

# EVALUATION OF AN IMPACT SPRING-COIL-MAGNET SYSTEM WITH 3D-PRINTED SETUP

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**Abstract.** For several energy harvesting applications impact generators are one approach of generating energy to perform wireless transmissions to notify about an event. The goal is to harvest enough energy for a notification of a BLE-Chip to notify about one impact. Therefore magnet coil systems are one common approach. There are many variances assemble different arrangements of magnet, coils and springs. With this report we give an overview to behavior of coil behaviors by transmission of magnets. Therefore a setup is built with a 3D-Printer to reduce constructional effort. This transmission behavior of several 4 mm N45 neodymium magnets with different coils (height from 1-10mm, 100-400 windings) and springs setups are giving an idea about the practical approach and some comparison about simulation and measurement is done.

## 1. Introduction

It is obvious from the physical principles of mechanical energy harvesting that a trade-off between design complexity, size and generated energy has to be found when realizing a mechatronic generator for a dedicated application [1]. It is therefore helpful to have a modular system available for characterizing different elements of such a generator - and even for building prototype generators - to find a best combination of features with respect to application-specific requirements. This report presents an easy way of building generators by characterizing different set ups of magnet-coil systems in an electromagnetic energy harvester.

As a boundary condition, the outer dimensions of this generator were fixed to the approximate size of a pocket lighter. This was done with a look at the potential application of such generators as body-worn systems: They could be used, for instance, as autonomous impact sensors for pedometers or as energy-autonomous switches in medical applications, to be operated by a patient for signaling a dedicated request to a patient monitoring system. For all these applications the overall goal is thereby to find a generator setup which is capable to deliver enough energy from a single impact to send a wireless notification to a base station nearby. For such an application usually a Bluetooth data link is used, as has been done here.

## 2. Realized test set-up for a modular induction generator

A schematic setup of the generators studied is shown in figure 1. It consists of a tube, which holds permanent magnets located on top of a spring. A spacer tube is slid over this inner tube, which can be



varied in its height to adjust the resting distance between magnet and coil. On top of the tube is a cover with a hole for a pushing piece which moves the permanent magnet through the coil, thus generating electrical energy via magnetic induction. The AC voltage generated in the coil is fed to a full-wave rectifier connected to a storage capacitor. With a given capacitance the energy extracted from a single movement of the magnet can be directly calculated from the change in the capacitor voltage. It is evident that already this simple set-up offers a large number of design parameters.

Coils with variable height from  $h_c = (1, 2, 4, 6, 8, 10 \text{ mm})$  number of windings  $n = (100, 200, 300, 400)$ , and wire diameters  $d = (0.055, 0.1, 0.22 \text{ mm})$  were evaluated.

Also, cylindrical N45 neodymium magnets with a diameter of 4 mm and different heights of 1, 2, 4 and 10 mm were used. In addition multiple magnets were stacked with both opposite and aligned poles. The AC voltage generated in the coil is fed to a full-wave rectifier connected to a storage capacitor. With a given capacitance the energy extracted from a single movement of the magnet can be directly calculated from the change in the capacitor voltage.

Figure 1 does also show a cross-sectional view of the realized test device, with a more detailed explanation of all parts. Building was done from acrylic photoresin with a Form Labs 2 stereolithographic printer: A base plate is printed together with a central tube for a co-axial alignment of the spring, the magnets and the coils, and for guiding the magnet movement with respect to the coil. It has an inner diameter of 4.5 mm and a wall thickness of 1.5 mm. The mechanical spring and the moving magnets are placed inside the tube, together with a pushing piece for initiating a movement of the magnet. On top of the tube is a threaded lid which aligns and holds the pushing piece.

To test different coil sizes, suitable bobbins were made via 3D printing and put over the tube using a second set of coaxial tubes as spacer, to fix their defined location. Taking the results of all experiments a final design of the generator was realized as shown in figure 4.

The main design improvement to be tested here is related to the distance of magnet and coil. Generally, to calculate the flux density  $B$  of a cylindrical magnet, the following equations can be used [2].

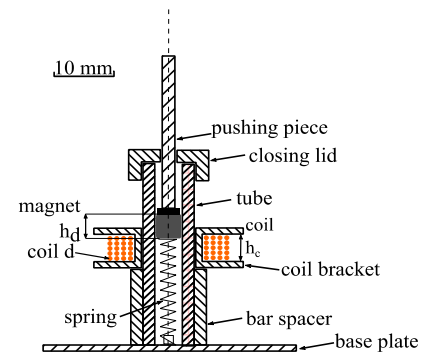
$$\text{With: } dB = \frac{U_{ind} \cdot dt}{N \cdot A} \quad (1) \quad B = \frac{B_r}{2} \left( \frac{h_d + z}{\sqrt{\left(\frac{d}{2}\right)^2 + (h_d + z)^2}} - \frac{z}{\sqrt{\left(\frac{d}{2}\right)^2 + z^2}} \right) \quad (2)$$

where  $B_r$  is the remanence field flux of the permanent magnet,  $h_d$  and  $d$  its height and diameter, respectively, and  $z$  the distance from one pole.

