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Maximizing harvested energy for linear vibration-based generators

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Abstract

This work presents a new method that increases the energy conversion for linear vibration-based generators. Actually, these generators are chosen to have their resonance frequency equal to the ambient vibration frequency that provides the maximum power amplitude of the acceleration. Nevertheless, there is a resonance frequency at which the acceleration power amplitude is lower but the energy is substantially higher since ambient vibration signals have several frequency components. A new method performing a spectrogram analysis, which does not miss the temporal information, as the Discrete Fourier Transform (DFT) analysis does, is realized. Thus, the harvested energy is considered instead of the harvested power. The method presented in this paper is validated with several real experiments.

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1. Introduction

Piezoelectric energy harvesting generators are becoming one of the most promising power source technologies for supplying autonomous low power electronic systems. They take advantage of motion and vibrations and, as literature points out, kinetic energy provides the most versatility and ubiquity in different scenarios [1].

The vibration signal sources are commonly characterized based on their peak acceleration and the frequency at which that peak takes place, so the piezoelectric generators (PEGs) and electrodynamic generators (EDGs) are tuned to this frequency [2-7]. This technique is correct for periodic signals, but this is not the case for real vibration signals that are varying both in amplitude and frequency [8, 9]. As the FFT algorithm is in the frequency domain, the

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duration of the maximum power amplitude, which affects the energy, is unknown. The proposed method performs the spectrogram of the acceleration signal obtaining information about the frequency spectrum over time.

The structure of the paper is as follows: section 2 explains the procedure for selecting the most profitable resonance frequency. Section 3 details the experimental setup, both the methodology and the equipment used, for tuning the PEG at a certain resonance frequency. Finally, section 4 draws results and main conclusions.

2. Selection of the resonance frequency

PEGs have been chosen for showing the methodology presented in the paper for selecting the resonance frequency of the energy harvesting transducer. First, the analysis of the ambient acceleration signal is required. Thus, the acceleration data stored as a function of time has to be converted to the frequency domain. In order to achieve this, literature [3-7] suggests that the Fast Fourier Transform (FFT) algorithm displays the resonance frequency to which the PEG has to be tuned. This algorithm provides the instant spectrum of the acceleration signal. F_{FFT} is the frequency with the maximum peak power.

Alternatively to the Discrete Fourier Transform (DFT), a Spectrogram analysis performs the Short Time Fourier Transform (STFT) algorithm that provides a sequence of spectrums. This analysis combines the Power Spectral Density (PSD) obtained at each frequency over time, providing a qualitative knowledge of the available mechanical energy at each frequency. F_{SP} is the frequency with the highest value obtained from integrating the PSD over time.

Five MATLAB simulations are performed using data from the Energy Harvesting Network [8, 9] where the DFT and the Spectrogram analysis are carried out for each acceleration signal. Thus, F_{FFT} and F_{SP} frequencies are obtained and the qualitative knowledge of the available mechanical energy at each frequency is obtained through spectrogram, showing that the harvested energy at F_{SP} is higher than at F_{FFT} . Fig. 1 shows both analyses performed to the same acceleration signal. This simulated statement is validated through experiments comparing the harvested energy provided by two PEGs tuned to both frequencies for each input signal.

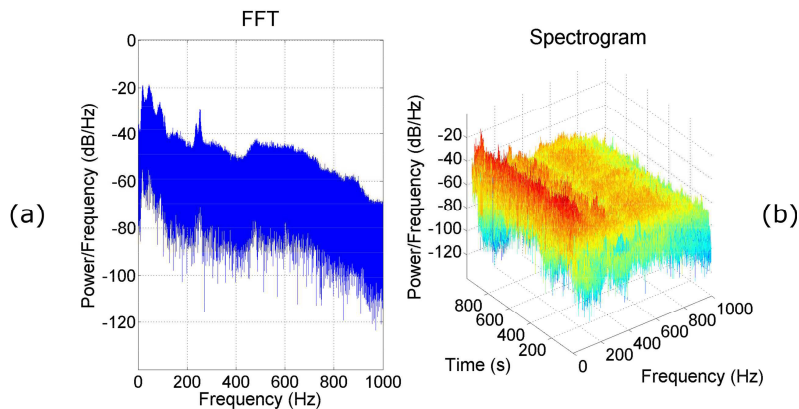


Figure 1: Fast Fourier Transform scaled to show the Power Spectral Density (a) and Spectrogram (b) of an acceleration signal measured in a car.

