Tunable Vibration Energy Harvester for Condition Monitoring of Maritime Gearboxes

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Abstract. This paper reports on a new tuning concept, which enables the operation of a vibration generator for energy autonomous condition monitoring of maritime gearboxes. The tuning concept incorporates a circular tuning magnet, which interacts with a coupling magnet attached to the active transducer element. The tuning range can be tailored to the application by careful design of the gap between tuning magnet and coupling magnet. A total rotation angle of only 180° is required for the tuning magnet in order to obtain the full frequency bandwidth. The tuning concept is successfully demonstrated by charging a 0.6 F capacitor on the basis of physical vibration profiles taken from a gearbox.

1. Introduction
The application of conventional vibration transducers (single spring-mass system) on variable-speed machinery is not practical since the bandwidth of these devices is very limited. In order to effectively generate energy from variable vibration frequencies, harvesters should be inherently broadband or should be tunable to the dominant frequency. To date a variety of tunable vibration harvesters have been reported in literature [1]. Varying the total spring stiffness is a favored tuning technique, which can be realized by magnetic, piezoelectric and electrostatic principles. The magnetic principle is a well-known tuning technique, which utilizes the magnetic stiffness between two magnets. This technique is well applicable to cantilever-based energy harvesters by attaching a coupling magnet to the transducer structure. An axial magnetic force is then generated if a second magnet (tuning magnet) is placed opposite to the coupling magnet [2]. A common approach for modifying the total spring stiffness and thus the Eigen-frequency of the energy harvester, is to adjust the distance between the coupling magnet and the tuning magnet by translational motion of the tuning magnet [3]. For this concept we identified two drawbacks: First, the coupling magnet and the tuning magnet can be configured either in attractive or repulsive mode. However, using both modes in combination would enhance the feasible tuning bandwidth. Second, this concept requires a linear actuator, which is more complex than a rotary actuator. Indeed, a rotary actuator can also be deployed, however, only in combination with a gearing mechanism.
In this paper we propose a magnetic tuning concept, which is based on the rotational motion of a circular tuning magnet. In this manner, both coupling modes (attractive and repulsive) can be utilized for tuning the Eigen-frequency of the energy harvester.

Figure 1. Gearbox (Reintjes) for work boats and ferries

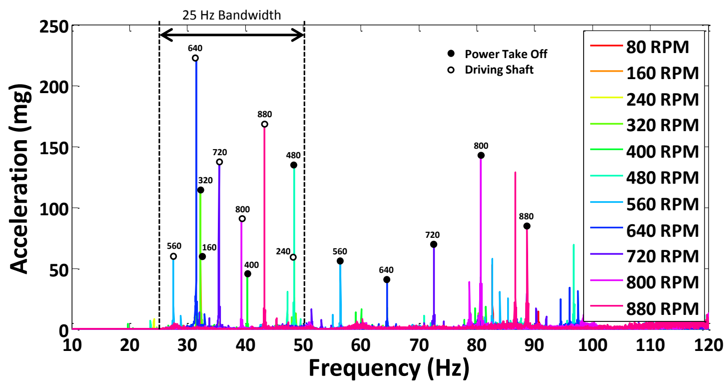


Figure 2. Frequency spectra of a gearbox (sensor position SP6, z-axis) operating at different revolution speeds

Moreover, the tuning magnet can be attached directly to a rotary actuator, making a gearing mechanism with its accompanying mechanical losses dispensable.

2. Vibration Analysis

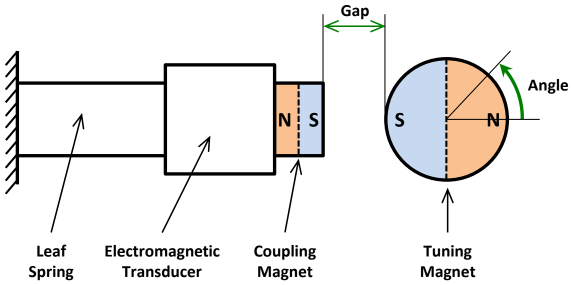
The movable parts of a gearbox as shown in Figure 1 operate at variable speed depending on the operation mode and the travel speed of the vessel. The revolution speed at the output shaft ranges from 80 RPM to 880 RPM when the driving shaft is driven at speeds from 236 RPM to 2600 RPM. The revolution speed in this paper is always denoted with respect to the output shaft.

