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Adaptives Energy Harvesting für Condition Monitoring Anwendungen im maritimen Umfeld

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Abstract

This paper reports on a frequency-tunable energy harvester, which is able to adapt its eigenfrequency to a variable environment. The power required for frequency tuning is delivered by the energy harvester itself. The tuning mechanism is based on a magnetic concept and incorporates a circular tuning magnet and a coupling magnet. In this manner, both coupling modes (attractive and repulsive) can be utilized for tuning the eigenfrequency of the energy harvester. The tuning range and its center frequency can be tailored to the application by careful design of the spring stiffness and the gap between tuning magnet and coupling magnet. Experimental results demonstrate that, in contrast to a conventional non-tunable vibration energy harvester, the net power can be significantly increased if a self-adaptive system is utilized, although additional power is required for regular adjustments of the eigenfrequency. The outcome confirms that active tuning is a real and practical option to extend the operational frequency range and to increase the net power of a conventional vibration energy harvester.

Keywords: Energy Harvesting, adaptive Systems.

Introduction

Vibration based energy harvesters are still rarely established in industrial environments. A major reason for that is the specific characteristic of a single eigenfrequency of common vibration energy harvesters with a linear resonant structure. The eigenfrequency is typically invariable due to the fixed ratio of spring stiffness and mass [1, 2]. If the mechanical parameters are carefully designed, the eigenfrequency can be matched to a dominant frequency in the spectrum of the ambient vibration source. However, a slight shift of the excitation frequency causes the energy harvester to operate off-resonant. As a consequence, the effectiveness of the energy conversion process reduces significantly.
In many applications, the location of dominant frequencies varies over time in accordance with the operating mode of the machine. This, for instance, happens on any machine with a variable-speed power unit. The corresponding frequency band with its dominant frequencies will depend on specific conditions and typically ranges from 25 Hz to 80 Hz [3]. Consequently, the process of effective energy conversion, characterized by the occurrence of resonant operation, becomes a random event for devices with a single, invariable eigen-frequency. Moreover, the operating frequency bandwidth of a vibration energy harvester is rather narrow and utilizing them on variable-speed machinery is not practical. Thus, energy autonomous sensor systems powered by vibrations are still found in niche applications only, despite the fact that machine vibrations are present all over in the industrial environment.
The indetermination of the operating conditions and therefore of the vibration source makes it difficult to achieve a reliable power supply by means of vibration energy harvesting. However, in order to establish vibration energy harvesters in industrial applications, the devices must become more reliable providing the right amount of energy at a particular time without failure. For achieving the required reliability, a self-adaptive system being able to adjust its properties to the given operating conditions seems an appropriate solution. In this respect, the effectiveness of harvesting energy from time-varying vibrations can be significantly increased by means of a self-tunable energy harvester.
In this work we demonstrate a concept which facilitates the process of automatic frequency-tuning of a vibration energy harvester. The demonstrator system is tunable over a frequency range from 30 Hz to 50 Hz. The development was based on the frequency spectrum of a marine gear box. The power

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required for tuning is delivered by the energy harvester itself. No energy is required for maintaining its new state.

State-of-the-Art

In general, the eigenfrequency of a linear oscillator can be varied by changing the stiffness or the mass of the system [2]. To date, a variety of solutions for tuning the eigenfrequency have been reported. A detailed overview about tuning concepts and specific solutions is given by Tang et al [2] and Zhu et al [4], respectively. From literature it can be identified that a cantilever-based oscillator is particularly suitable for frequency tuning. The application of a magnetic force to a cantilever-based oscillator seems to be a suitable method to adjust its eigenfrequency. The magnetic force can be applied in two different ways: perpendicular to the cantilever (in the direction of cantilever motion) or in axial direction. In the case that magnetic forces act in the oscillation direction of the cantilever, a nonlinear magnetic stiffness is introduced. The effective system stiffness results then from the superposition of cantilever stiffness and magnetic stiffness. By varying the distance between two sets of tuning magnets the magnetic stiffness and hence the eigen-frequency of the oscillator can be altered [5, 6]. If a magnetic force is applied in axial direction (orthogonal to the oscillation direction of the cantilever), the structure is exposed to strain. As a consequence, the stiffness of the mechanical structure changes accordingly. A possible implementation of this particular tuning technique comprises two axially polarized magnets, a coupling magnet attached at the end of the cantilever and an adjustable tuning magnet attached to the frame [7, 8]. By translational motion of the tuning magnet the eigenfrequency can be varied. However, the coupling magnet and the tuning magnet can be configured either in attractive or repulsive mode. Using both modes in combination is not possible. 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 eigenfrequency resulting in a larger tuning bandwidth. Moreover, the tuning magnet can be attached directly to a rotary actuator, making a gearing mechanism with its accompanying mechanical losses dispensable.

