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Autonomous Tuning Methods for Piezoelectric Energy Harvesting Generators

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Abstract

This paper explores two different methodologies that are able to change the resonance frequency of a piezoelectric cantilever. In real-life energy harvesting applications like logistics, condition or structural health monitoring, the ambient frequency is changing. A drawback of harvesting energy from ambient vibrations is the fact that the frequency of the ambient vibration and the resonance frequency of the piezoelectric generator should match. Therefore, in order to sufficiently and continuously harvest energy from ambient vibrations, it is necessary to be able to change the resonance frequency of the piezoelectric generator. To overcome this challenge, two frequency tuning methodologies that can be applied autonomously in operation are presented. A 10 % frequency tuning is desired for example by applications in logistics.

Key words: energy harvesting, piezoelectric generator, frequency tuning, resonance frequency.

Introduction

A summary of tuning methodologies is given in [1] where either manual or autonomous methods are described. The ambient frequency with higher acceleration amplitude does not remain constant with time [2]. Therefore, for a real application, it is necessary to be able to tune the resonance frequency autonomously during operation.

The tuning concepts presented in the paper are suitable for this variant. Both methods use a piezoelectric bimorph cantilever as energy harvesting generator.

Following the generic model based on inertial kinetic energy harvesting developed by Williams and Yates [1], the natural resonance frequency of a piezoelectric energy harvester is:

$$\omega_n = \sqrt{\frac{k}{m}} \qquad (1)$$

where k is the stiffness and m the weight of the harvester.

Therefore, the natural resonance frequency can be changed by modifying the stiffness k of the harvester. The first method presented in this paper modifies the stiffness of the harvester by connecting a parallel capacitor to one piezoelectric layer of a bimorph cantilever. This methodology has been presented previously in [3]. Nevertheless, the fact that the frequency tuning works in the tuning range between the resonance and anti-resonance frequency has not yet been pointed out.

The second method for tuning the resonance frequency of a piezoelectric presented in the paper employs a magnetic force. The magnetic force applied changes by varying the rotation angle of the magnet [4], see Fig. 1, and not the distance between magnets [1], to influence the stiffness of the cantilever and therefore its resonance frequency. This method reduces the required volume for the generator compared to [1].

The tuning ratio of a mechanical harvester is given by eq. (2) [3].

$$Tuning\ ratio = \frac{f_{r,max} - f_{r,min}}{f_{r,min}} 100 \qquad (2)$$

where $f_{r,max}$ is the maximum resonance frequency and $f_{r,min}$ is the minimum resonance frequency. The tuning ratio is a figure of merit to characterize the tuning capabilities as a ratio and not as an absolute number.

The paper concludes with a summary of the results and highlights the work still pending.

Capacitive Tuning Methodology

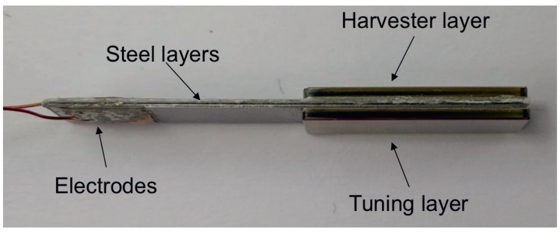

Fig. 1 Piezoelectric bimorph with PZN-5.5%PT

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Fig. 1 shows the bimorph cantilever structure, employed for the capacitive frequency tuning. One piezoelectric layer is used for harvesting and the other one is used for frequency tuning by connecting it to an external capacitor C_s. By connecting C_s to the piezoelectric cantilever, the parallel resonance frequency [5] is modified as described by eq. (3).

$$f_p = \frac{1}{2\pi\sqrt{L_1 C_1 \left(C_p + C_s\right) / \left(C_1 + C_p + C_s\right)}} \quad (3)$$

where L_1 is the motional inductance in the equivalent electric circuit, C_1 is the motional capacitance in the equivalent electric circuit, C_p is the parallel capacitance in the equivalent electric circuit and C_s is the shunt electrical capacitance added to the piezoelectric harvester for tuning purposes.

