

Self-sufficient electronic control for nonlinear, frequency tunable, piezoelectric vibration harvesters

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Abstract. Research in vibration energy harvesting focuses increasingly on nonlinear harvesters. In comparison to linear harvesters they show an inherent larger bandwidth through hardening or softening effects and higher conversion efficiency. A further increase of the bandwidth and thus a higher energy yield can be achieved by controlled tuning of such a nonlinear system. In this paper a self-sufficient tuning control electronic, which is directly powered by the harvester, is presented.

1. Introduction

In the last few years the research in the field of vibration energy harvesting has focused on nonlinear systems [1-3]. As illustrated in figure 1, these systems show an inherently larger bandwidth due to their nonlinear frequency response which leads to a higher conversion efficiency over a wide frequency band. Therefore, in contrast to linear systems, no trade-off between the output power and the bandwidth is necessary.

However, nonlinear systems show a characteristic hysteresis whereby the harvester is either located in a preferable high oscillation orbit or in a low oscillation orbit depending on the change of the excitation (indicated by the arrows in figure 1).

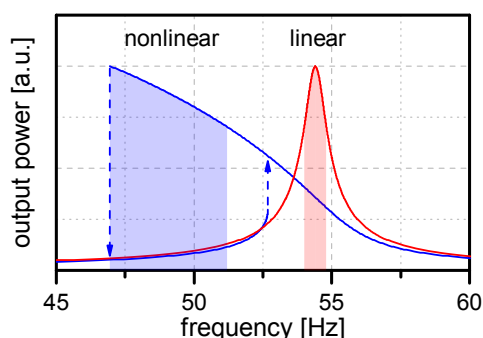


Figure 1. Typical frequency response of a nonlinear (blue) and a linear system (red).

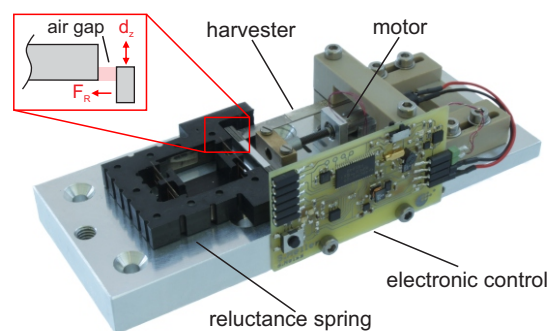


Figure 2. Photo of the nonlinear harvester and the control circuit.

The transition points between both orbits depend on the harvester's resonance frequency and degree of nonlinearity. Therefore, in order to be able to reach the high oscillation orbit and to further increase



the bandwidth, the resonance frequency has to be made tunable by an electronic control. Within the research on linear harvesters, this task is accomplished by using the phase shift between the excitation signal and the system response [4]. However, [5, 6] use controls based on a look-up table in which the optimal working point for every excitation frequency is stored. The disadvantage of this open-loop control is its inability to react to interferences such as the degradation of the piezo ceramics which could cause a shift of the resonance frequency. Only [5] addresses this problem and proposes a combination of an open-loop and a closed-loop control. The control is based on a look-up table but the values stored there are verified at longer intervals by a measurement of the phase shift.

2. Nonlinear vibration harvester

The starting point of the presented work is the nonlinear vibration harvester depicted in figure 2. The nonlinear behavior is produced by a patented reluctance spring [7] which is leading to a nonlinear restoring force F_R on the seismic mass in function of the deflection d_z . For the adjustment of the resonance frequency the gap width between the seismic mass of the harvester and the reluctance spring will be changed. This is realized by an electric motor which is coupled to the reluctance spring by a spindle gear.

Figure 3 shows the frequency responses for different gap widths between 0.5 mm and 1.5 mm at an excitation level of 5 m/s^2 . Over a gap width change of 1 mm a resonance frequency between 53.6 Hz (1.5 mm) and 63.9 Hz (0.5 mm) is achieved. The relative hysteresis width varies between 4.3% and 16% of the nonlinear resonance frequency depending on the gap width. The corresponding phase responses recorded with an infinite load resistance (see figure 4), prove that even for nonlinear systems the point of maximal amplitude occurs at a phase shift between excitation and system response of -90° .

