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Measurement of Weak Signal Energy at Acoustic Frequencies by using RMSHI as a Passive Conditioning Circuit

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***Abstract*—To enable low-power recognition of slowly evolving acoustic events generated by weak acoustic sources, we investigate always-on circuit architectures for extraction of signal energy at arbitrarily selected bands of acoustic frequencies. To improve sensitivity and power consumption of existing always-on low-power acoustic event detectors, we consider the application of passive electromechanical systems. In this paper we investigate the Random Mechanical Switching Harvester on Inductor (RMSHI) for rectification of the weak sensor signal and measurement of its energy. The proof-of-concept system has been realized, functionally tested and characterized in terms of sensitivity and resolution. The sensitivity of the presented circuit is around 3 mV/nJ and the resolution is ±0.66 nJ. The active part of the system consumes 6.3 µW. The validity of the approach encourages us towards an integrated weak sensor signal measurement device, using a MEMS switch driven by the acoustic energy.**

Keywords—weak signal energy measurement, low-power, acoustic event, frequency selective, wake-up, RMSHI

I. Introduction

Recognition of infrequent acoustic events is of interest in many fields (environmental monitoring [1], safety and security [2]–[4], agriculture, health monitoring [5]). However, this is a power-hungry task as it requires continuous operation of the wireless embedded system [2]. Power consumption can be lowered by adding an always-on frontend which wakes up a wireless embedded system only upon detection of some specific signature [6]–[9].

Many acoustic events can be recognized based on their time-frequency signature [1], which can be approximated by an ordered sequence of discrete time-frequency states (Fig 1.a). Each state is defined by an arbitrarily chosen time interval, frequency band, and some feature, which quantifies the signal within it [6]. In our previous work we investigated instantaneous envelope as a feature quantifying the signal [10]. However, it is shown in [11] that for very slow evolving acoustic events from weak signal sources, integral signal features may be more suitable. Hence, here we explore energy as a feature quantifying the signal within each time-frequency state.

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Always-on wake-up frontends for acoustic event recognition typically incorporate weak sensor signal amplification, filtering, rectification, quantization and rudimentary classification [10]. To lower power consumption of these processing blocks, research has been done towards implementing them as zero-power electromechanical systems [12].

To improve sensitivity and power consumption of our current always-on low-power acoustic event detector [11], we look for application of an electromechanical system in rectification of the weak input signals. It should be noted that the diode bridge rectifier works only in presence of input waveforms having higher amplitude in respect the diode threshold. Furthermore, active rectifiers increase and affect the total budget of the entire converter [13]. A promising approach, applied for the similar problem in energy harvesting, is Random Mechanical Switching Harvester on Inductor (RMSHI). There, energy from a weak vibration source drives a magnetically biased electromechanical switch. Its random switching action boosts the inductor's voltage over the diodes rectifier's threshold, enabling the rectification of very weak signals with a fully passive architecture. Also, being non-resonant, the RMSHI has a broad frequency range of operation [14], [15].

In this paper we investigate the application of the RMSHI for rectification of such weak sensor signals and measurement of their energy, at arbitrarily selected bands of frequencies within the acoustic frequency spectrum. The presented system consists of a preamplifier, a band-pass filter and a macro model of an electromechanical switch operating at the same frequency band, an inductor and a rectifier.

The proof-of-concept system has been realized, functionally tested and characterized, and the validity of the approach has been shown. To the best of our knowledge, this is the first solution presented in the literature, which demonstrates the possibility of using the RMSHI as a low-power passive conditioning circuit for weak signals. This paves the road to the realization of a micromechanical measurement structure able to continuously listen for surrounding acoustic sources and recognize them based on the time-frequency distribution of signal's energy.

The paper is organized as follows: Section II describes the proposed solution. Section III reports the experimental setup and the measurement method. The results are presented in Section IV, while the concluding remarks are given in Section V.

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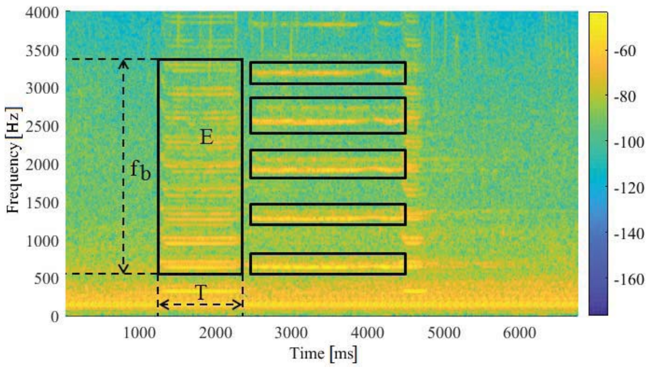
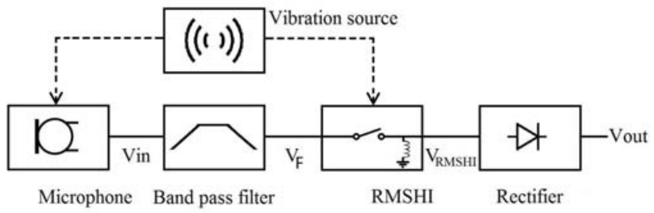
II. PROPOSED CIRCUIT DESCRIPTION