The piezoelectric material employed is PZN-5.5%PT and free samples were provided by [6]. The dimensions of the cantilever beam are summarized in Tab. 1.

Tab. 1: Materials and dimensions employed for the bimorph piezoelectric cantilever with capacitive tuning

	Material	L x W x T (mm)
Piezoelectric element	PZN-5.5%PT	15 x 5 x 0.8
Shim layer	Steel	30 x 5 x 0.2
Electrode	Copper	5 x 5 x 0.07
Conductive layer	CW2400	25 x 5 x 0.04
Non-conductive layer	Super glue	40 x 5 x 0.08

Fig. 2 shows the admittance of the tuning layer of the bimorph piezoelectric cantilever. f_m is the frequency at maximum admittance whereas f_n is the frequency at maximum impedance [6]. The value of f_n is close to f_p and frequency f_m is close to f_s, motional series resonance frequency, eq. (4).

$$f_s = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad (4)$$

Tab. 2 shows the values for f_m, f_s, f_n and f_p obtained without C_s, open circuit, and with different values of C_s measured at the tuning layer of the bimorph cantilever. The tuning ratio of this tuning method depends on the distance between f_m and f_n since adding C_s moves f_n towards f_m. Capacitive tuning can only be performed with piezoelectric materials that provide values of f_m and f_n. The frequency at which the maximum power is achieved at the piezoelectric harvesting layer is somewhere between f_m and f_n.

Fig. 3 shows the measured resonance frequency as a function of C_s normalized to the piezoelectric capacitance C_p with 10.5 % frequency tuning achieved. C_p is 3.4 nF, for the piezoelectric element under test of Tab. 1. As expected, a change in C_s brings a change to the resonance frequency in a defined region. For the cantilever bimorph of Fig. 1, the resonance frequency can vary from 441.5 Hz, if the tuning layer is in open circuit, to 399.5 Hz, if C_s = 200 nF is connected to the tuning layer.

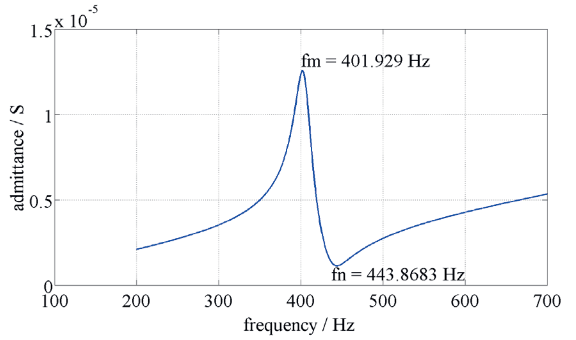

Fig. 2. Admittance as function of frequency for the piezoelectric harvesting layer of the piezoelectric bimorph cantilever

Tab. 2: Maximum admittance f_m and maximum impedance f_n values with different C_s

C_s (nF)	f_m (Hz)	f_s (Hz)	f_n (Hz)	f_p (Hz)
without C_s	401.93	404.88	443.87	441.10
0.535	403.78	407.13	436.82	433.15
0.954	403.10	406.96	432.88	428.68
2.2	401.82	406.93	426.45	421.05
8.25	399.95	407.01	419.52	412.04
142	402.90	406.95	409.3	406.95
174	405.10	406.88	407.70	406.88

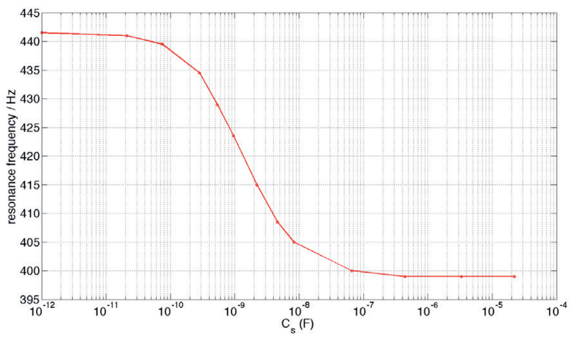

Fig. 3. Resonance frequency as a function of the ratio between capacitance C_s and piezoelectric electrical capacitance C_p.