Analysis of the application environment

The movable parts of a marine gearbox as shown in Fig. 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. In this paper, the revolution speed is always denoted with respect to the output shaft.

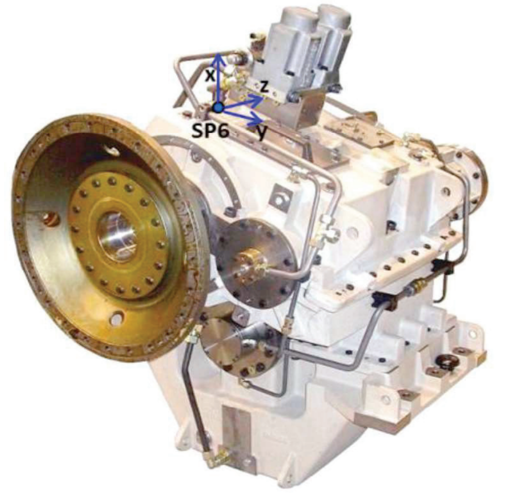

Fig. 1: Marine gearbox for work boats and ferries (Source: Reintjes GmbH)

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 Fig. 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. At sensor position SP6 (Fig. 1) the dominant frequencies below 25 Hz always have amplitudes below 10 mg. At higher frequencies the excitation amplitude is between 50 mg and 250 mg (Fig. 2). In consideration of both main shafts a frequency band can be identified, 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 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.

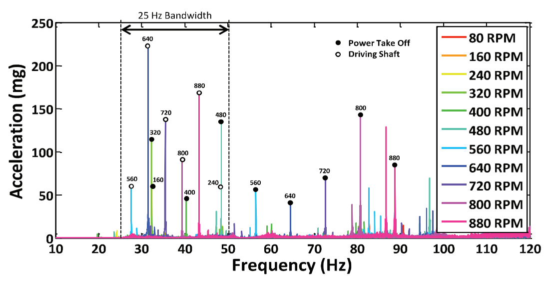

Fig. 2: Frequency spectra for SP6 at varying revolution speeds

Tuning concept

The concept of the frequency-tunable energy harvester is described in Fig. 3 and comprises a coupling magnet attached to a cantilever-based electromagnetic transducer and a circular tuning magnet. By rotation of the tuning magnet the eigenfrequency of the tunable energy harvester can be varied. The lowest eigenfrequency f_{min} is obtained at an angular position of 0° due to a pure repulsive coupling between the coupling magnet and the tuning magnet. Pure attractive coupling occurs at an angular position of 180° at which the highest eigenfrequency f_{max} is obtained. At an angular position of 90° repulsive and attractive forces between the coupling magnet and the tuning magnet cancel each other out. The resulting eigenfrequency is defined as the center frequency of the tunable frequency bandwidth.

The frequency bandwidth and the center frequency describe two important system parameters, which can be customized for a particular target environment. The frequency bandwidth can be adjusted by varying the gap between the tuning magnet and the coupling magnet. The center frequency of the tunable frequency band is determined by the stiffness of the spring (given that the mass of the transducer is constant). By careful design of the leaf spring and the gap the tunable energy harvester can be adjusted within certain limits to the application needs.