3. Experimental setup

The first step of the experimental setup consists in performing a first tuning of the PEG using different masses in order to locate the target frequencies (F_{FFT} and F_{SP}) between the resonance and the anti-resonance frequencies of the PEG. This process is performed through the calculation of the admittance loop of the PEG, which is measured with the equipment shown in Fig. 2-1.

The second step of the experimental setup is a second tuning process by changing the tip mass of the PEG again. An electrodynamic shaker excites the PEG with a sinus sweep near the target frequency. The amplitude of that mechanical vibration corresponds to the mean value of the ambient vibration signal in order to set the amplitude of

the signal as real as possible. The PEG is a programmable resistance in order to sweep and find the load resistor that provides the maximum output power. The equipment used is shown in Fig. 2-2.

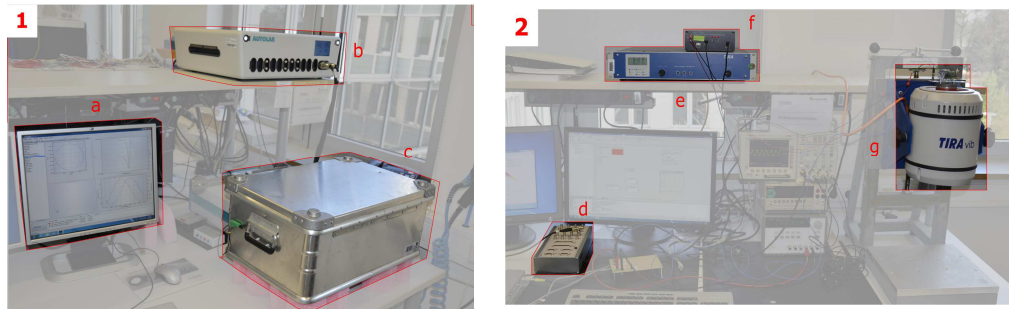


Figure 2. 1- Equipment used for the characterization of the PEG and performing the first tuning; (a) NOVA 1.10 software, (b) potentiostat/galvanostat -Autolab PGSTAT302N, (c) Faraday cage. 2- Equipment used for performing the second tuning and the testing with the real vibration signal: (d) dSPACE DS1104, (e) Power amplifier TIRA BAA120, (f) programmable resistance decade box, (g) Electrodynamic shaker TIRA S52110

The relevance of this second step is clarified by Fig. 3, where it is possible to distinguish how the resonance frequency of the PEG is affected by the amplitude of the acceleration signal and the resistance load [10]. For the comparison of the tunings performed, the mechanical vibration amplitude corresponds to the mean value of the ambient vibration signal that is being analysed. Fig. 3-a shows the behavior of the PEG after the first tuning, whereas the Fig. 3-b shows the behavior of the PEG after the second tuning. It is remarkable how the maximum power output obtained after a second tuning is located at the resonance frequency chosen since the power at the target resonance frequency after the first tuning is almost three times less than the maximum power achieved. Fig. 3(a) and (b) correspond to the first and the second sweep for the F_{iFFT} frequency at the first experiment. At the top, the maximum power harvested at each frequency measured is shown. The text boxes indicate the power at the specific frequency, F_{iFFT} in this case, and the ratio between the maximum power value and the value at the specific frequency.