Capacitive Self-tunable piezoelectric harvester

A frequency tuning algorithm must be able to tune the resonance frequency of the piezoelectric harvester to the ambient frequency. Some tuning algorithms [7,8] employ the piezoelectric voltage as input parameter. When either the voltage or the power reach their maximum value, it is assumed that the piezoelectric harvester is tuned. This methodology has been used for the algorithm of the capacitive self-tunable piezoelectric harvester.

Values of C_s between 75 pF and 65.6 nF are inside the linear region of the curve shown in Fig. 3.

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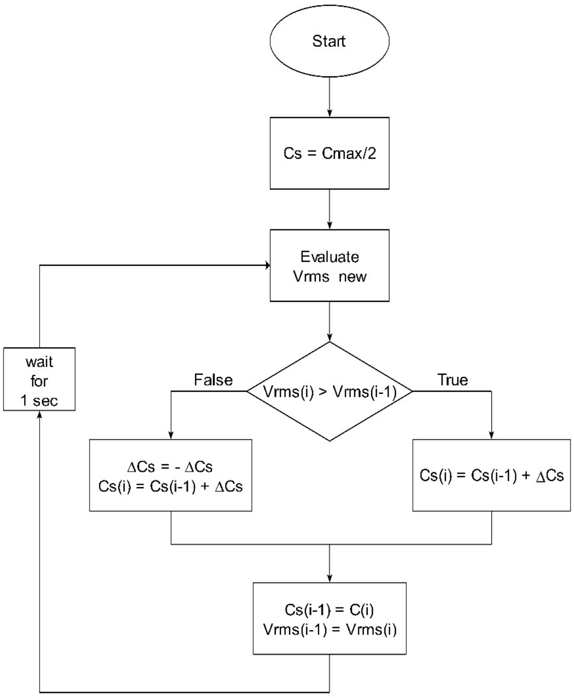

Fig. 4. Flowchart of the perturb and observe algorithm for frequency tuning

A perturb and observe algorithm [9], see Fig. 4, has been implemented with a DS1104 dSPACE R&D controller board in Simulink. The algorithm starts at half the value of the maximum value of Cs inside the linear region, C_{max}. An array of capacitors and switches were connected in parallel [1] and driven by the DS1104 board in order to connect the appropriate value of C_s in parallel to the harvesting layer of the bimorph cantilever. The value of Cs is given by eq. (5).

$$C_s = \sum_{i=0}^{N-1} 2^i C_i \qquad (5)$$

where N = 8 bit, C_i is the value of the capacitor connected in series with switch i, $\Delta C_s = 2^i C_i$. For example, C_0 = 100 pF and C_7 = 12.8 nF. Thus, the minimum value of C_s is 100 pF and its maximum value is 24.78 nF.

However, a method that maximizes the piezoelectric voltage is not suitable for frequency tuning when the acceleration amplitude of the ambient vibration changes with the time, which happens often in real applications, since the piezoelectric voltage will change too.

Experimental Results for the Capacitive Self-tunable piezoelectric harvester

Fig. 5. shows an experimental measurement of the capacitive tuning. Fig. 5(a) displays when the perturb and observe algorithm is started. Fig. 5(b) shows the ambient frequency applied to the harvester as a function of time. Fig. 5(c) shows the value of Cs selected by the tuning algorithm and connected to the tuning layer. The output power of the harvesting layer is represented both employing the perturb and observe algorithm for maximizing the rms voltage of the harvesting layer and without using it, see Fig. 5(d). The resistive load at which the harvested power is maximum remains constant for all the values of Cs. The ambient frequency decreases with time and the output power remains constant between 441.5 Hz and 399.5 Hz while the MPPT algorithm runs.