The transducer of the energy harvester comprises a closed magnetic circuit and is described in more detail by Hoffmann et al [9].

Mechanical setup

The mechanical part of the adaptive energy harvesting device is shown in Fig. 4 and includes an energy converter, a circular tuning magnet and a small stepper motor as the actuator. The circular tuning magnet is coupled to the driving shaft of the stepper motor without any gear mechanism. The stepper motor is a bipolar device from Faulhaber (AM2224) with a diameter of 20 mm and a height of 30 mm. At this stage a stepper motor with a full step angle of 15° is employed. Consequently, the adjustment of the eigenfrequency can only be performed in

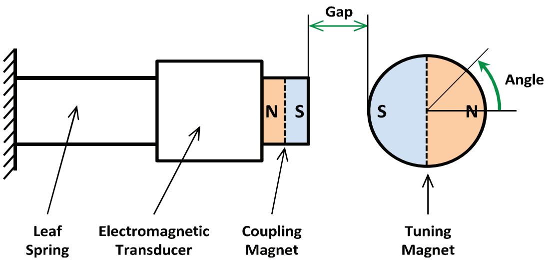

Fig. 3: Schematic (top view) showing the concept of the tuning mechanism

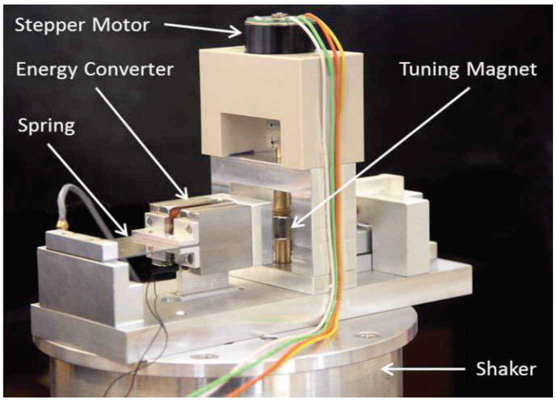

Fig. 4: Schematic (top view) showing the concept of the tuning mechanism

discrete steps according to Fig. 5. The stepper motor can be operated by supply voltages between 2.5 V and 4 V. At the minimum supply voltage of 2.5 V the stepper motor requires a minimum time of 50 ms of current flow in order to carry out a single step reliably. During current feed the consumed current is 825 mA on average. As a result, an energy packet of 124 mJ is required to perform one step.

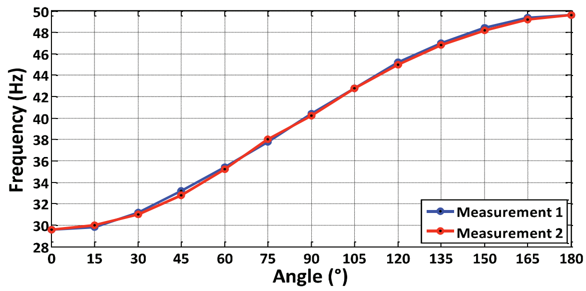

Fig. 5: Schematic (top view) showing the concept of the tuning mechanism

The self-adaptive energy harvesting device is set-up in such a manner that a center frequency of 40 Hz and a tunable frequency bandwidth of about 20 Hz are obtained (Fig. 5) in accordance to the requirements of the application environment of a marine gearbox (Fig. 2). From Fig. 5 it follows, that a maximum of 12 steps are required to tune the eigenfrequency from the lower bound (30 Hz) to the upper bound (50 Hz) of the frequency band. Consequently, 1.49 J of electrical energy is required in total to tune the device from 30 Hz to 50 Hz.