The proposed circuit has to be able to extract selected frequency bands from the input signal and then measure the energy contained in them. The circuit consists of three main processing blocks, as can be seen in Fig. 1. A more detailed schematic of each processing block is given in Fig. 2.



a) Spectrogram



b) Block diagram

Fig. 1. a) Example of a spectrogram of a signal of interest. T represents the duration, f_b the frequency band and E the energy of each state within the time-frequency pattern. b) Block diagram of the presented approach. The energy measurement circuit consists of a band pass filter, an RMSHI and a diode rectifier.

The frequency band of interest is extracted from the input signal by a low-power programmable active analog band pass filter, see Fig. 2.a. The filter has been developed in the general impedance converter (GIC) topology, using a dual low-power operational amplifier (MCP6142). This topology enables independent tuning of the central frequency and bandwidth of the filter spanning between 200 Hz and 2.5 kHz. The current consumption of the filter is 3.5 µA, making it suitable for use in a low power circuit. A more detailed description and characterization of this filter can be found in [11].

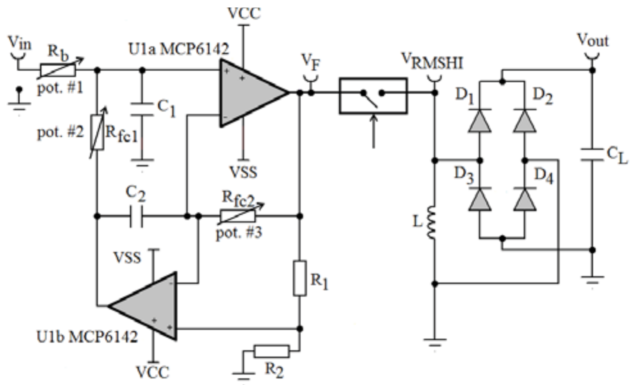
The energy contained in the extracted band is measured by using a passive architecture featuring Random Mechanical Switching Harvester on Inductor (RMSHI) [14]. It consists of an electromechanical switch, an inductor, a diode bridge and a load capacitor (see Fig. 2.a).

The electromechanical switch is composed of a cantilever beam having a stopper on the upper part and a tunable magnetic system able to modify the elastic factor and, as consequence, the spectral response of the system as function of the input signal, as shown in Fig. 2.b and Fig. 2.c. Mathematically, this transducer can be modeled using a second order nonlinear differential equation that can be written as follows:

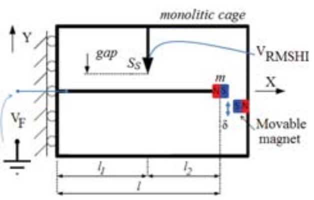
$$m\ddot{x} + d\dot{x} + \frac{\partial U_T}{\partial x} = F(t)\Big|_{U_T=\delta x^4} \qquad (1)$$

Where m and d are the mass and the damping coefficient respectively. The term x is the displacement of the tip of the beam and the dotted terms represent the first and the second derivate of the displacement (velocity and acceleration of the cantilever respectively). U_T is the potential energy function which is nonlinear taking into the account the stopper and the external magnet which acts as tunable factor. This latter contribution is expressed with the term δ. In presence of external vibration source the beam will move and two main conditions will appear: 1) when the beam touches the stopper S_s, all the current provided by the low power filter flows through the inductor L, (see Fig. 2.a); 2) when the contact between both is open, the residual current cannot be instantaneously canceled, so it generates an overvoltage peak across the inductor that overcomes the thresholds of the diodes. In this case it is possible to convert the low level signals into a DC voltage across the load capacitor C_L in order to give the information of the input signal energy.