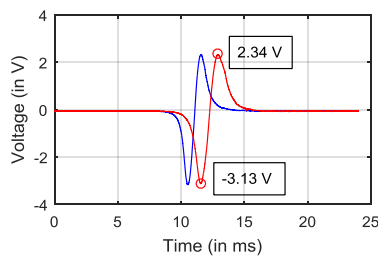
### 3. Measurements with single coils

The spring used in these experiments is 17.5 mm long, with a diameter of 2.33 mm and a spring constant of 0.536 N/mm. For all measurements, the spring is compressed for one centimeter by exerting vertical force onto the magnet via the pushing rod. After a sudden release of this force, the magnet is pushed upwards, thus traveling through the coil. The resulting induced voltage at the coil is traced with a PicoScope 3206 MSO. Figure 2 shows the voltage characteristic of such an event. The minimum voltage and the maximum voltage values of the measurements are measured, as well as the reaction time. The measurements are repeated five times and the average and standard deviation is calculated. Overall, 241 combinations are measured with the first set up.

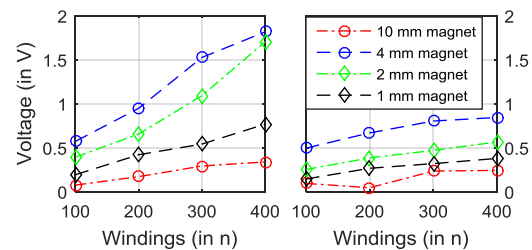
The results of the most promising are displayed in figure 3. It is remarkable that the 10 mm magnet induces less voltage than the 4 mm magnet. This is presumably related to the smaller change of the magnetic field. Also, a magnet of a higher mass must have a lower velocity with the same given input energy, when passing the coil, hence,  $dB/dt$  will be smaller.



**Figure 1.** Basic design of the test setup, cross-sectional view of the 3D-printed realization.



**Figure 2.** Voltage peak induced sequentially at two coils, with  $n=400$ , wire diameter  $d=0.1\text{mm}$ ,  $h_c = 4\text{mm}$ , 4 mm magnet.



**Figure 3.** Maximum induced voltage with  $h_c = 4\text{ mm}$  and  $d = 0.1\text{ mm}$  on the left and N45 magnet with  $d = 0.22\text{ mm}$  as function of magnet size and turns.

In table 1 a collection of the most important measurements is shown. By assessing the basic parameters and combinations with the mean peak voltage of five measurements, all configurations were characterized regarding the maximum power to be harvested. The most promising configuration is used to evaluate further assemblies with parallel and serial coils as well as with stacked magnets.

**Table 1.** Table of most important measured values, sorted by peak power downwards.

Magnet height	Coil height	Wire diameter	Windings n	Resistance	$U_{\text{peak mean}}$	Standard deviation	Peak Power
4 mm	4 mm	0.22 mm	200	4.6 $\Omega$	700 mV	40.5 mV	106.52 mW
4 mm	4 mm	0.1 mm	400	32.8 $\Omega$	1814 mV	35.6 mV	100.32 mW
4 mm	4 mm	0.22 mm	300	6.9 $\Omega$	802 mV	26.4 mV	93.22 mW
4 mm	4 mm	0.1 mm	300	27.7 $\Omega$	1524 mV	31.4 mV	83.85 mW
2 mm	4 mm	0.1 mm	400	36 $\Omega$	1710 mV	66.3 mV	81.23 mW
4 mm	2 mm	0.1 mm	300	29 $\Omega$	1375 mV	141.7 mV	65.19 mW
4 mm	4 mm	0.22 mm	400	11 $\Omega$	840 mV	29.0 mV	64.15 mW
4 mm	4 mm	0.1 mm	200	15.5 $\Omega$	950 mV	80.5 mV	58.23 mW
4 mm	2 mm	0.055 mm	400	124 $\Omega$	2666 mV	98.9 mV	57.32 mW

#### 4. Improved Setup

Based on the results of the experimental study, an improved design of a mechanoelectric generator was realized, figure 4. As one central measure, the wall thickness of the central tube was reduced to only  $260\text{ }\mu\text{m}$  and the coil is directly wound on this. The setup has a coil height of  $h_c = 4\text{mm}$ ,  $n=700$  windings, a  $h_d = 4\text{mm}$  N45 magnet giving the best performance in respect to peak voltage and power. This gives the big advantage that the coil can be mounted much closer to the magnet, which as a result of equation (2) leads to an increase in the induced voltage. Apart from that, it is possible to measure coils in serial and in parallel connection. The obvious disadvantage is that the tube material is very sensitive due to the strongly reduced stiffness of the thin walls. The mechanical spring with a spring constant of  $0.54\text{ N/mm}$  (peak voltage  $5.5\text{ V}$ , 700 windings, 4 mm coil height) is changed to a stronger spring with a spring constant of  $0.854\text{ N/mm}$ . This leads to an increase of the peak voltage to  $6.3\text{ V}$  and a faster movement of the magnet, whereas the transit time is decreased from  $3.143 \pm 0.09\text{ ms}$  to  $2.671 \pm 0.02\text{ ms}$ . This, however, is reducing the charging time of the capacitors as well.



