Characterization of a variable reluctance harvester

M. Kroener[1], N. Moll, S. K. T. Ravindran, P. Mehne, and P. Woias

Group Manager, *Micro Energy Harvesting Technologies*
University of Freiburg, Department of Microsystems Engineering – IMTEK,
Laboratory for Design of Microsystems, Freiburg, Germany

E-mail: michael.kroener@imtek.uni-freiburg.de

Abstract. In our last year's PowerMEMS contribution we presented a proof-of-concept of a variable reluctance harvester for the application in a railroad surveillance system. It was shown that intermittently closing a magnetic circuit could supply power output in the range of mW's. The test setup used showed unwanted energy pickup from the electro motor used. In this paper we present thorough measurements of the reluctance circuit with a compressed air motor to exclude the effects of the above mentioned magnetic stray fields. The effects of eddy currents and moment of inertia on the output power, the optimal coil position on the stators, and effects of different magnetic field strengths are studied. The gap width is set to a fixed value of 14 mm, representing a realistic scenario.

1. Introduction

In previous publications we have shown that a wireless sensor node mounted to a railroad track can be powered by vibrations of a passing train [1]. Applications for this systems lie in the field of structural health monitoring in tunnels, but also other applications are feasible and useful, such as train position or passage detection, or wheel health monitoring of the passing train [1]. In continuation of this research we have presented a contactless energy harvester tailored for the energy autonomous train passage detection [2].

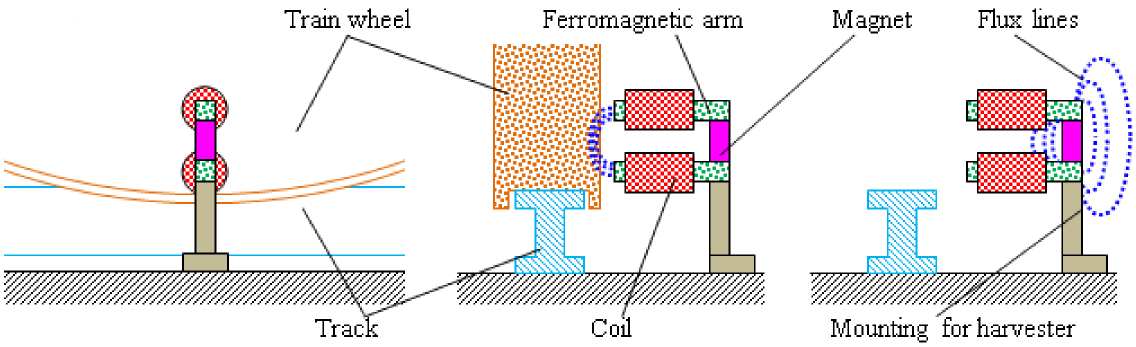

Figure 1. Schematic of the harvester mounted on a railway track. (a) shows the front view whereas (b) and (c) show the scenarios with and without the wheel, respectively [1].

[1] To whom any correspondence should be addressed.

It is based on a variable reluctance in a magnetic circuit: The train's soft magnetic wheel intermittently closes and opens the U-shaped circuit when passing by. This induces a voltage in the coil wound around one of the soft magnetic arms of the harvester (Figure 1). In literature variable reluctance circuits are used for resonance-frequency tuning of vibrational energy harvesters [3], as well as in energy autonomous anti-lock braking systems in automotive applications [4], which has a similar design as our system. The system presented in [3] is similar to our design but has a clearance between the harvester and the moving parts in the order of 100 µm. In this study the gap between stator and rotor has been increased from 10 mm to 14 mm to further increase the safety margin for the intended use in a railway monitoring application, where the position of the passing wheel is not constant (Figure 1b).