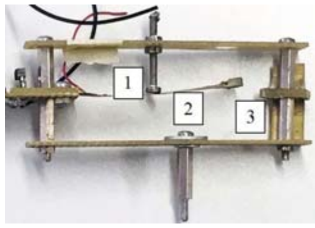
In particular the electromechanical switch used in this study is composed of a brass beam with a length (l) of about 55 mm, width of about 8.3 mm and thickness of about 0.2 mm, with the distance (l_1) between the anchor of the cantilever and the stopper of about 28 mm, as shown in Fig. 2.c.



a) Proposed circuit schematic



b) Random mechanical switch principle



c) Random mechanical switch photograph

Fig. 2. a) A detailed schematic of the energy measurement circuit. It consists of an active programmable analog band pass filter, an RMSHI part, a full bridge rectifier and a load capacitor C_L. b) Principle of the random mechanical switch used as part of the conditioning circuit for measurements of very weak input sources. c) A photograph of the random mechanical switch. 1) Stopper, 2) Cantilever beam, 3) Movable magnet.

III. MEASUREMENT SETUP AND PROCEDURE

The goal of these measurements was to perform a functional test of the proposed circuit, to select design parameters and to characterize its sensitivity and resolution.

A. Measurement Setup

For all the following measurements the circuit was adjusted in the following way. The central frequency of the filter was tuned to 300 Hz by setting the values of the trimmer resistors R_{fc1} and R_{fc2} (as shown in Section II, Fig. 2.a) and its pass band width was set to 200 Hz using the trimmer resistor R_b. The magnet opposite to the switch's cantilever beam, Fig. 2.b, was used to set the frequency at which the switch has the highest output voltage to match the central frequency of the filter.

The block diagram and a photograph of the measurement setup can be seen in Fig. 3. and Fig. 4. respectively. The measurement setup consisted of a function generator (Voltcraft FG-506) connected to the input of the circuit. The energy measurement part of the circuit was positioned on a shaker (Smart Material Energy Harvesting Kit 1.2.). In order to decouple the input signal used for the characterization and the RMSHI, we have used a second function generator (Agilent 33250 A) to drive the shaker and to move the mechanical transducer operating with the same waveform and frequency. The output voltage was acquired by a digital oscilloscope (Rigol MSO4014) in duration from 5 s to 20 s.

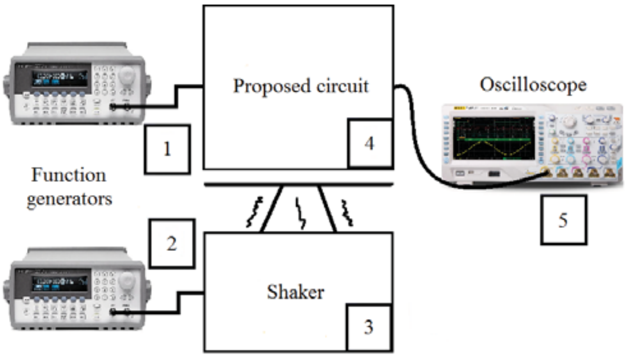


Fig. 3. Block diagram of the measurement setup which consists of the proposed circuit, a pair of function generators, a shaker and a digital oscilloscope.

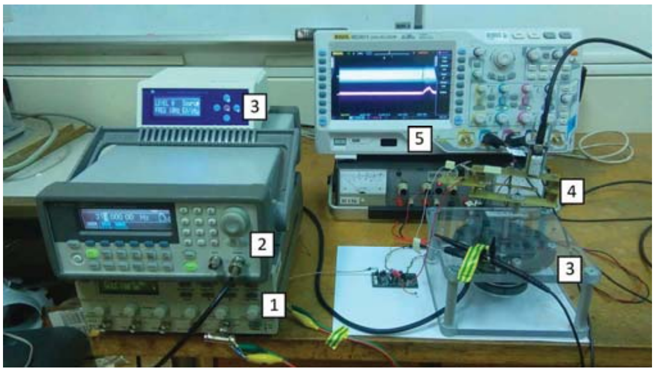


Fig. 4. A photograph of the measurement setup. 1) Voltcraft FG-506 function generator, 2) Agilent 33250 A function generator, 3) Smart Material Energy Harvesting Kit 1.2. shaker, 4) Proposed circuit, 5) Rigol MSO4014 oscilloscope.

B. Measurement Procedure

1) Design parameter selection

The goal was to select the load capacitor C_L in regards to output signal ripple and response time. A higher capacitance means reduction of ripple, but it also causes longer response time. Frequency of the input signal was set for maximal output voltage (to 315 Hz) and peak-to-peak input voltage was set to 50 mV. The output voltage was measured for capacitors of 10 nF, 33 nF, 100 nF, 470 nF and 1 µF.