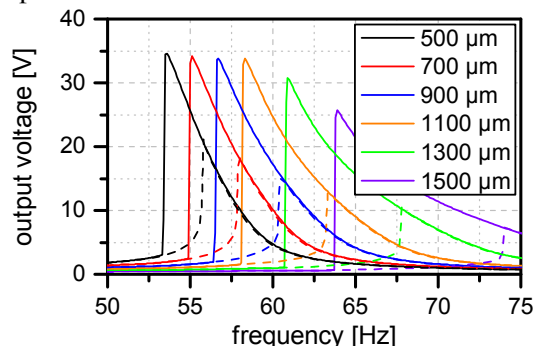


Figure 3. Frequency responses for different gap widths at an excitation level of 5 m/s^2 .

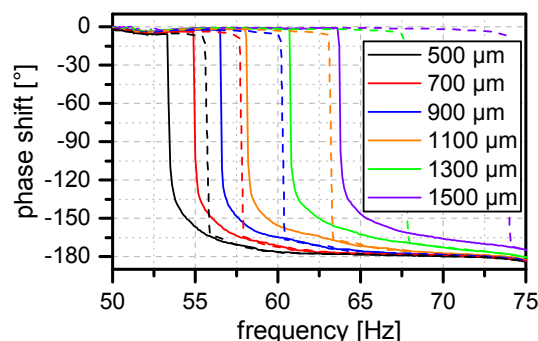


Figure 4. Phase responses for different gap widths at an excitation level of 5 m/s^2 .

3. Control concepts

3.1. Tuning concept

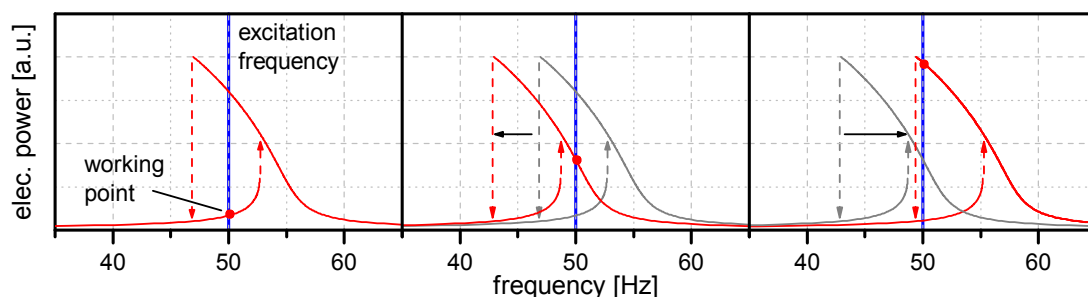


Figure 5. Tuning concept for transitions from the low oscillation orbit to the high oscillation orbit.

For every frequency inside the hysteresis band of the frequency response; two stable states exist as previously described: one in the high oscillation orbit and one in the low oscillation orbit. To enable the transition from the low oscillation orbit into the high oscillation orbit, a tuning concept as illustrated in figure 5 was developed: Starting from the low oscillation orbit (left), the nonlinear resonance frequency (respectively the stiffness of the system) has to be increased until the working point jumps from the low oscillation orbit to the high oscillation orbit (middle). Afterwards, the resonance frequency has to be decreased by reducing the stiffness of the system to reach the optimal working point (right).

3.2. Continuous monitoring

Due to an insufficient stability of the system at the point of maximum output voltage, a definition of the working point at a phase shift of -90° is not practical. A better way is the definition of a phase window, which corresponds to the bandwidth of the harvester and allows for sufficient stability while granting high-enough output power to enable the self-sufficient supply of the harvester. Moreover, the number of tuning steps can be dramatically reduced by this approach. For an unloaded harvester the phase window extends from -135° to -150° . Due to the electrical damping the phase response shift is reduced, so that the practical phase window extends from -75° to -100° in case of an electrical load.

The control loop starts with the measurement of the actual phase shift. When the phase shift is outside the phase window, the gap width is adjusted in accordance to the measured phase shift. To check the set gap width, the phase shift is measured again. This procedure repeats until it is close to the optimal working point. If this is the case the control electronic is powered down for 30s in favour of a higher output power. Afterwards, the procedure is restarted.