2. Design concept and experimental setup

The realized magnetic circuit is shown in Figure 2, with the concept shown on the left, and the realized test setup on the right. Two iron cores are mounted onto a rotating wheel, which is mounted to the compressed air motor. With these iron cores, the reluctance circuit is periodically closed inducing a voltage in the coil located on the static part of the magnetic circuit according to equation 1:

$$U_{ind} = -N \cdot A \cdot \frac{dB}{dt} \quad (1)$$

With N the number of turns of the coil (N = 700) and the cross-sectional area $A = 7.29\ cm^2$. The coil is wound with a 0.22 mm enamelled copper wire. The length of the coil equals l = 10 mm, the coil resistance is measured with an *Agilent 4263B* LCR meter to be $R_{coil} = 23.4\ \Omega$. The stationary U-shaped part of the reluctance harvester is composed of a low-grade steel reluctance core as a flux guide and NdFeB (*supplier: Supermagnete.com*) magnets as the magnetic source, both with a cross-sectional area of $10 \times 10\ mm^2$.

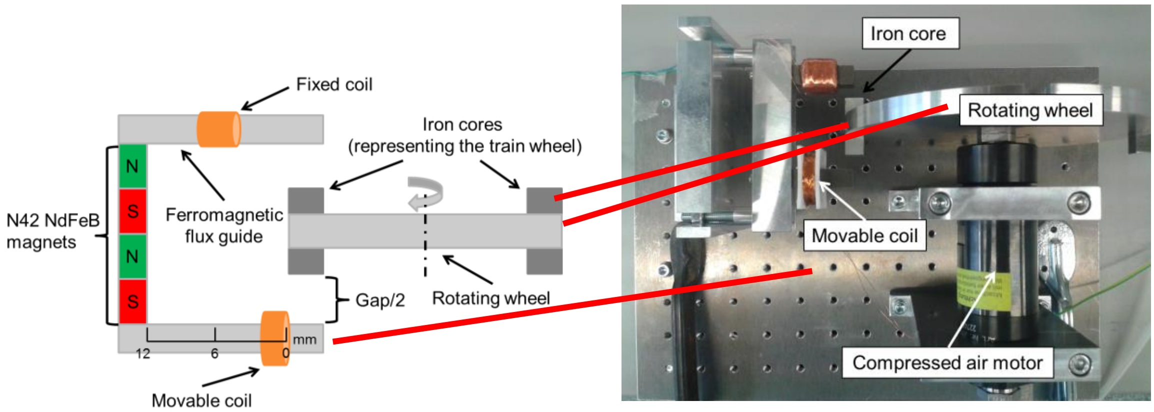

Figure 2. Concept of the variable reluctance circuit (left). The movable coil is used for all of the experiments to determine the optimal coil position and dimension. The rotating wheel carries two soft magnetic iron cores, which periodically close the magnetic circuit. In the experiment (right) the rotating wheel is driven by a compressed air motor to prevent unintended magnetic stray fields from the formerly used electromotor.

The gap between the stationary arms and the rotating iron cores is defined by magnets of different height and is set to a fixed value of 14 mm for all experiments. The relative permittivity of the low-grade steel was determined to be μ_r=666, measured with a self-built test setup according to the *DIN Norm 50 460* for soft magnetic materials. The voltage waveform is measured and recorded with a

Tektronix TDS 2002 oscilloscope, which is later used for calculation of the harvested energy per passing event.
The rotating disc has a diameter of 160 mm (Figure 2 left and right) and is fabricated from aluminium and PVC to determine the effect of eddy currents slowing down the disc. Additionally different brass weights have been used to cross correlate the effect of different moments of inertia. The electro motor used in the former study [1] was replaced by a compressed air motor *MRD 38-1460* from *Mannesmann-Demag* (Figure 2 right). This motor was used to circumvent the pickup of magnetic stray fields formerly observed from the experiments with the electro motor. The air motor could not be operated in the same rpm range (0-100 Hz) due to a limited available air pressure. By that, experiments were conducted only in the range of 5 – 25 Hz (corresponding to 10-50 Hz due to the two iron cores mounted). For rates lower than 5 Hz, the motor stalled because of internal frictional effects. Magnets with different flux density were used (N42, N45, N50) to evaluate if saturation effects in the soft magnetic core of the reluctance circuit play a role in the energy output.