2) Sensitivity of circuit to input signal frequency within the selected frequency band

The goal was to determine the relation of output signal voltage to change of input signal frequency, within the selected frequency band. The load capacitor of 33 nF was chosen. The frequency of the input signal was swept from 290 Hz to 330 Hz with increment of 5 Hz. The input signal peak-to-peak voltage was set to 5 mV, 10 mV, 20 mV, 30 mV, 40 mV and 50 mV. For each combination of input signal frequency and voltage, output voltage was recorded in duration of 20 s. The recorded waveforms were processed in MATLAB to obtain the RMS value of the output voltage.

3) Energy measurement characterization

The goal was determination of the proposed circuit's energy measurement performance. The frequency of the input signal was 315 Hz, at which the RMSHI has the maximal output voltage. The peak-to-peak values of the input voltage were set at 5 mV, 10 mV, 20 mV, 30 mV and 40 mV respectively. For each input voltage value, 10 measurements in duration of 5 s were done. After acquisition the measurement data was processed in MATLAB. The output of the energy measurement circuit was given as the maximal output voltage during the 5 s period, averaged over 10 consecutive measurements. The measurement error ε was calculated as:

$$\varepsilon = 3A = 3\sqrt{\frac{std^2(Max1, Max2, \dots, Max10)}{10}} \tag{2}$$

Where A is the uncertainty and std is the standard deviation of the maximal voltage values of the 10 measurements.

The input signal energy E in nJ was calculated from peak-to-peak value of the input signal voltage V_{in}, circuit input resistance R_{in} and measurement duration T_m, as shown in (3).

$$E = \frac{{V_{in}}^2}{R_{in}} T_m \tag{3}$$

IV. Results

The obtained results are organized in two sections. First section covers functional tests and the second characterization of the proposed circuit.

A. Functional Test

The result of the functional test in Fig. 5. shows the waveform of the proposed circuit's output voltage with and without use of the RMSHI. It can be seen that using the RMSHI increases the output voltage of the proposed circuit, which validates the principle and indicates its usefulness in low-power devices for energy measurement. Also, as the RMSHI adds no additional active components to the circuit, the only active part of the circuit remains the band-pass filter. Thus the overall power consumption of the proposed circuit is 6.3 µW (3.5 µA at 1.8 V supply).

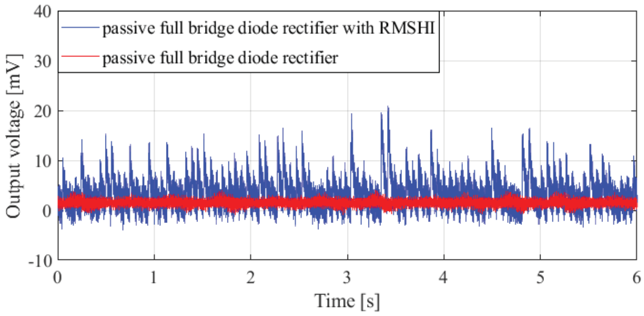


Fig. 5. The waveform of the output voltage with (blue) and without (red) the mechanical switch operational. Input signal voltage peak-to-peak 50 mV, frequency 315 Hz, load capacitance C_L = 33 nF.

B. *Circuit Characterization*

1) Design parameter selection

As described in Section III, analyses in terms of load capacitors have been pursued. It is clear from the waveforms shown in Fig. 6. that the 33 nF load capacitor works well for our application in both terms of output voltage ripple and response time.

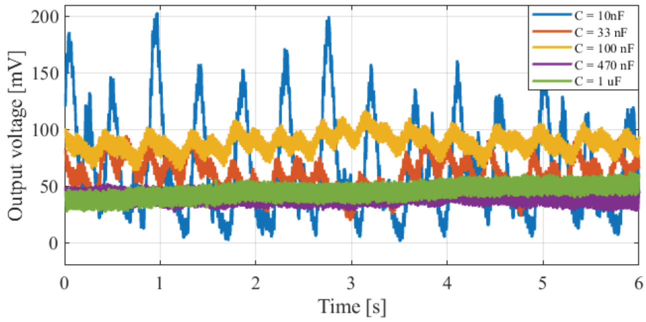


Fig. 6. The waveform of the output voltage for different values of load capacitance C_L. Input signal voltage peak-to-peak 50 mV, frequency 315 Hz.

2) Sensitivity of circuit to input signal frequency within the selected frequency band

Fig. 7. shows that the electromechanical switch has the maximal output voltage for the excitation vibration frequency of around 315 Hz, this result is a consequence of a tuning procedure of δ (see Section II, eq.1). That motivates us to use this as the central frequency for the other sets of measurements.