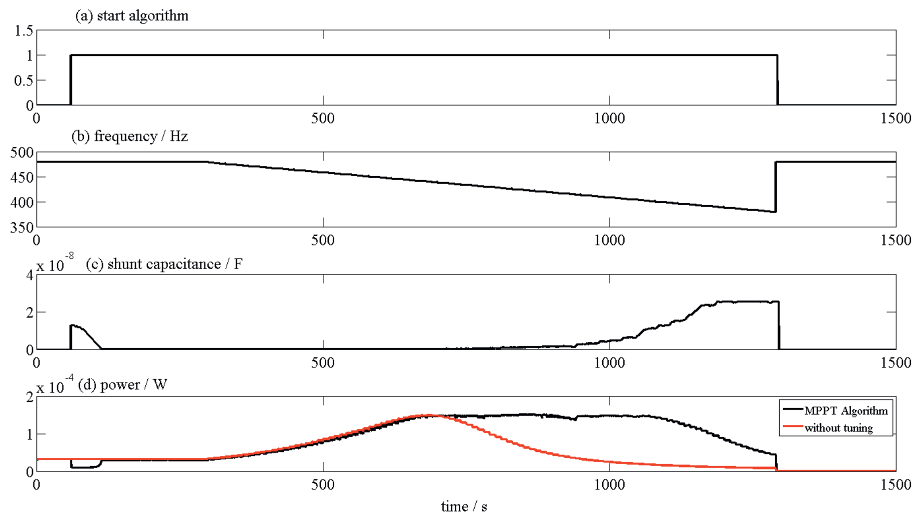

Fig. 5. Experimental measurement of the capacitive tuning, (a) indicates when the algorithm starts, (b) frequency of the ambient vibration, (c) shunt capacitance C_s, (d) output power of the harvesting layer with and without MPPT algorithm

Magnetic Force Tuning Methodology

The stiffness of the harvester can be changed by using a magnetic force, either attractive or repulsive and therefore a frequency tuning can be made.

Fig. 6 shows the structure employed for the bimorph tunable cantilever. Fixed magnets are attached to the upper and bottom end of the cantilever structure. The rotating magnets are located at a certain distance of the fixed magnets. The upper and bottom rotating magnets are moved at once by the same gear.

Fig. 7 shows that the frequency tunability has a linear region for an α angle between 30˚ and 150˚. The tuning ratio achieved with a magnet height of 3 mm and a distance between the fixed magnet at the cantilever and the rotating magnet of 8.5 mm is 9.8 % for 0.1 g acceleration, see Fig. 8. This methodology can be implemented with any piezoelectric material. The output power is reduced by using a magnetic force since it adds a damping to the piezoelectric cantilever.

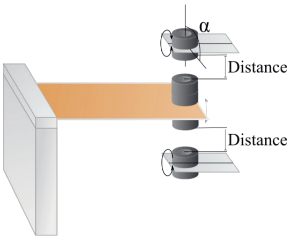

Fig. 6. Bimorph cantilever with magnetic tuning by rotating upper and bottom magnets

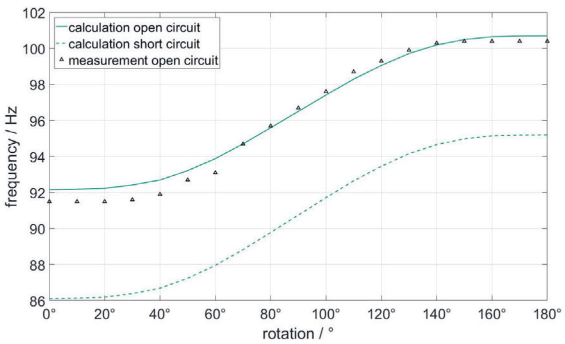

Fig. 7. Harvester frequency at different rotation angles of the magnets in open and short circuit with 0.1g acceleration amplitude