3. Experimental results and discussion

3.1. Results

Figure 3 shows the measured energy per passage of the soft iron core with respect to different test setup configurations to compare the results of the electro motor and the compressed air motor. The movable coil is additionally varied in distance from the moving iron core, see Figure 2 left. For these experiments a PVC disc is used without an additional weight to exclude the effect of eddy currents in the else used Aluminium disc. The energy per passage was calculated numerically from the recorded voltage waveforms according to eq. (3), including the optimum load-matched conditions ($R_{load} = R_{coil}$).

$$E_{pulse} = \sum U^2 /(4R_{coil}) \cdot \Delta t \qquad (2)$$

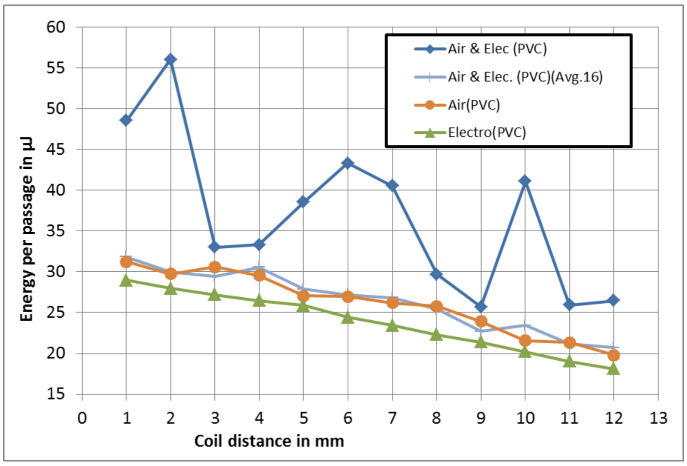

Figure 3. Measured energy per passage of the soft iron core for different test setup configurations. The two blue lines represent the setup with compressed air motor with the electromotor running close to experiment to show the effect of its magnetic stray fields. The top line is measured without averaging. It can clearly be seen that a large amount of energy is induced in the coil, which is not related to the reluctance circuit.

Four different test setups are compared in this experiment (lines from top to bottom):

1. The compressed air motor drives the disc & the electromotor is place next to the experiment, to show the effects of the magnetic stray field (top blue line). The voltage waveform is not averaged in the oscilloscope.

2. Same conditions as in one, with averaging over 16 measurements.
3. The compressed air motor drives the disc, with the electro motor being absent. No magnetic stray fields are picked up in the coil.
4. The electromotor drives the disc with averaging over 16 measurements.

These experiments clearly prove that the electro motor induces large amounts of energy into the reluctance harvester from magnetic stray fields. The experiments also shows that averaging over 16 measurements, as we did in the previous study [2], effectively eliminates these side effects. The small deviation in the harvested energy between the electro motor and the compressed air motor is related to small geometrical differences, which occur if changing the test setup.

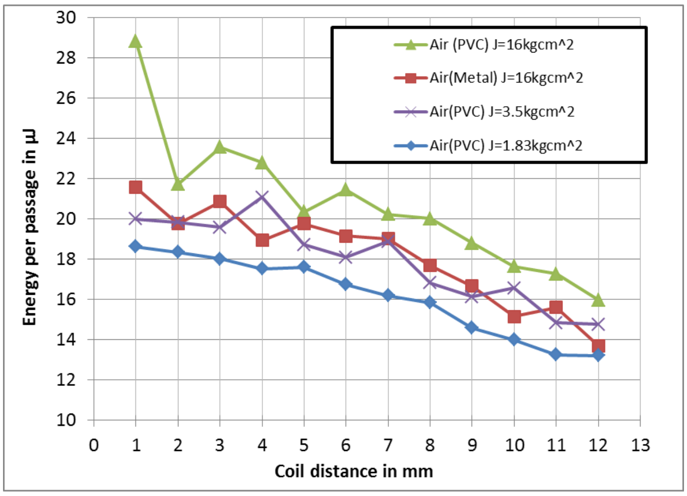

Figure 4. Measured energy harvested per passage of the moving soft iron core, and energy generated per pulse (right), with respect to the train velocity for three different clearance widths between the moving and stationary ferromagnetic parts of the reluctance circuit.