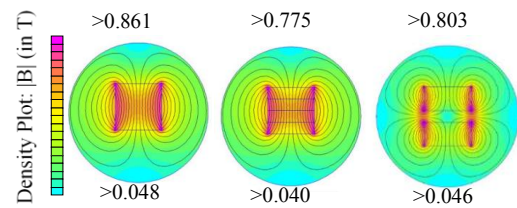
**Figure 4.** Improved setup with two coils, with  $n=700$ , wire diameter  $d=0.1\text{mm}$ ,  $h_c = 4\text{mm}$ , 4 mm magnet.

After evaluation this improvement does increase the peak voltage, but not the maximum power to be harvested. Also, the characteristics of the full wave rectifier play a significant role. The PMEG1201AESF is used. It has a very low forward voltage of  $160\text{ mV}$  [3] is showing the best performance compared two different models (BAT 41 & BAT 43). Disadvantageous is the small package, which is very difficult to handle compared to the wired alternatives.

##### 4.1. Results with multiple coils, magnets, diodes and capacitors

To increase the harvested energy, alternative configurations were experimentally evaluated and also studied by simulations. First, different magnet setups are investigated. Figure 5 shows a simulation of the magnetic density flux of three variants. The measurements indicated a slightly higher voltage peak

when using 4 x 1 mm magnets instead of one single 4 mm magnet. With this simulation the reason is made visible: At the edges of the magnets there is still a slightly higher magnetic flux density than for a single magnet. The configuration using oppositely directed poles induces a higher single voltage peak, but the reaction time is slower. This is also understandable by evaluation of the simulation on the right hand side of figure 5, where a short and fast change is visible, but the flux density in the working area around the magnet is lower. Equation (1) is used to compare the measured data with the simulations. Assuming a constant magnetic field, the voltage would increase linear. With lower winding numbers, the theoretical values are matching, and of course the induced voltage will drop higher distance of the coil from the magnet. This is an expected behavior which can be seen in simulation, measurement and calculation.



**Figure 5.** Finite Element Method Magnetics simulation of N45 magnets with 1 x 4 mm (left) 4 x 1 mm (middle) and 2 x 2 mm (right)

#### 4.2. Final Design and data transmission

The following design has seven coils. Every coil has an individual full bridge diode rectifier and a capacitor to store and evaluate the transformed energy. Two aligned magnets are used with a spacer of 4 mm in between. This leads to a higher number of trespassing magnets in respect to the coils, when using more magnets and additionally increasing the weight, which has some impact on the spring power. Assuming the available spring tension (0.54 N/mm) when pushing it one cm down, there are 26.8 mJ available. Integrating the power over time, we reach with 2 magnets and seven coils 6.37 mJ in the setup in table 2. This is 23.46 % in the construction volume. Summing up the available energy in table 2, on the single capacitors, 360  $\mu$ J are stored. This is only 5 % of the possible energy to transform. Nevertheless 360  $\mu$ J could be enough for some transmission protocols, like enOcean is able to transmit with 50  $\mu$ J [4]. Using Bluetooth low energy, the voltage levels are matched not to exceed 3.8 V. With a RF DUINO it is possible to send two notification if it is in sleep mode. If combining a battery to supply the sleep mode, and the coils, the chip needs 109  $\mu$ J.

**Table 2.** Resulting voltages on capacitors using setup with seven coils and two magnets.

Capacitor #	Voltage (V)	Capacitance ( $\mu$ F)	Energy ( $\mu$ J)
1	2.73	9.63	35.89
2	2.09	43.5	95.01
3	1.89	63.3	113.06
4	2.04	43.5	90.51
5	2.64	28.8	100.36
6	3.18	9.63	48.69
7	2.58	9.63	32.05
<b>Total</b>	17.15	2.45	360.3

## 5. Conclusion

Some interesting effects are made visible, especially in respect to the magnet arrangements. It is more efficient to use aligned poles of the magnets with some spacers, that the coils are inducing voltage while trespassing. With 6.37 mJ is enough energy available in the system for radio transmissions, but the poorly energy extraction with the full bridge and multiple capacitors is some effort with low return of 360  $\mu$ J. In future, further works has to concentrate on the energy extraction and an oscillating system has to be compared. Further designs with other magnet types are interesting as well. To decrease energy demand, there seems to be some possibilities to improve the Bluetooth chips heavier. So even with the presented set up it could be possible to perform transmissions.

## 6. Acknowledgement

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