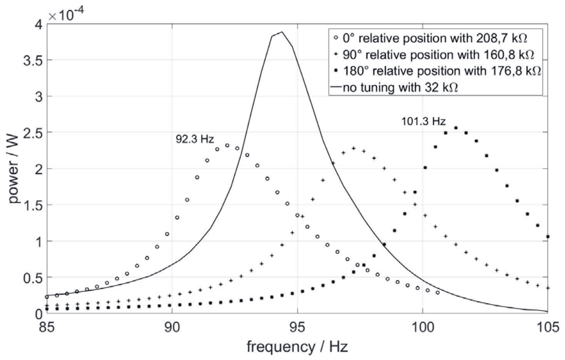

Fig. 8. Output power as a function of frequency without tuning and with an α rotation of the magnet at the optimum load

Magnetic Force Self-tunable piezoelectric harvester

Fig. 9 shows the set-up of the piezoelectric cantilever with the rotating magnets and a stepper motor. 64 mJ/Hz are required for rotating 120˚, between 30˚ and 150˚, the magnets and achieve 9.8 % tuning ratio with the stepper motor selected. Thus, it is necessary to harvest energy for 42 minutes at the resonance frequency for rotating the magnets 120˚.

The fact that the phase shift between the displacement of the harvester and the excitation displacement is 90˚ at resonance has been used by [10,11] in self-tuning algorithms. A PLL is used in [10] for determining the phase shift between both displacements and the algorithm compares the result with a reference voltage. An accelerometer and the piezoelectric harvester are employed in [11] for calculating the phase shift. A look-up table is employed by the tuning algorithm for achieving the resonance frequency of the harvester at the ambient vibration in [11]. The look-up table can be updated with new values. However, there is no information whether the tuning methods are robust against vibrations with more than one frequency component and with different vibration amplitudes.

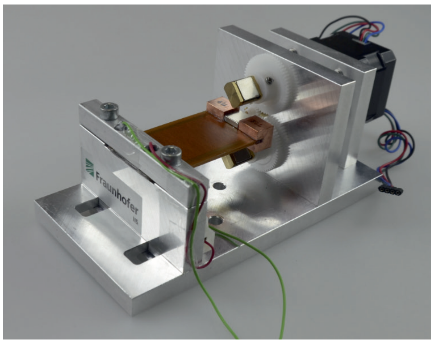

Fig. 9. Set-up of the piezoelectric harvester with stepper motor

The first issue to solve for the self-tuning of the piezoelectric harvester is how to detect that it is in resonance or how far away it is from resonance. The piezoelectric harvester is at resonance if its open circuit voltage and the acceleration of the ambient vibration have a phase shift of 90˚ [12]. Thus, the open circuit voltage and the acceleration of the ambient vibration are the measured signals for calculating the ambient frequency and phase shift parameters needed for implementing the algorithm shown in Fig. 11. The algorithm drives the stepper motor that sets α.

The frequency tuning algorithm has been implemented with the DS1104 dSPACE R&D controller board in Simulink and drives a dual full-bridge LN298 board.

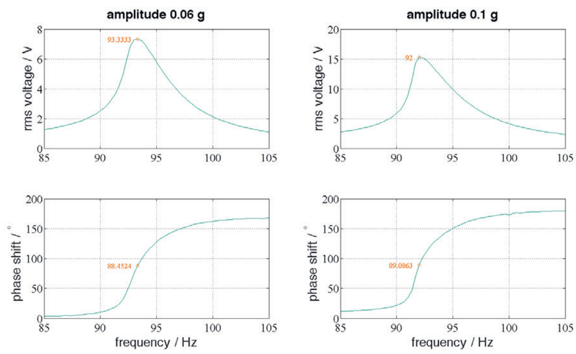

Fig. 10 Open circuit voltage of the piezoelectric harvester and phase shift between the open circuit

voltage and the accelerometer response to the ambient vibration for a frequency range 85 Hz – 105 Hz for α = 0°

Fig.10 shows the calculated phase shift between the open circuit voltage of the piezoelectric harvester and the ambient vibration frequency for a frequency sweep of the ambient frequency between 85 Hz and 105 Hz with α equal to 0˚. The validity of this method is proven by plotting the effective voltage of the piezoelectric generator and corroborating that its maximum takes place at 90˚ phase shift. Similar results have been obtained with α equal to 90˚ and 180˚.