Figure 4 shows measurements of the energy harvested for different moments of inertia J conducted with the air motor for a fixed rotational frequency of 30 Hz. The results of the PVC disc are shown along with an experiment with an aluminium disc. It can be seen, that the higher the moment of inertia, the higher the harvested energy. It is also shown that the aluminium discs produces less energy for the same value of $J = 16\ kg*cm^2$. This proves the effect of eddy currents occurring in the aluminium disc, slowing down the system especially when the reluctance circuit is closed by the moving soft iron core.

Figure 5 shows measurements with magnets of different magnetization strengths (N42, N45, N50) with respect to the rotational frequency of the disc (PVC). It can be seen, that the strongest N50 magnet does not provide more energy than the weaker N45 magnet. Saturation effects in the soft magnetic material limit the maximum achievable energy. With the N42 magnets this maximum is not yet reached so a lower energy output is observed.

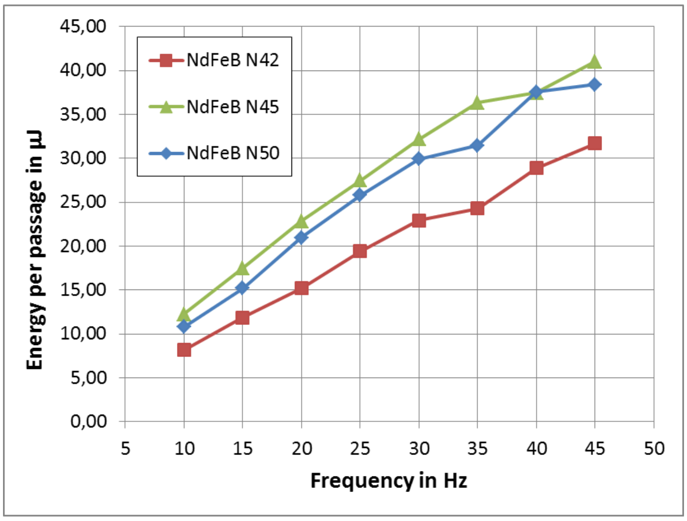

Figure 5. Measured energy per passage with respect to magnets of different strength and in relation to the rotational frequency.

3.2. Discussion

The focus in this study was set to the thorough characterization of the reluctance harvester alongside with the test setup used. Previous research revealed some magnetic stray effects supposedly coming from the electromotor which was used [2]. This side effect was proven by experiments with a compressed air motor and the electromotor four different test setup shown. While the pickup of additional energy from surrounding magnetic fields, which will occur in the application of train passage detection, is rather an opportunity than a problem, one has to consider the protection of the electric circuits behind the harvester. We could observe voltages easily going up to 10 V, which were out of the rated range of the capacitor used in the system from [5].

While the effect of eddy currents slowing down the wheel in the test setup, thereby generating less energy, certainly is not a challenge in the real application, where a very heavy train (~100's of tons) passes by. Still in other technical applications, e.g. health monitoring of tools in rotational machinery, might affect the functionality. In general, the measured energy from the test setup shown is more like a lower limit of what actually can be expected from the application.

4. Conclusions

While the applicability to use a variable reluctance was already demonstrated in the previous study, we now can derive an optimum design for the reluctance harvester and determine the limits and the boundary conditions for the electronics used to manage the harvested power. Now the harvesting principle needs to be tested in a real application to see if the technology is feasible to be used in an unclean environment, where small magnetic particles may disturb the long term use of such a harvester.

[1] Wischke M, Masur M, Kroener M, Woias P, 2011, Smart Mater. Struct. 20, 085014.
[2] M Kroener et al, 2013, J. Phys.: Conf. Ser. 476 012091, doi:10.1088/1742-6596/476/1/012091.
[3] Ayala-Gacia Ivo, Mitcheson Paul, Yeatman Eric, Zhu Dibin, Tudor M.J. and Beeby S.P., Magnetic tuning of a kinetic energy harvester using variable reluctance. *Sensors and Actuators: A Physical* **189** (2013), 266-275.
[4] Parthasarathy D., Energy harvesting wheel speed sensor, *Master thesis*, Chalmers university of technology, Goeteborg, Sweden, 2012.
[5] Woias P, Wischke M, Eichhorn C, Fuchs B, An energy-autonomous wireless temperature monitoring system powered by piezoelectric energy harvesting, *Proc. PowerMEMS* (2009), 209-212.