Variable reluctance harvester for applications in railroad monitoring

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Abstract. We present the design, realization, and testing of a variable reluctance energy harvester for the detection of moving ferromagnetic parts, e.g. the wheels of a train while passing over a train passage detector. Measurements were done to determine the output voltage, the energy output per event and the power output with the frequency of the moving ferromagnetic body. Results are compared with finite element analysis (FEA) to estimate the change in magnetic flux and the output voltages. A maximum energy output of 131 µJ per pulse was measured for a simulated condition of a train wheel passing with a speed of 81.5 km/h, which results in a mean output power of 5.9 mW, with a spacing of 10 mm between wheel and the reluctance circuit. This shows that the variable reluctance principle, a well-known method used for numerous sensor applications, is also a comfortable, energy-autonomous and reliable method to detect passing train wheels or other moving ferromagnetic parts, with a simple setup and fairly high useable output power.

1. Introduction

In a previous study we have proven that vibrations of a passing train provide enough power to supply a wireless sensor node from a piezoelectric energy harvester mounted at the sleeper of a track [1]. Although initially these wireless sensor nodes were intended to be used for structural health monitoring in tunnel buildings, alternative applications, e.g. for train passage detection were proposed [1]. In continuation of this research we now present a contactless energy harvester tailored for energy autonomous train passage detection. The concept uses a modulated reluctance in a magnetic circuit: A wheel passing by the tips of a U-shaped magnetic core will redirect the flux through the magnetic circuit into wire-wound coils, thus inducing an electric voltage (Figure 1). Variable reluctances have been shown in literature for tuning the resonance frequency of vibrational harvesters [2] and in automotive applications as autonomous sensors [3]. The system design 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 our setup gaps ranging from 6 to 14 mm have been realized, which are more suited for train surveillance applications.

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2. Design concept and experimental setup

The concept of the realized variable reluctance circuit is shown in Figure 1: A stationary magnetic circuit, made of ferromagnetic materials, permanent magnets and one or two wire-wound coils is positioned aside from the rail (Fig. 1 left and middle). A passing train wheel will redirect the flux in the magnetic circle, and a significant part of the flux generated by the permanent magnets is now guided through the arms. After the wheel passage the magnetic flux returns into its stationary pattern, where most of the flux is running through the – shorter – air gap between the poles of the permanent magnet. Train passage will therefore produce two dynamic variations of the flux pattern inducing electric voltage in the coils. Energy can be harvested from this event and used to power up a wireless train passage detector.

![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.](image1)

The test set-up used in this study consists of a small piece of ferromagnetic material, called a “moving arm” that is mounted to a rotating plate, resembling the passing wheel of a train. Under rotation, the moving arm is intermittently closing the gap in a U-shaped magnetic circuit (“stationary arm”), mounted close to the trajectory of the passing wheel. The magnetic circuit consists of a U-shaped 10×10 mm² cross section low-grade steel reluctance core with 10×10 mm² N42 NdFeB (supplier: Supermagnete.com) magnets providing the magnetic flux.

![Figure 2. Test set-up for the harvester (left) and schematic top view of the reluctance circuit (right).](image2)

Different magnets with thicknesses of 10 and 2 mm were used to evaluate different magnetic fluxes and to enable different clearances between the stationary moving arms of the magnetic circuit. The coil wound around one of the stationary arms consists of 2000 turns of 150 µm diameter enameled copper wire. The coil series resistance and inductance were measured with an Agilent 4263B LCR...
meter to be $R_{\text{coil}} = 110.8 \, \Omega$, and $L_{\text{coil}} = 148.1 \, \text{mH}$ at a measurement frequency of 100 Hz. The rotating plate carrying the $30 \times 10 \times 10 \, \text{mm}^3$ moving arm has a diameter of 160 mm (Figure 2 left and right) and is fabricated from aluminium. It carries two moving ferromagnetic arms to compensate the mass imbalance otherwise occurring. The air gap between the core and the shaft is set to 6, 10 and 14 mm, representing a realistic scenario for the application as a train passage detector. Smaller gap distances are assumed to be unsafe for operation in traffic applications. The induced coil voltages are measured with a Tektronix TDS 2002 oscilloscope and also peak diagrams are recorded for later calculations of the per peak energy generation. The rotating plate is driven by a Pophof asynchronous motor in combination with a Pophof i55 frequency converter control. The rotational frequencies ($f$) were varied between 5 to 45 Hz, corresponding to linear velocities of 9 to 82 km/h.

