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Energy Harvesting Employing a Drive Similar as a Clock Unit

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Abstract: An energy harvesting device for frequencies of less than 2 Hz with amplitudes of several cm was developed. A pendulum is driving a gear mechanism similar as a clock unit which is driving a wheel carrying 36 magnets. Next to the magnets there are mounted 18 coils generating voltage. This way, a maximum voltage and power of 21.5 V and 114 mW are achieved at 1.25 Hz and 57 mm amplitude.

Keywords: low-frequency, wind power station, alignment gear box

Introduction

Energy harvesting devices often need to be small and comparatively cheap to fulfill the requirements of the intended application (Harne and Wang 2013; Kim, Kim, and Kim 2011; Szarka, Stark, and Burrow 2012; Saadon and Sidek 2011; Ulukus et al. 2015). The device described here was designed to provide an autarkic energy source for a sensor and a transmitter inside of rotor blades of wind power stations. The sensor shall observe the structural integrity of the rotor blades by measuring its resonance frequencies. Cable connections to the tower are not allowed because they would attract lightning strokes.

Inside of a rotor blade there is plenty of space and it is no problem to mount a device with dimensions of approximately $20 \times 20 \times 40$ cm^3 and a few kg in weight. The centrifugal force is on the order of 500 m/s^2, and therefore the comparatively small change of acceleration due to the orientation in the gravitational field cannot be employed for energy harvesting. On the other hand, the amplitude of vibrations normal to the surface of the blade is up to 15 cm. A limitation for energy harvesting are the low frequencies of the vibrations of less than 2 Hz.

A small device should avoid rotating wheels because their surface is large compared to their volume and friction will reduce efficiency. That is the reason why vibrating piezo beams are a promising solution for small energy harvesting devices. As a consequence, small devices need to be driven at higher frequencies to generate enough power. Contrarily to this, a larger device excited at a larger amplitude of several cm employ rotating wheels, can be driven at less than 1 Hz with 57 mm amplitude and although generate several mW. Some energy harvesting devices based on the geometry of a pendulum were already under investigation (Kęcik 2013; Wiercigroch, Najdecka, and Vaziri 2011; Alevras, Brown, and Yurchenko 2015). This paper describes an energy harvesting device equipped with a drive similar to a clock unit. Gear wheels were arranged such that a pendulum generates unidirectional movement of a rotating wheel carrying 36 magnets. These magnets are inducing voltage in a ring of coils.

Testing Equipment

The energy harvesting device was tested mounted on a lever, 1.9 m in length (cf. Figure 1). The device was mounted at a distance of 1.8 m from the hinge of the lever. The lever was driven at its end driven by a rod connected to an electric motor. This way, the lever is excited to a sinusoidal motion. The excitation frequency was adjusted by the voltage of the power supply of the motor and the mechanical amplitude was set by the position of the connection rod on the motor driven disc.

All measurements were recorded with impedance matching except the measurement of charging curves. If the impedance of an electrical load is equal to the output impedance of its energy source, the power transfer is maximal. This is called impedance matching. All measurements were carried out with a high-impedance line driver (CA3140 from Intersil, California: typical 1.5 TΩ input resistance) and the data acquisition tool USB-6009 from National Instruments.

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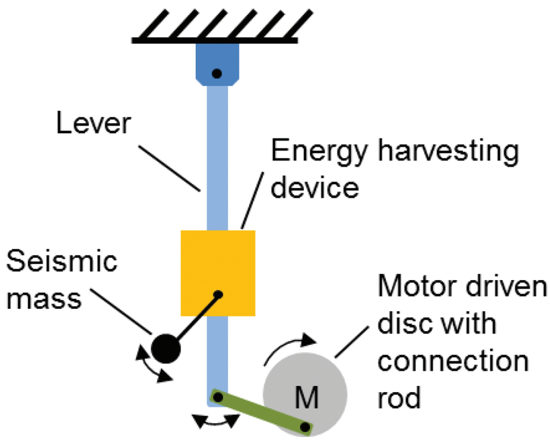

Figure 1: Test equipment.