Vibration profiles were recorded at 6 different positions using triaxial accelerometers. The revolution speed at the output shaft was varied from 80 RPM to 880 RPM in steps of 80 RPM. A frequency spectrum was calculated for each position, axis and revolution speed. The frequency spectra of a particular position and axis were then combined into a single diagram as shown in Figure 2. The dominant frequencies are directly correlated to the revolution speed of the two main shafts of the gearbox (driving shaft, power take off). The fundamental oscillation modes of the driving shaft are located in a frequency band between 4 Hz and 45 Hz. In general, the amplitude of the dominant frequencies varies with the revolution speed and strongly depends on the measurement position. However, dominant frequencies below 25 Hz (i.e. < 500 RPM) always have amplitudes below 10 m**g**. In consideration of both main shafts a frequency band can be identified (see Figure 2), which comprises dominant frequencies of all revolution speeds with usable amplitudes except 80 RPM. Since smaller vessels such as work boats do not operate at constant speed, the revolution speed of the gearbox also varies over time. In this respect, a potential tunable energy harvester must be able to adjust its Eigen-frequency within a frequency band of 25 Hz to 50 Hz.

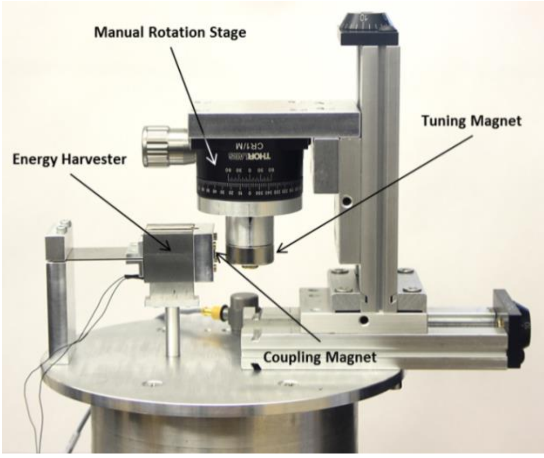
3. Concept and Setup

The concept of the tunable energy harvester is shown in Figure 3(a) and comprises a coupling magnet attached to a cantilever-based electromagnetic transducer and a circular tuning magnet. The tunable frequency band can be defined by adjusting the gap between the tuning magnet and the coupling magnet whereas the center frequency is determined by the stiffness of the leaf spring. By rotation of the tuning magnet between 0° and 180° the Eigen-frequency can be varied between a minimum value (repulsive coupling) and a maximum value (attractive coupling).

The electromagnetic transducer incorporates a closed magnetic circuit suspended on a cantilever and a fixed coil. The thickness of the leaf spring is 0.7 mm. The architecture of the electromagnetic transducer and significant parameters are described in more detail in [4].



(a)



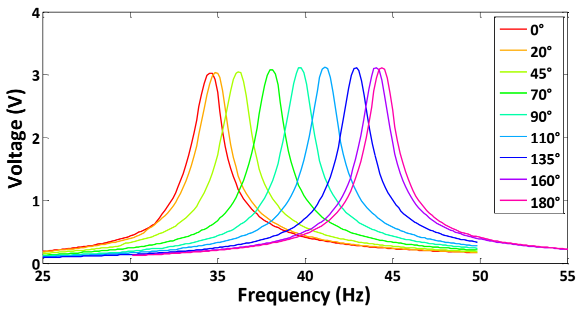
(b)

Figure 3. (a) Schematic (top view) showing the concept of the tunable vibration energy harvester. (b) Proof-of-concept implementation of the tunable energy harvester with manual rotation stage