3. Simulation of the reluctance circuit

To evaluate the magnetic flux density change inside the ferromagnetic arms a magnetic simulation in ANSYS 13.0 was set up. The model comprises the parts shown in Figure 2 on the right, without the coil. The surrounding air is modelled by a sphere set around the reluctance circuit including infinity elements on the exterior. The magnetic flux density is calculated inside the static ferromagnetic part of the system by averaging the magnetic field in longitudinal direction over the whole cross-section at three different slices. By this the location of the coil is taken into account, and the induced voltage can be calculated from the change of the magnetic field with respect to the changing position of the moving ferromagnetic arm in the reluctance circuit. Two different simulations were set up:

1. A simulation that correspond to the rotation as occurring in the experiment to compare and validate simulation and experiment
2. A simulation using a linearly passing metal plate sized three times as high as the moving rotor, instead of the rotating arm moving between the stationary arms, to model a passing wheel train more precisely.

Figure 3 shows the waveforms for changes of the magnetic field $dB/d\theta$ (rotation) and $dB/dx$ (linear), both for clearances between moving and stationary arm of 10 mm. Additionally the calculated coil voltage is shown in the graph for the linear motion.

![Figure 3. Simulated change of reluctance for a rotational motion (left) and linear motion (right) with 10 mm clearance widths.](image)

From these simulations the voltage waveforms and values can be calculated according to eq. (1) (rotation) and eq. (2) (linear motion), respectively, where $N$ is the number of turns and $A$ the cross-sectional area of the ferromagnetic arms:

$$U_{\text{rot}} = -N \cdot A \cdot 2\pi \cdot f \cdot \left( \frac{dB}{d\theta} \right)$$

$$U_{\text{lin}} = -N \cdot A \cdot \left( \frac{dB}{dx} \right) \cdot \left( \frac{dx}{dt} \right)$$

Figure 4 shows a comparison of the measured and simulated peak-to-peak voltages for the rotational motion. Clearly the simulation shows a steeper rise in voltage.
The slower increase in the experiment might be attributed to the significant eddy currents appearing at higher rotational speeds.

![Figure 4. Comparison of simulated and measured peak to peak voltages for the rotational system. The clearance for this was 10 mm. The data used was taken from another experiment, than those for calculating the energy and power output. The alignment of stationary and moving arms has a strong influence on the coil voltages.](image)

4. Experimental results and discussion

4.1. Results

The coil voltage was measured for a rotational frequency \( f \) between 5 to 45 Hz, corresponding to a passing wheel velocity of 9 to 82 km/h for three different clearance distances of 6, 10 and 14 mm. Figure 5 shows the measured peak-to-peak voltages (left) under no-load conditions, and, and the maximum extractable energy generated per pulse (right), with respect to the wheel speed. The pulse energy was calculated numerically from the recorded oscilloscope signals according to eq. (3), including the optimum load-matched conditions (\( R_{\text{load}} = R_{\text{coil}} \)).

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E_{\text{pulse}} = \sum U^2 / (4R_{\text{coil}}) \cdot \Delta t
\] (3)

![Figure 5. Measured open-circuit coil voltage (left), 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.](image)

The mean power output with respect to velocity is calculated straightforward according to \( P_{\text{mean}} = E_{\text{pulse}} \cdot f \), and is shown for three different measured clearances in Figure 6. Smaller clearances enhance the power output strongly.

4.2. Discussion

From previous research [1, 4] we have found that a realistic minimum voltage and power consumption for a wireless sensor node can be 2.0 V and 60 µW [4]. As traffic safety requirements may require higher RF transmit power or several sequential transmissions, a power of 500 µW at slightly higher...
system voltages seems to be more realistic [1]. With these data, the presented reluctance harvester is capable to detect train passages from speeds above 20 km/h at 10 mm clearance.  

For a proof-of-concept the temperature measurement system with RF module presented in [4] was powered from the reluctance harvester. The system could be operated with speeds corresponding to calculated optimal-matched output powers above 1 mW in Figure 6. However, one has to notice that this combination happened under non-ideal conditions, i.e. without a matched load and, hence, without an optimal energy transfer. During the experiments it was found that this low-power system, with an average power consumption of approximately 60µW, sometimes started operation without any rotation at all. As a source for this unexpected behaviour, the coil pick-up of magnetic stray field fluctuations was found, especially from the control of the asynchronous motor used. A more detailed investigation showed that these additional pick-ups did not have a remarkable influence during operation of the electric motor, but occurred more dominant in short periods of its stopped condition, when the electronic control employed an electronic holding operation for the motor. On a greater perspective this is a disadvantage for an accurate characterization of such a system under laboratory conditions, but may even be an advantage for its practical application. Using reluctance circuits obviously provides an opportunity to also harvest from close alternating magnetic fields, which may be present in a train system anyway.

5. Conclusions
The results found within this study clearly show the applicability of variable reluctance harvesters as a train passage detector, or in any other environment with rotating or periodically moving ferromagnetic parts. With power outputs beyond the mW regime, energy-autonomous systems can be easily powered. The simulations of the output voltages have a higher slope than actually measured values, which has to be investigated in more detail in future work to figure out the relatively large deviation.

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