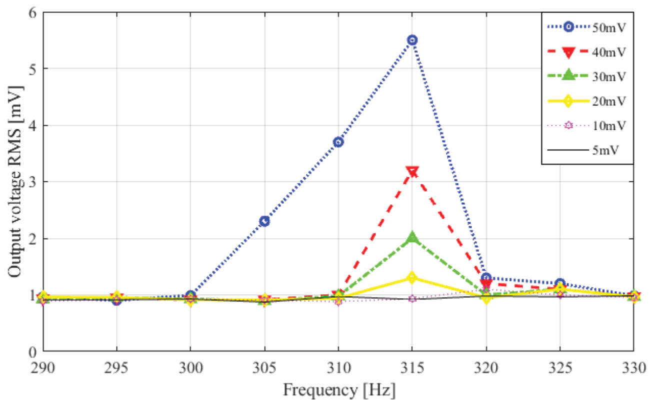


Fig. 7. Sensitivity of circuit to input signal frequency within the selected frequency band. The output RMS voltage is shown. Input signal voltage peak-to-peak from 5 mV to 50 mV, frequency changed by 5 Hz from 290 Hz to 330 Hz, load capacitance C_L = 33 nF.

3) Energy measurement characterization

In Fig. 8. the relation between the input energy and output voltage is shown. It can be seen that the maximum measurement error (deviation from the linear interpolation) is around -2 mV, measured at input energy of 0.4 nJ.

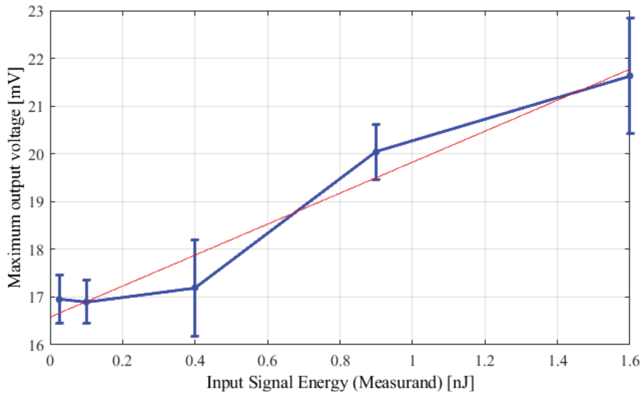


Fig. 8. Output voltage maximum value versus input signal energy. Input signal frequency 315 Hz, load capacitance C_L = 33 nF. The dots and the blue line represent actual measurement data. The red line represents a linear interpolation.

Fig. 9. shows the calibration curve of the proposed circuit. The sensitivity of the measurement circuit is around 3 mV/nJ and the resolution is around ±0.66 nJ.

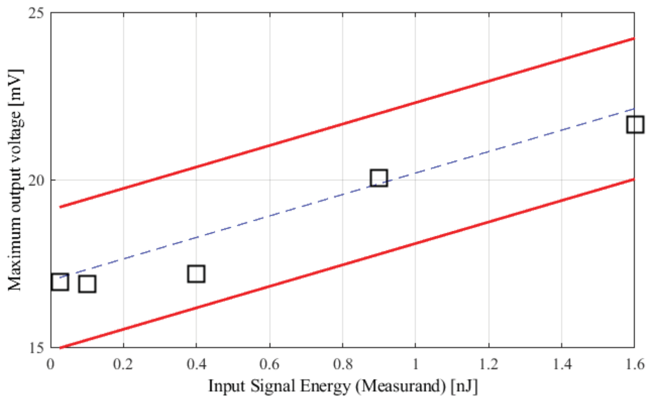


Fig. 9. The calibration curve of the energy measurement circuit. The black squares are the measurements. The blue line represents the linear interpolation. The two red lines represent the maximum measurement error.

V. Conclusion

In this paper a proof-of-concept system featuring the RMSHI as a passive conditioning circuit for rectification and measurement of weak signal energy was presented. Using energy as a feature enhances detection of very slow evolving acoustic phenomena. The advantage of the proposed approach is that the single mechanical structure can be tuned to various frequency bands within acoustic frequency spectrum. Thanks to utilization of the RMSHI, we accomplished sensitivity of the presented circuit is around 3 mV/nJ. With the maximum measurement error in mind, the resolution is around ±0.66 nJ. The active part of the system consumes around 6.3 µW.

This work represents the first step towards an integrated weak sensor signal measurement device, using a MEMS switch driven by the acoustic energy. The results presented here shall be used in modeling and development of the future integrated device.

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