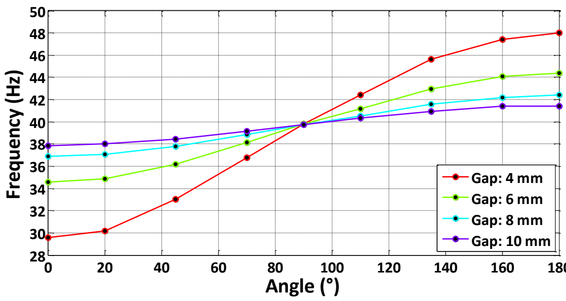
A proof-of-concept implementation of the tunable energy harvester is shown in Figure 3(b) utilizing a manual rotation stage for rotational manipulation of the tuning magnet. The horizontal and vertical position of the tuning magnet can be modified using conventional translation stages. The frequency response (output voltage) of the energy harvester is shown in Figure 4(a) for different angles between 0° and 180°. The gap between coupling magnet and tuning magnet is 6 mm. The resulting frequency bandwidth is about 10 Hz ranging from 34.5 Hz to 44.5 Hz. By varying the gap between the two magnets the tuning bandwidth can be tailored to the application. The smaller the gap the larger is the bandwidth of the tunable Eigen-frequency of the energy harvester (Figure 4(b)). A gap of 3.5 mm is required in order to achieve a tunable frequency band of 25 Hz to 50 Hz. Hereby, the center frequency is around 40 Hz, which is determined by the stiffness of the leaf spring and the mass of the magnetic circuit. By varying the thickness of the spring element and thus its stiffness the center frequency can also be tailored to the application.

4. Experimental Characterisation

For characterization of the tunable energy harvester physical vibration data (sensor position 6, z-axis) from the gearbox was replicated on a shaker system. First, a load resistance of 800 Ohm was attached to the coil and the instantaneous power output was measured for each vibration profile over time. The total play time for each vibration profile was 1 min. The energy harvester was manually tuned to the

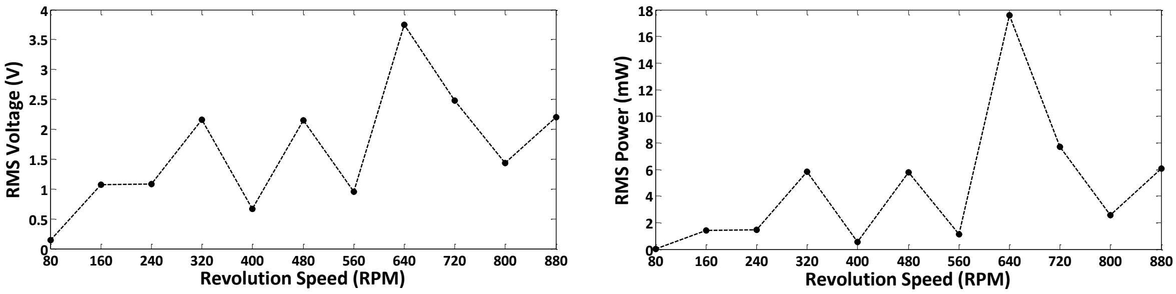


(a)



(b)

Figure 4. (a) Frequency response of the tunable vibration energy harvester at a gap of 6 mm for different angle adjustments of the tuning magnet. (b) Eigen-frequency as a function of the angle position for different gaps between the coupling magnet and the tuning magnet



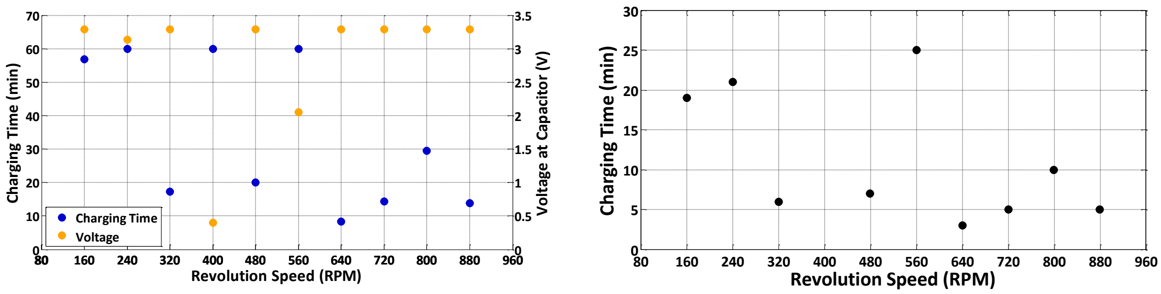
(a) (b)