3.3. Continuous monitoring

The drawback of the previously presented control concept is it measures the phase shift at fixed points in time. Therefore, depending on the temporal change of the excitation, the phase shift is measured too often or not often enough. In both cases this leads to higher power consumption. Ideally, the phase shift is measured only when a change in the excitation occurs. Therefore, a second concept was developed which uses an additional ultra-low power accelerometer to measure the excitation level during the sleep phase. The output voltage of the harvester is used to monitor the excitation frequency. If one of these quantities changes over a defined tolerance, the microcontroller wakes up immediately and initiates a measurement of the phase shift.

4. Control electronic

For the realization of the two control concepts the self-sufficient control electronic depicted in figure 6 was developed. The energy and information flows between the different parts are shown in figure 7.

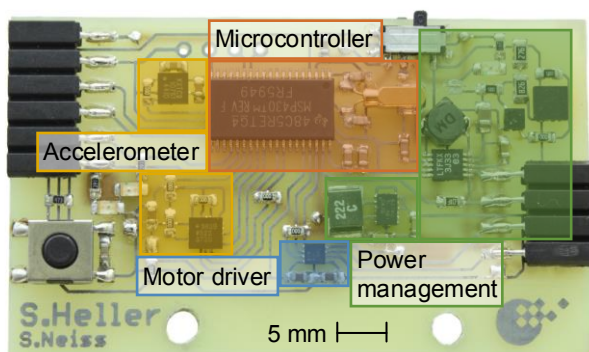


Figure 6. Photo of the circuit board with the control electronic.

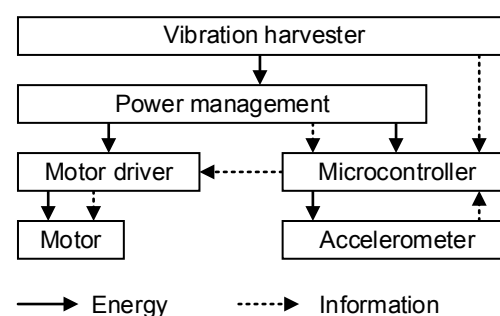


Figure 7. Block diagram of the electronic control.

The core of the system is a low-power microcontroller (MSP430FR5949, *TI*) which calculates the phase shift using the output signal of an analog accelerometer (KXTC-4100, *Kionix*) and the output voltage signal of the harvester. Furthermore, the microcontroller is used for the control of the motor (RE6, *Maxon Motor*) via a motor driver (DRV8838, *TI*). For the realization of the control concept with continuous monitoring an ultra low power accelerometer (ADXL362, *Analog Devices*) is used.

An efficient power management is needed for the self-sufficient operation of the control. First, a combination of a bridge rectifier and a buck converter (LTC3588-1, *Linear Technology*) produces a constant output voltage of 3.3V from the harvesters AC output voltage. This voltage is used to charge a super cap (GW209F, *CAP-XX*) with a capacity of 0.14 F. The electric motor, as well as the motor driver is powered at 3.3V, whereas the microcontroller and the sensors are powered at 2V. This has the advantage that the power consumption can be reduced further. To produce the 2V supply voltage a further high-efficient buck-converter (TPS62740, *TI*) is used.