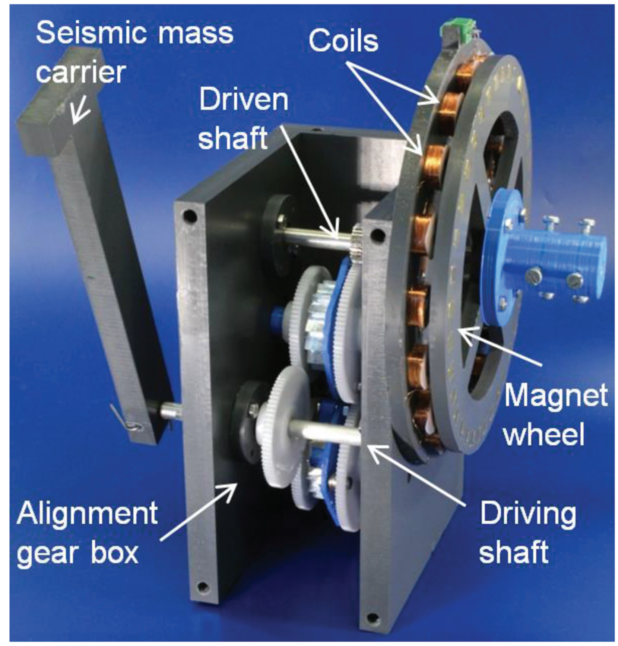

Figure 2: Energy harvesting system.

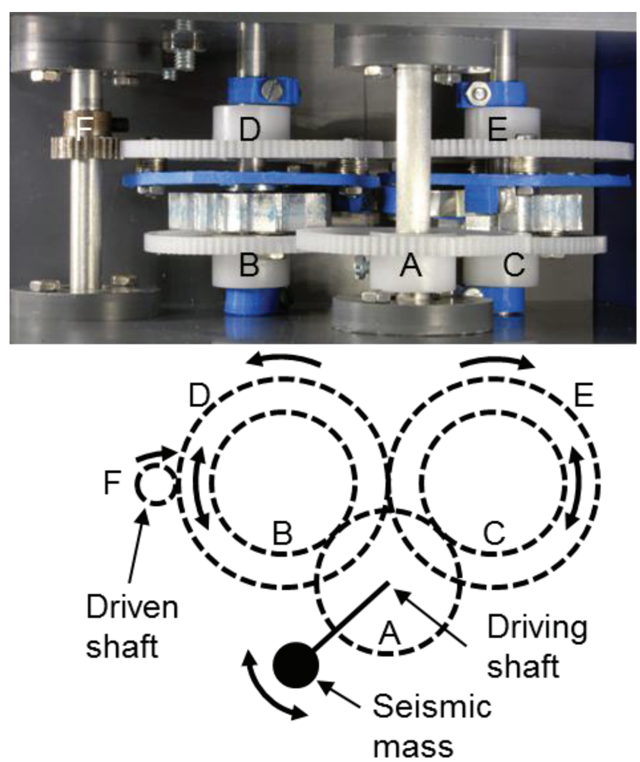

Figure 3: Alignment gear box and its principle.

Design and Construction

If the vibratory energy inside of the rotor blade of a wind power station shall be harvested by induction, the comparatively low frequency in the order of 1 Hz is a problem, because a moving body carrying permanent magnets or coils need to move fast through a strong magnetic field to achieve a sufficiently large voltage. More than 3 V is desirable to charge a battery because otherwise rectification of alternating voltage cannot be achieved and a certain minimum voltage is required to drive transmitter and sensor.

To achieve the necessary speed, it is enlarged by a factor of four in a gear box (cf. Figure 2). The bidirectional movement of a seismic mass at the end of a pendulum is converted into a unidirectional rotary motion. The so-called alignment gear box performs that conversion (Figure 3). The alternate motion of the pendulum is driving the propulsion gear wheel A, 41 mm in diameter, driving two secondary gear wheels B and C with the same diameter. Movable on the same shafts as the secondary wheels there are mounted the gear wheels D and E, both 51 mm in diameter, which are engaged with each other.

Gear wheel B is connected to gear wheel D only when it is turning left, and gear wheel C is connected to gear wheel E only if it is turning right. This way, the alternate movement of gear wheels B and C is converted into a unidirectional right rotation of gear wheel F, 13.5 mm in diameter, which is engaged with gear wheel D.