In the range between 20˚ and 155˚ phase shift, there is a linear behaviour between the phase shift and the signal frequency, see Fig. 10 Thus, only in this phase shift range it is possible to determine if the resonance frequency of the piezoelectric harvester should be increased or decreased to match the ambient frequency and proceed to tune the resonance frequency.

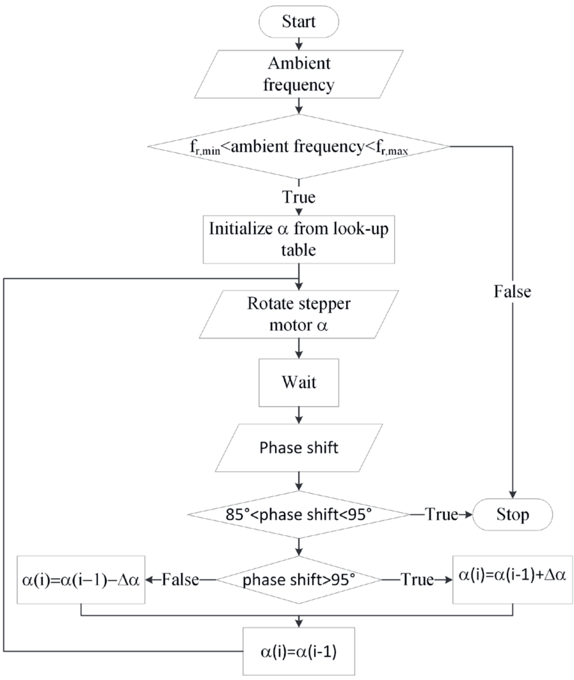

Fig. 11 Algorithm for the frequency tuning

The algorithm for the frequency tuning is represented in Fig. 11. If the ambient frequency is in the tuning range, the algorithm runs. A look-up table has been created and is used for setting the position of the magnet depending on the frequency. Therefore, the magnets are rotated and afterwards a perturb and observe algorithm is implemented until the resonance frequency matches the ambient frequency by detecting a 90˚ phase shift.

Experimental Results for the Magnetic Force Self-tunable piezoelectric harvester

Fig. 12 shows the FFT of the acceleration signal employed for testing the self-tuning capability of the piezoelectric harvester. The acceleration signal is a combination of 6 different frequencies with a main signal of amplitude of 0.1 g and other 5 components with amplitudes up to 0.03 g and frequencies between 50 Hz and 150 Hz. This experiment pursues to determine the robustness of the tuning algorithm

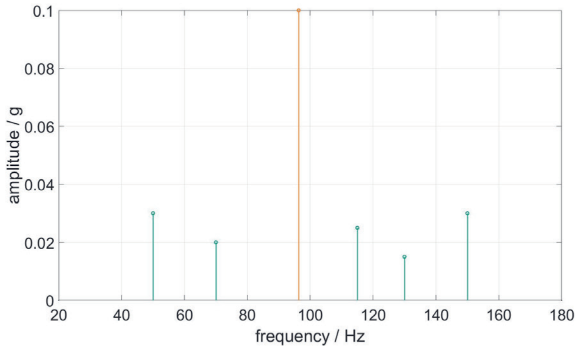

Fig. 12. FFT of the ambient acceleration employed for the tests summarized in Fig. 15

Fig.13 plots a summary of the experimental results with six different subplots. Fig.13-1) displays the ambient frequency of the main acceleration signal with amplitude 0.1 g fixed for the experiment (green) and the calculated frequency (orange). The tuning index indicates when the algorithm for the frequency tuning is running. If the tuning index is 0, the tuning process is running while if the tuning index is set to 1, the tuning process is finished.