Power management

In order to store the energy harvested from vibrations and to make this energy available for powering the stepper motor and a possible application a power management circuit was developed. The power management unit as shown in Fig. 6 includes a high side switch for over voltage protection, an energy storage (supercapacitor) with a capacitance of 0.6 F, a hysteresis function for safe start-up and a

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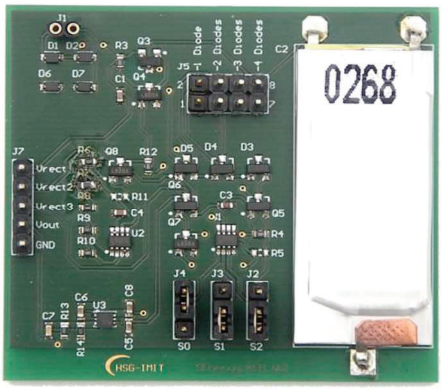

Fig. 6: *Power management unit on PCB*

charge pump to obtain a regulated output voltage of 3 V. The high-side switch limits the voltage at the energy storage to 3.8 V. The hysteresis function activates the charge pump when the voltage at the energy storage reaches a level of 2.9 V. If the voltage level falls below 1.9 V the regulated output voltage is disabled. For the charging characteristic of the energy storage two phases can be defined: the cold start time is the time required to charge the energy storage from 0 V to the upper hysteresis level (2.9 V). The charging time for increasing the voltage from the lower hysteresis level (1.9 V) to the upper level is called warm start time.

Experimental method

The frequency tunable energy harvesting system is mounted on a laboratory shaker system as shown in Fig. 4. The vibration shaker is controlled by a specific software package running on a personal computer (PC). The stepper motor for manipulating the tuning magnet is driven by a motor controller unit from Texas Instruments (DRV8835). The motor controller and the stepper motor are exclusively powered by the power management circuit. An external power supply is not involved (except for the PC and the shaker system). At this state the stepper motor was controlled via LabView.

A harmonic vibration profile was defined by a sequence of eight phases as listed in Table 1. According to the vibration analysis of the marine gearbox a low-level acceleration amplitude of 0.2g was used. The vibration profile was played consecutively until it was stopped manually at some point. For each phase an equal time period of 70s was used. Experiments were carried out with and without frequency adaption. In case of frequency adaption, the stepper motor was activated manually at the beginning of each phase in order to rotate the tuning magnet to the required angular position. The angular position of the tuning magnet was initially set to 0°.

Tab. 1: *Harmonic vibration profile with 0.2g acceleration amplitude*

Vibration Phase	Frequency (Hz)	Number of Motor steps
1	40	(6) / 4
2	35	2
3	47	5
4	38	4
5	45	3
6	49	3
7	40	5
8	31	4

The number of motor steps required for adjusting the eigenfrequency of the energy harvester to the specific frequency of each period is listed in Table 1. For instance, at the beginning the tuning algorithm must execute 6 motor steps in order to adapt the eigenfrequency from initially 30 Hz to 40 Hz (phase 1). When phase 2 starts two steps are necessary for adjusting the eigenfrequency. When phase 8 finishes, phase 1 starts again and 4 motor steps are then required to tune the eigenfrequency from 31 Hz to 40 Hz. On average 3.8 motor steps per adjustment procedure are necessary for this particular vibration profile. For experiments without frequency adaption the eigenfrequency of the energy harvester was fixed to a value of 38 Hz. Before each experiment, the energy storage was initially charged to the upper hysteresis level (2.9 V). The vibration profile was then started and the time-dependent voltage progression at the energy storage was recorded. In order to visualize the tuning-state of the energy harvester (resonance or off-resonance) the voltage potential of one coil port with reference to ground is also displayed.

Results and discussion

In the case of no frequency adaption (Fig. 7) the voltage at the energy storage does not increase within the first three phases since the eigenfrequency of the energy harvester is not tuned to the frequency of the respective vibration phase. Only for the duration of phase 4 is the eigenfrequency (38 Hz) equal to the excitation frequency and thus the voltage at the energy storage increases. After about