The unidirectional transmission from gear wheels B to D and C to E is achieved by ratchet wheels fixed to gear wheels B and C, respectively (cf. Figure 4(a)). Pawls on gear wheels D and E are pressed by springs against the ratchet wheels (Figure 4(b)) and, this way, the rotation of gear wheels B and C is transferred to gear wheels D and E only when they are turning left and right, respectively. On the driven shaft, there is fixed a magnet wheel (Figure 4(d)) carrying at its circumference 36 cubic magnets from $Nd_2Fe_{14}B$ from Webcraft GmbH, Germany with

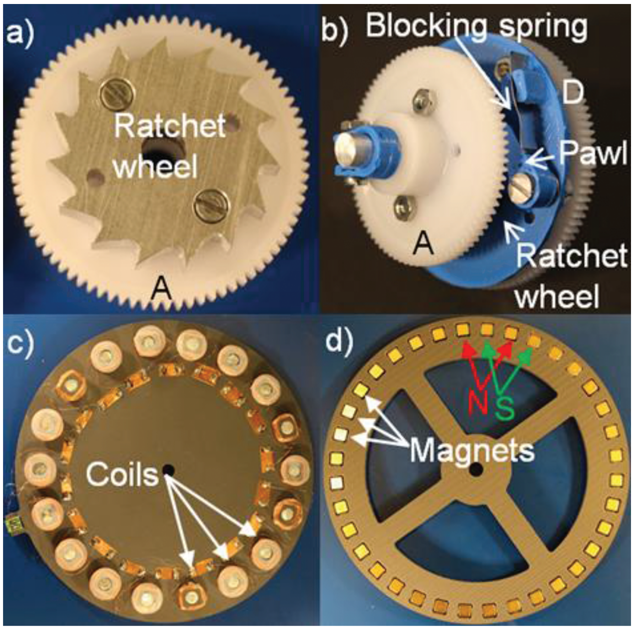

Figure 4: Components of the system.

5 mm edge length. The magnets were mounted with alternating orientation of their magnetic fields and their distance to the shaft center is 58.5 mm.

At the housing of the gear box and surrounding the driven shaft, there is fixed a disc with 18 coils (Figure 4 (c)), each with 400 turns from a copper wire, 100 µm in diameter, wound around a square-shaped spool carrier fixed by an aluminum bolt. All coils are connected in series. Each coil has a $5 \times 5\ \mathrm{mm}^2$ square profile, internal resistance, inductance and length of 31.7 Ω, 1.62 mH and 5 mm, respectively. The gap between coils and magnets is 1 mm wide.

The overall dimensions of the device are $250 \times 140 \times 150\ \mathrm{mm}^3$. It exhibits a weight of 1.33 kg plus the seismic mass (300–500 g).

The ratchet wheels (Figure 4(a)) were milled from aluminum and the pawls and their holder discs (blue parts in Figure 4(b)) were 3d-printed from polylactide (PLA). Pendulum, gear box housing, coil carrier disc and magnet wheel where milled from polyvinyl chloride (PVC). Gear wheels A through E, gear wheel F, and shafts were commercially acquired and made of polyacetal (POM), machining steel, and aluminum, respectively. The driving and the driven shaft are both mounted with ball-bearings to decrease friction losses.

Measurements

The maximum voltage is observed with an open circuit measurement. However, this does not provide the required information on the power which can be generated with an energy harvesting device. The maximum power is generated when the impedance of the load is as large as the one of the generator. Therefore, this so called impedance matched output voltage was measured over a load resistance R of 570 Ω.

Figure 5 shows the typical impedance matched induction voltage with an excitation frequency, mechanical amplitude, seismic mass and pendulum length of 1.25 Hz, 57 mm, 500 g, 135 mm, respectively. Figure 5 includes also the mechanical deflection of the pendulum as function of time. When the pendulum reaches its rest position (zero deflection) during oscillating operation, it has the highest velocity, which should result in maximum induction voltage. The induction voltage reaches its maximum in position A, but not in position B, which is caused by manufacturing inaccuracies. At these conditions, a minimum power of 44 mW is generated at the load resistance.