First test is made with an ambient frequency of 95 Hz. The magnets are rotated first with the data stored at the look-up table and afterwards Δα until the resonance is achieved with α = 75˚. Then, the tuning index is set to 1. After 17 s, the frequency of the main acceleration is fixed to 100 Hz. Once the frequency tuning is activated, tuning index is 0, the magnets are rotated to α = 110˚ according to the look-up table. Then, the magnets are rotated in 10˚ steps until ca. 90˚ phase shift is achieved. The ambient frequency is again changed from 100 Hz to 93 Hz. The point in the tuning index indicates that the tuning algorithm is started. However, no tuning is possible since the error in the frequency calculation leads to a frequency value outside the frequency tuning range. At the last test, the main frequency increases to 96 Hz. The algorithm starts and the magnets are rotated first to α = 75˚ and later to α = 85.˚

Conclusions and Future Work

The capacitive tuning moves f_n towards f_m. The tuning ratio available for this methodology is limited to $(f_n-f_m)/f_m$ with the harvesting layer in open circuit. PZN-PT piezoelectric crystals have this property but in PZT crystals f_m and f_n are very close. Nevertheless, the magnetic tuning is not restricted to a certain kind of piezoelectric crystal.

Comparing both methods from the hardware side, the capacitive tuning requires just the control of several MOSFETs for the connection of the appropriate C_s whereas in the magnetic tuning driving a stepper motor is needed.

The tuning algorithms should be programmed in a low-power microcontroller and tested. Further tests with real acceleration data should be done to get to know the limitations of the tuning algorithm.

The capacitive tuning should be tested employing the algorithm based on phase shift between the acceleration of the ambient vibration and the piezoelectric harvester.

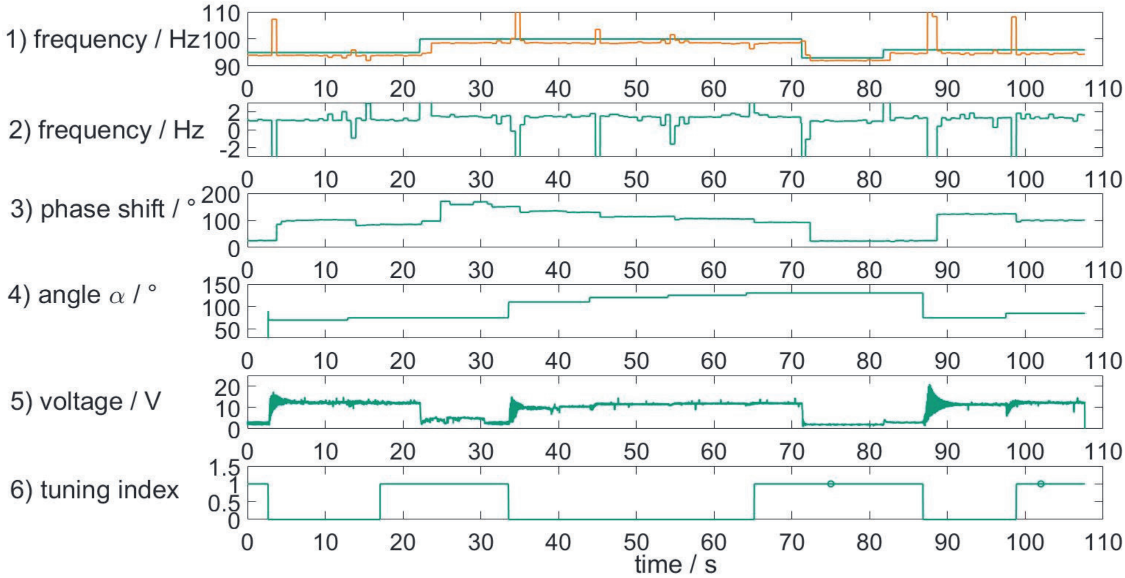

Fig. 13. 1) Frequency of the main ambient vibration signal (green) and measured frequency (orange), 2) frequency difference between the main signal and the measurement 1), 3) phase shift in °, 4) angle α of the magnets, in °, 5) open circuit voltage in V and 6) tuning index

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