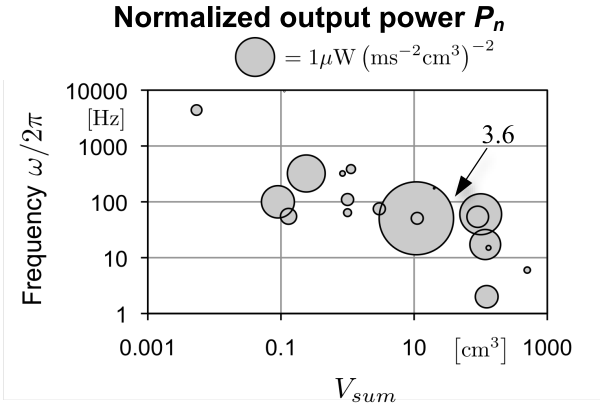

Figure 1. Normalized output power of energy harvesters; area of circle proportional to value [5].

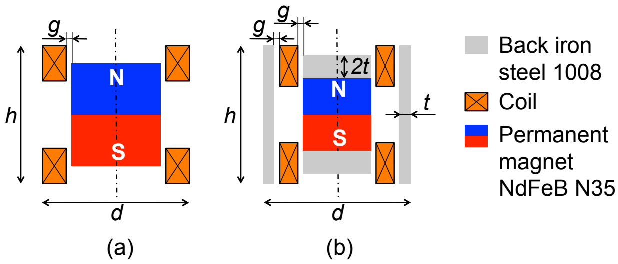

Figure 2. Analyzed cylindrical setups with (a) and without (b) back iron

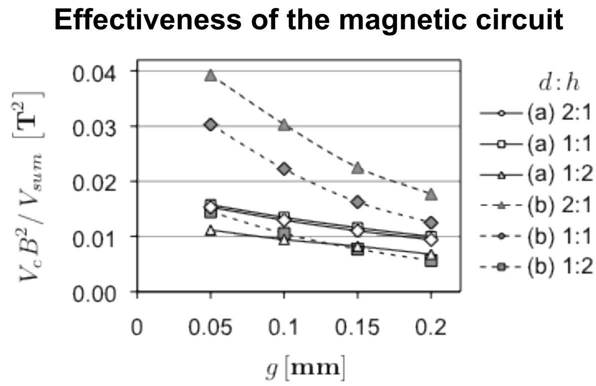

Figure 3. V_cB^2/V_{sum} with respect to the airgap g and the aspect ratio d:h for setup (a) and (b).

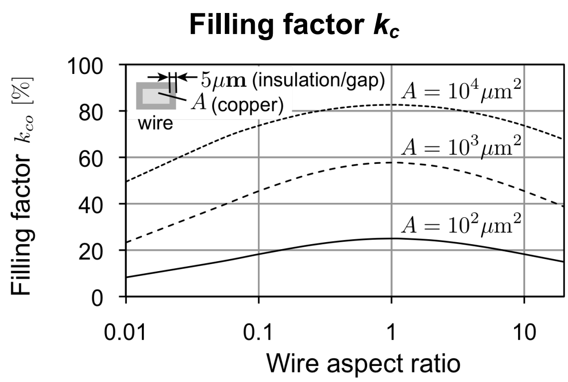

Figure 4. Filling factor with respect to the coil aspect ratio and the wire cross section A for an insulation thickness or half gap width of 5 µm.

B^2 appears similar in each case. It evidences that the ratio of coil width (outer radius minus inner radius) to height highly influences V_cB^2. Figure 6 demonstrated this impact for setup (a) and (b) provided that the larger value of thickness and height can be adapted in steps of 0.1 mm and the shorter accordingly. For each design the maximum V_cB^2 appears for a ratio of coil width to height between 0.2 and 0.5. Higher values would dramatically decrease B^2 so that the outer parts of the coil just add resistance. Thus, using technologies producing coils with high width-to-height ratio and abstaining from using multiple layers maximization of $V_ck_cB^2$ is challenging. Even with planar multilayer coils it is difficult to reach high k_c, because of the thickness of the isolation or the substrate the coil is deposited on [6].
Regardless of the fabrication technology, when the coil is not correctly aligned in the region of high effective flux density the output power will be low. Equation (2) gives only the peak value of the output power at constant B. But the magnetic field is mostly nonlinear as exemplarily shown in figure 5. The output power in the time domain is proportional to $(B\,\mathrm{d}x/\mathrm{d}t)^2$. To maximize the power one has to fit the velocity curve $\mathrm{d}x/\mathrm{d}t$ of the oscillator to the curve of B [3]. Therefore, a setup as used in [21] with a magnet oscillating towards a coil has the disadvantage of a maximum B at zero velocity. Finally, V_c scales down at miniaturization and reduces the power according to equation (2).