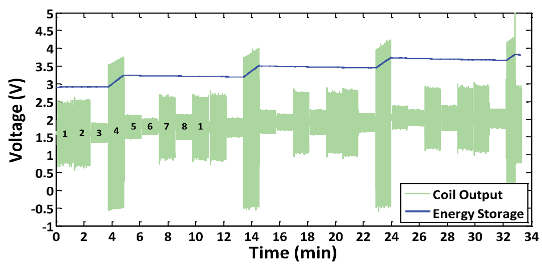

Fig. 7: *Voltage progression at the energy storage without frequency adaption*

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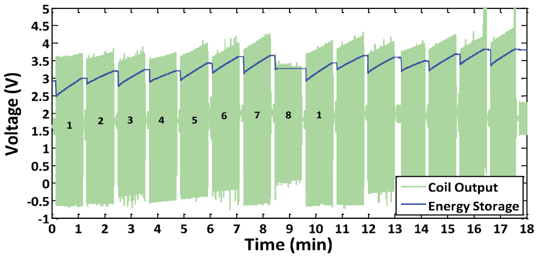

Fig. 8: Voltage progression at the energy storage with frequency adaption

33 min the voltage potential reaches the upper limit of 3.8 V and the high-side switch is activated. In contrast, Fig. 8 shows the voltage progression obtained with frequency adaption. Since the vibration phase changes every 70s, the frequency tuning is also carried out at the same rate. From Fig. 8 it is evident that the time required to charge the energy storage from 2.9 V to the upper limit (3.8 V) is just half of the time when no tuning is performed. This first result shows that there is a positive energy balance despite the tuning effort. Therefore, charging the energy storage with frequency adaption occurs much quicker for this particular vibration profile. The upper voltage limit of 3.8 V is reached within a time of 16.5 min (Fig. 8). In this time period a total of 53 motor steps were performed (14 tuning procedures). Considering the energy required to carry out a single step (124 mJ), the total amount of energy used for tuning becomes 6.6 J. With respect to the charging time of 16.5 min, the average power necessary for the frequency adaptions is therefore 6.7 mW. The energy gain at the energy storage (due to the voltage increase from 2.9 V to 3.8 V) is 1.81 J. This corresponds to an average net power of 1.83 mW. In case of no frequency adaption the average net power is 0.9 mW. As a result of tuning the net power was doubled, although the vibration profile applied here required an average of 3.8 motor steps per adjustment procedure. In conclusion, the outcome confirms that active tuning is a real and practical option to increase the net power of a conventional vibration energy harvester.

Conclusion

In this work a self-powered tuning mechanism was demonstrated. The system is able to adjust its eigenfrequency between 30 Hz and 50 Hz. The tuning mechanism is based on a magnetic force approach using a circular tuning magnet.

The experimental results demonstrate that in contrast to a conventional non-tunable vibration energy harvester, the net power can be significantly increased if frequency tuning is utilized, even though additional power is required for regular adjustments of the tuning magnet. This is because the total power output can be several times higher when the eigenfrequency is tuned to the frequency currently dominant in the vibration spectrum. In this case, sufficient energy is available for powering both the tuning mechanism and a potential application. However, the effective increase of both total power and net power will eventually depend on a number of parameters. Important factors of influence are the vibration profile (acceleration amplitude and rate of frequency shifts), the tuning mechanism, the required tuning rate and the size of the energy harvester. It must be pointed out that the overall effectiveness of a self-powered frequency tunable energy harvesting system will strongly depend on the vibration profile and thus on the application.

The tuning mechanism demonstrated in this paper is not yet completely self-sufficient since the stepper motor was controlled via LabView running on a PC. Preliminary measurements show, that the execution of the tuning algorithm on a low-power microcontroller in active mode consumes an average power in the range of 500 µW to 700 µW. This particular power demand is only a fraction of the power required for driving the stepper motor. Therefore, a completely self-sufficient system with a microcontroller-based control unit seems feasible. We are currently working on the implementation of such a control unit.

A specific characteristic of the current implementation of the self-adaptive system is its discontinuous tuning capability. This is because the system is equipped with a stepper motor with a full step angle of 15°. This seems to be a disadvantage in the first place in particular when addressing applications where the dominant frequency shifts continuously within a defined frequency band. On the other hand, for applications requiring a tuning bandwidth smaller than 20 Hz, the distance between tunable frequency steps reduces and tuning with better frequency resolution will be possible.

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