Figure 6 shows the maximum output voltage for different seismic masses as a function of frequency. The

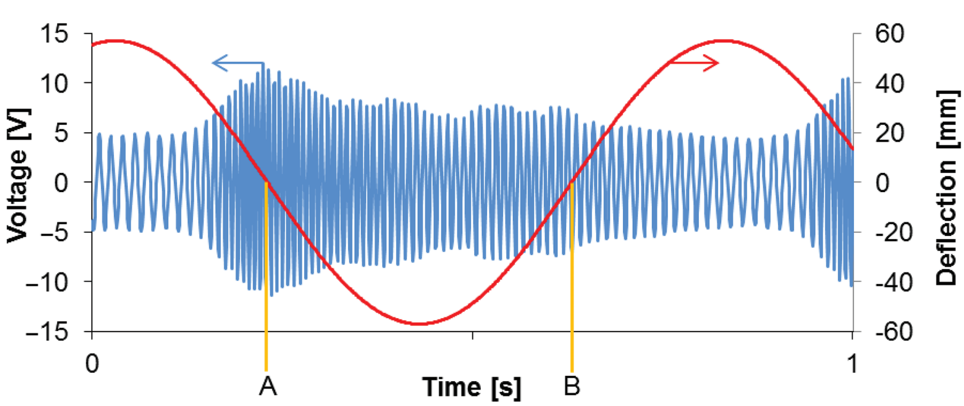

Figure 5: Impedance matched measurement of induction voltage near to resonance and mechanical deflection of the pendulum.

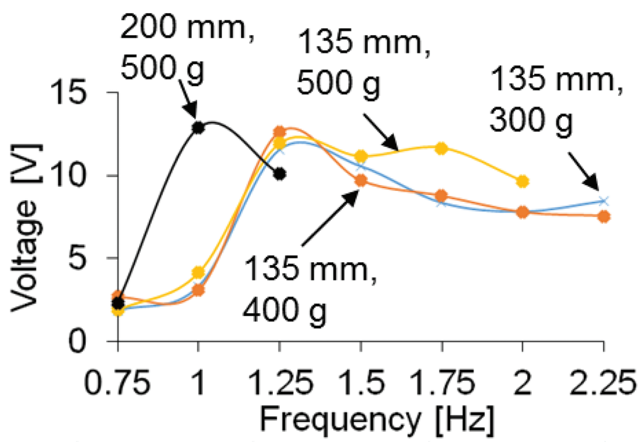

Figure 6: Impedance matched measurements of maximum voltage amplitudes for different seismic masses and carrier lengths.

blue, orange and yellow curves were measured with a pendulum length of 135 mm. All three curves show a similar resonant behavior around 1.25 Hz and a voltage decreasing slowly with higher excitation frequencies. A variation of the seismic mass did not show much impact on the voltage amplitude. In addition, another measurement was performed with a seismic mass carrier length of 200 mm (black curve). As expected, the resonance frequency was shifted downwards. In order to achieve an as large as possible working range, it is important to set the resonance frequency as low as possible.

The energy harvesting device was also connected to a capacitor via a rectifying circuit. A typical charging curve measured at the capacitor with frequency, seismic mass and amplitude 1.25 Hz, 500 g and 57 mm, respectively, is shown in Figure 7. The energy W stored in a capacitor with capacitance C and voltage U can be calculated by:

$$W = \frac{1}{2} C U^2 \tag{1}$$

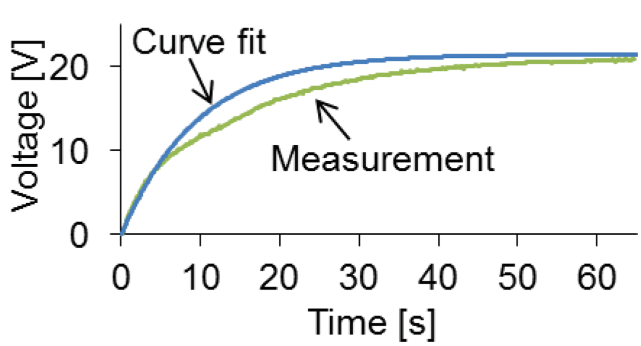

Figure 7: Charging curve and corresponding curve fit: $U_0 = 21.5$ V and $\tau = 9.5$ s.