Volume utilization highly influences the output power. In many prototypes the oscillator comprises only a small fraction of the total volume [4, 6-11, 13-21]. An increase of this fraction by 10 % potentially causes a 19 % higher output power at the same excitation. Indeed, the higher oscillator volume implies a larger oscillator displacement, which increases the penetrated volume. But referring to the subsection *damping* this volume is usually small compared to the total volume, because low generator heights give high mechanical damping.

Damping, namely Stokes, Newton's and squeeze film damping, is generally reduced proportionally to the lateral dimension when harvesters are scaled down equally in all three dimensions. Also the Reynolds number drops, since firstly, the characteristic lengths decrease and secondly, the vibration velocity drops proportionally to m^2 / d_m^2 [3]. Therefore the risk for turbulent flows and Newton's damping, which is neglected in the model, is reduced as well.
But fabricating harvesters in microtechnologies which are mostly two dimensional usually implies that the harvester is flat. According to equation (2) the absolute power drops with m^2 / d_m and $V_c/(V_c+cd_m)$, c constant, whilst downscaling. In order not to loose power the width can usually not be scaled down to the same extend as the height to keep the oscillator mass high. For Stokes and squeeze film damping this is contra-productive, because both scale with the lateral

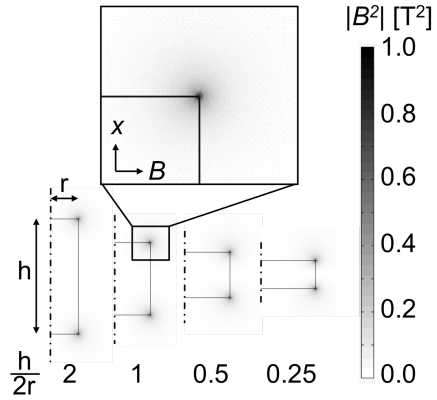

Figure 5. Distribution of B^2 of cylindric magnets with different aspect ratio.

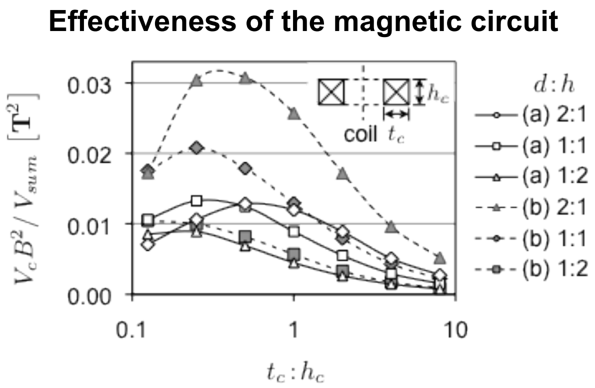

Figure 6. V_cB^2/V_{sum} with respect to the ratio of the coil thickness t_c to height h_c and the aspect ratio d:h for setup (a) and (b) at an airgap g = 0.1 mm.

dimensions. Newton's damping stays in the same range in case the volume of the harvester is not changed.
To allow downscaling of the lateral dimensions one could cascade several microharvesters. Stokes damping would be constant because it is proportional to the characteristic structure length times the number of structures. Squeeze film damping increases proportionally to the number of cascaded harvesters cascaded [22]. Newton's damping also increases according to this number. The reason is, that air gaps have to be scaled down to keep B^2 constant at miniaturization.
This is why 2D microtechnologies, i.e. planar coils and oscillators often limit the performance of micro energy harvesters. The requirement for low ratios of coil width to height in the setups (a) and (b) is supported by the damping issues. A 3D approach is mandatory to effectively utilize the volume, maximize $V_ck_cB^2$ and reduce damping. However,

DESIGN SUGGESTIONS

To reduce or even overcome the drawbacks we suggest considering the limitations both in the generator design and the fabrication process design. Finding a good solution requires to recursively quantify the boundary conditions and potential drawbacks of design approaches and fabrication technologies. In the second step geometric optimization can be applied.

We propose to include back iron into the design. Integration of multiple magnetic circuits could add to a better flux concentration and reduce effort for flux conducting components. Simulations demonstrated that this approach is highly beneficial at the disadvantageous aspect ratio discussed with figure 3.

The design should be highly integrated, e.g., to use a high fraction of the total volume for the oscillator of a resonant harvester.

Small airgaps can be realized using anisotropic structuring. In precision mechanics one should consider the fabrication limitations in an early design step to keep tolerances small.

The usage of 3d-microcoils as introduced by Kraft et al. [23], wire material deposition with high aspect ratio or planar multilayer coils help to realize high $k_c V_c$.

To reduce squeeze film damping one could part large areas or add holes enabling air exchange. Another approach could be to prevent airflow and utilize cavities as springs.

CONCLUSIONS

The direct approach to calculate the output power of electromagnetic harvesters enables to quantify that a well designed magnetic circuit with back iron, small airgaps, an appropriate coil aspect ratio and a high volume utilization can increase the output power to more than 250 %. We discussed that mechanical damping often increases when planar technologies are used. It is highly recommended to pursue a holistic design approach and estimate the potential drawbacks of fabrication technologies and a certain design approach before geometric optimization.

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