Maximum Power: 268.469 μ W at Frequency measured: 22.2Hz

Maximum Power: 314.552 μ W at Frequency measured: 23Hz

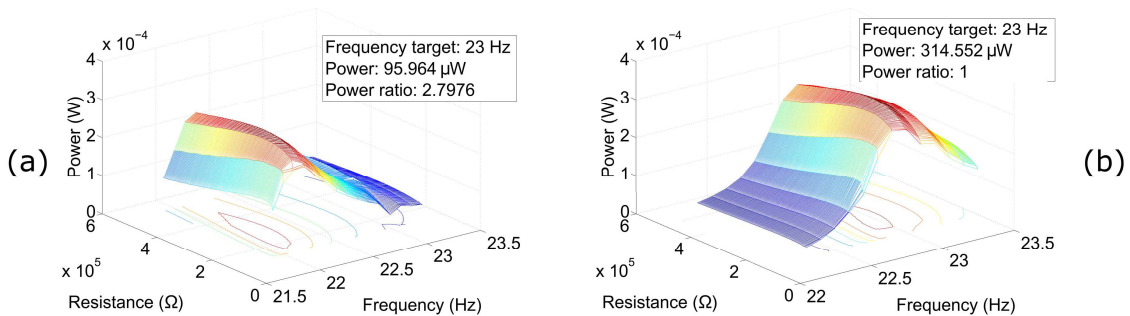


Figure 3. Comparison of the output power at the PEG, (a) after the tuning at the Impedance analyser and (b) after the tuning at the Shaker

Finally, the PEG is excited with a real ambient vibration signal and the harvested energy generated is measured. The experimental setup used for this part of the experiment is shown in Fig. 2-2. The real ambient vibration signal is replicated through a dSPACE DS1104 board connected to a power amplifier and the electrodynamic shaker. The optimal load, obtained as result of the second tuning, is connected to the PEG to obtain the maximum power at its resonance frequency. The power is saved over time in order to obtain the energy for the ambient vibration signal. This process is repeated for every F_{iFFT} and F_{SP} of each experiment.

4. Results and conclusions

Table 1 shows the results obtained for the five experiments performed. For each experiment, the energy harvested by the piezoelectric generators with both resonant frequencies F_{FFFT} and F_{rSP} is measured, making a quantitative comparison possible. Measurements indicate an increase in the harvested energy between 15% and 1149% if the PEG is tuned at F_{rSP} instead of at F_{FFFT} .

The method proposed in this work is based on a Spectrogram analysis instead of a DFT analysis used by the traditional method. The results of this work prove that the use of a Spectrogram analysis, as part of the piezoelectric generator designing process, enhances the amount of energy recovered from a mechanical ambient vibration.

Table 1. Experiment results.

		Frequency (Hz)	Maximum Harvested Power (W)	Load resistance (Ω)	Harvested Energy (J)	Energy Increase with F_{rSP}
Exp. 1. Van-Dashboard (x-axis)	F_{FFFT}	23	9.60E-05	2.57E+05	1.76E-05	30%
	F_{rSP}	29	1.81E-04	1.95E+05	2.29E-05	
Exp. 2. Van-Near air filter (x-axis)	F_{FFFT}	32	5.58E-04	1.85E+05	1.46E-05	15%
	F_{rSP}	29.25	4.11E-04	1.85E+05	1.68E-05	
Exp. 3. Ford Fiesta – Front suspension arm (y-axis)	F_{FFFT}	44.31	5.12E-05	1.38E+05	3.80E-05	339%
	F_{rSP}	41.99	7.02E-04	1.30E+05	1.67E-04	
Exp. 4. Van-Dashboard (y-axis).	F_{FFFT}	46	2.25E-04	1.40E+05	8.49E-06	1149%
	F_{rSP}	29	4.86E-04	1.87E+05	1.06E-04	
Exp. 5. Van-Wheel suspension (y-axis).	F_{FFFT}	50	9.87E-04	1.10E+05	2.97E-06	128%
	F_{rSP}	16.25	1.03E-03	3.26E+05	6.76E-06	

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