Figure 5. Output vs. revolution speed at 800 Ohm load resistor: (a) RMS voltage. (b) RMS power

respective dominant frequency of each vibration profile. The average output power was calculated and plotted as a function of revolution speed (Figure 5(b)). At the lowest possible revolution speed (80 RPM) the average output power is almost zero (some µW). In this case the dominant frequency resides below 25 Hz and thus the energy harvester cannot be tuned. In general, the excitation amplitudes at 80 RPM are very low. For the remaining revolution speeds the power output is equal to or greater than 1 mW except for 400 RPM (0.5 mW). The highest power output (about 18 mW) was achieved at the critical revolution speed of 640 RPM. At this particular revolution speed the dominant frequency is located at 31.5 Hz exhibiting an amplitude of 225 mg (Figure 2).

The targeted condition monitoring system requires a current of 30 mA for a time period of 10 s in order to perform one measurement task. Assuming an acceptable voltage drop of 1 V at the energy storage, a capacitance of 0.6 F is required for performing the measurement. The activation cycle is one hour. A power management unit was designed and implemented for charging the capacitor and to power the condition monitoring system at a regulated output voltage of 3.0 V. The upper and lower threshold value of the integrated hysteresis is 2.9 V and 1.9 V, respectively. If the upper hysteresis threshold is reached (voltage at capacitor = 2.9 V), the voltage-regulated output port is enabled. If the voltage at the capacitor falls below 1.9 V, the output port is disabled. From this point of view there are two charging scenarios: start-up charging (cold start, the initial capacitor voltage is equal to zero) and operation charging (warm start, the capacitor voltage is 1.9 V). In case of a cold-start the upper hysteresis level is 3.3 V.

Since the activation cycle of the condition monitoring system is 1 hour, a charging time of 59 min and 50 sec is available to charge the capacitor. The charging time for the cold-start scenario is shown in Figure 6(a). For most revolution speeds the time required to charge the 0.6 F capacitor to a voltage



(a) (b)

Figure 6. (a) Start up charging time and voltage level at the capacitor vs. revolution speed. (b) Charging time during operation vs. revolution speed

level of 3.3 V is less than 60 min. For example, at a revolution speed of 160 RPM a charging time of 57 min is necessary. At a revolution speed of 560 RPM a voltage of 2 V is gained after a time period of 1 hour. Figure 6(b) shows the charging time for the warm-start scenario (the voltage level at the capacitor is 1.9 V). For all revolution speeds except 80 RPM and 400 RPM the upper hysteresis level of 2.9 V at the capacitor is achieved in less than 30 min. Once the capacitor is pre-charged to a level of 1.9 V an activation cycle of 1 hour appears possible with respect to the worst case (revolution speed of 560 RPM). In this case, there are 35 min left for harvesting energy for the tuning mechanism. Within 35 min the capacitor can be recharged at least one more time from the lower hysteresis level (1.9 V) to the upper hysteresis level (2.9 V). Consequently, an energy packet of 1.44 J is available for the tuning mechanism. In other words, a current of 0.3 A is available for 1s.

5. Conclusion

In this work we presented a new concept for tuning the Eigen-frequency of a cantilever-based electromagnetic energy harvester. The functionality and feasibility of the concept was demonstrated on the basis of a proof-of-concept implementation, which included a manual tuning mechanism.

The demonstrated tuning concept is based on a magnetic principle and incorporates a circular tuning magnet, which interacts with a coupling magnet attached to the active transducer element. The circular tuning magnet merely requires a rotational motion with angle adjustments ranging from 0° to 180°. In this manner the tuning magnet can be attached directly to a rotary actuator without the need of a gearing mechanism. Only a half turn of the actuator is required for utilizing the entire tuning range.

The tuning range can be designed by careful adjustment of the gap between tuning magnet and coupling magnet. The smaller the gap the larger is the tuning bandwidth. The center frequency of the tuning bandwidth is adjusted by the stiffness of the cantilever in consideration of the mass of the magnetic circuit. In this work the tuning bandwidth and center frequency was tailored to a specific condition monitoring application targeting the monitoring of maritime gear boxes.

The new concept proposed in this paper will facilitate a simple and energy efficient implementation of a self-powered and self-tunable energy harvesting system, which is part of the ongoing work.

Acknowledgements

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