5. Results

5.1. Frequency sweep

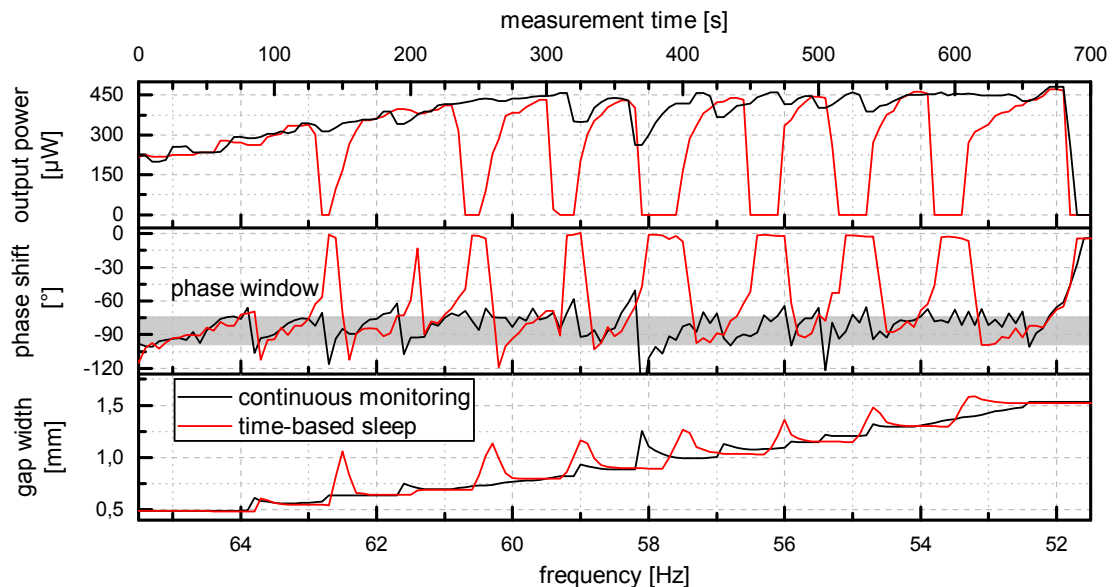


Figure 8. Comparison of the two control concepts in the working area for a frequency drift from 80 Hz to 50 Hz by means of the output power, the phase shift and the gap width at an excitation level of 5 m/s^2 .

To characterize the control concepts, the control performance at a slow, continuous sweep of the excitation frequency of 0.1 Hz/s at a constant excitation level of 5 m/s^2 was investigated. The gap width, the output power of the harvester and the phase shift were recorded.

For an up-sweep no significant differences between the two concepts were found. The working point stayed most of the time inside the phase window, the gap width decreased gradually from 1.5 mm to 0.5 mm while an average output power of the harvester of $350 \mu\text{W}$ was achieved.

Substantial differences appear for the down-sweep (see figure 8). With the concept of the time-based sleep the harvester falls into the low oscillation orbit while sleeping whereby the output power drops to $0 \mu\text{W}$. To get back into the high oscillation orbit after waking up, first the gap width has to be reduced and afterwards increased, as described in section 3.1 and easily seen at the spikes in the course of the gap width in figure 8. With the concept of the continuous monitoring in contrast, the harvester stays all the time in the high oscillation orbit. Thus, the energy yield for the whole sweep is increased by 39% to 307 mJ. Moreover the energy consumption of the actuator is reduced by 49% to

139 mJ. Taking into account the higher power consumption for continuous monitoring the net output power is 114 mJ whereas for the time-based sleep concept it is -72 mJ.

5.2. Recovery time

To compare the harvester system to other linear and nonlinear systems, the recovery time at an excitation level of 5 m/s^2 was measured. The recovery time was defined as the time period needed to harvest the energy which is required for a tuning process after a jump in the excitation frequency over the whole working area (52.5 Hz to 64.5 Hz). As the results in table 1 show, the recovery time for the concept of continuous monitoring is 30% longer in comparison to the concept of time-based sleep due to higher power consumption. In spite of a longer adjustment travel for a jump from the upper to the lower border of the working area, the recovery time is 36% less which can be explained by a lower mechanical damping at lower frequency and thereby a higher output power of the harvester.

Table 1. Recovery time for the two different control concepts at an excitation level of 5 m/s^2 .

	52.5 Hz to 64.5 Hz	64.5 Hz to 52.5 Hz
Time-based sleep	518 s	375 s
Continuous monitoring	662 s	497 s

6. Control electronic

The presented results verify that a self-sufficient closed-loop control of a nonlinear vibration harvester based on the measurement of the phase shift between excitation and system response of the harvester is possible. At an excitation level of 5 m/s^2 an average output power of $350 \mu\text{W}$ is measured which leads to a recovery time of the system between 375 s and 662 s depending on the used control concept and the direction of the change in the excitation frequency.

The choice of the optimal control concept mainly depends on the temporal change of the excitation. For a constant excitation over a long period of time the concept of time-based sleep is preferable because of the lower power consumption. However, in case of a frequently changing excitation the concept of continuous monitoring is better suited because the fall into the low oscillation orbit can be avoided and therefore a significant amount of energy needed for the actuation can be saved.

Acknowledgements

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