The voltage rise is with maximum voltage U_0, time t and charging time constant τ:

$$U = U_0 \left(1 - e^{-\frac{t}{\tau}}\right). \tag{2}$$

The power P is the derivative of the energy with respect to time:

$$P = \frac{dW}{dt} = \frac{\partial}{\partial t} \frac{1}{2} C U_0^2 \left(1 - e^{-\frac{t}{\tau}}\right)^2 = \frac{C U_0^2}{\tau} \left(1 - e^{-\frac{t}{\tau}}\right). \tag{3}$$

Maximum voltage U_0 and charging time constant τ were determined by a fit to the measured data (cf. Figure 7). According to eq. (3), the power is maximum when charging starts at t = 0. The measurement at 1 Hz was carried out with a capacitor of 470 µF. In all other measurements, a capacitor with 4700 µF was employed. Figure 8 shows the maximum power as a function of frequency.

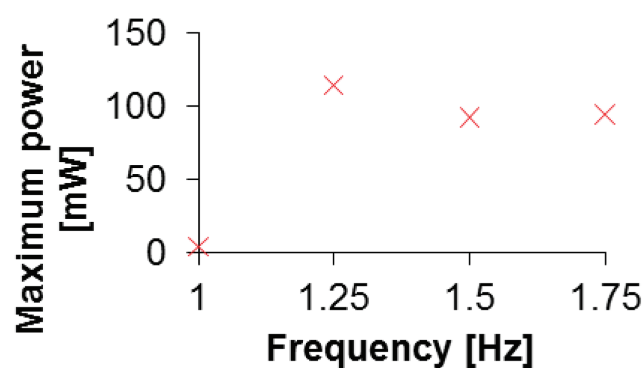

Figure 8: Maximum power as a function of excitation frequency.

For the determination of the efficiency, it is irrelevant whether the driven shaft is oscillating or rotating constant in to one direction, the connection between the gear wheels D and E provides full force transmission in both operating modes. To determine the efficiency of the device the pendulum was replaced by a wheel (Figure 9). A 0.65 m long thread was wound around this wheel and a mass of 374 g was fixed at its loose end. Subsequently, the mass was released and the sinking mass caused the magnet wheel to rotate for 4.5 s. The energy E transferred to the mass m respectively the harvester was calculated with:

$$E = mgh, \tag{4}$$

to 2.4 J. The voltage was measured again with impedance matching and with:

$$\bar{P} = \frac{\bar{U}^2}{R}, \tag{5}$$

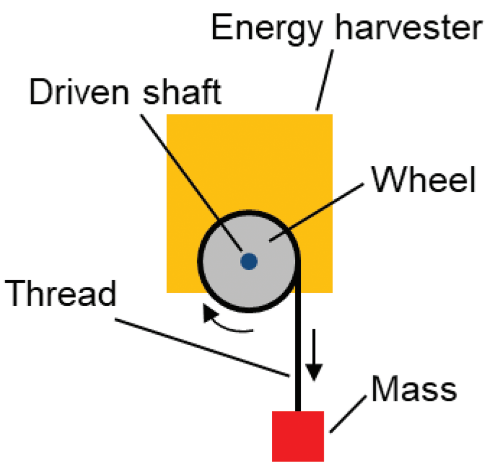

Figure 9: Test equipment for the determination of the efficiency.

an average power $\bar{P}$ of 53 mW was calculated, corresponding to an electrical energy of 0.24 J. The efficiency was calculated as the ratio of input and output energy to be 10 %.

Conclusions

Energy harvesting devices in the rotor blades of wind power stations can be comparatively large and heavy and vibration amplitudes of more than 10 cm are available. On the other hand, the device needs to work at less than 2 Hz.

At these conditions, an energy harvesting device similar as a clock unit appears to be a suitable solution. The device investigated here generated more than 114 mW at 1.25 Hz excitation with 57 mm amplitude. Thus, even when the available vibrations diminish for some time because of a calm, the energy required for a sensor and a transmitter (approximately 1 mW) can be provided from an accumulator or capacitor charged by the energy harvesting device. The energy harvester is comparatively large and heavy compared to most others, but the extreme low excitation frequency of approximately 1 Hz in combination with the alignment gear box and the high ouput power are the unique selling point.

An important issue not jet addressed in this paper is the possible live time of the energy harvesting device. Such a device will only be an advantage if it lasts much longer than a battery pack.

The device described here was constructed to investigate the principle of an energy harvesting device working at low frequencies and large amplitudes. Professionally fabricated clock units last for decades. Therefore, it is assumed that a professionally manufactured energy harvesting device like the one described here but from metal gear wheels and bearings would also work for a lot of years without maintenance.

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