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A Versatile and Fully Instrumented Test Station for Piezoelectric Energy Harvesters

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1. Abstract

This paper describes the implementation of LabVIEW software to control instruments and acquire data from a piezoelectric energy harvesting test station which is based on a cantilever structure. The experiment is run in the Clean Energy Laboratory on the Ambient Energy Harvester Test Station. A digital multimeter, a programmable resistance selector, an arbitrary waveform generator, a shaker table, an accelerometer and a laser displacement sensor are used to control and acquire data in terms of harvested energy as a function of vibration frequency, vibration level and load resistance. LabVIEW software is used to control the test station which makes near real-time data measurements, displays waveforms on a PC screen, and stores data for later analysis. Acquired waveforms are presented in terms of frequency versus voltage of the vibrating cantilever at preselected ranges of load resistances in terms of either AC or DC voltages. The vibration of the cantilever beam is measured with an accelerometer and beam movement is measured with a laser displacement meter. Test results are stored in a comma separated variable text file which can be imported into any data analysis software package. All experiments are performed on an isolated optical bench to avoid interference from mechanical noise that may exist in the surrounding environment. The systems provides an integrated approach to characterize key performance indicators for energy harvesting materials and devies.

Key words: Piezoelectric energy harvesting; LabVIEW; Cantilever

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2. Introduction

Recent developments in ultra-low power microelectronic devices such as wireless sensor nodes (WSNs), active radio-frequency identification (RFID), and nano-transducers lead to increased demands for piezoelectric energy harvesting applications [1] to provide self-powered systems. The conversion of low-grade ambient environmental energy, such as mechanical vibration or heat, into useable electric energy is known as 'energy harvesting' or 'energy scavenging'. Sensors nodes are widely used in a number of applications such as: security networks, structure health monitoring, and many military applications [2]. These active sensors require a self-contained power supply which in most cases is the conventional battery pack. The task of replacing the battery is not practical and cumbersome for remote locations or inaccessible locations including 'limited access' or 'no access structures' and toxic environments. The need to replace batteries can also be time-conuming and complex to manage, particularly for systems where a large numbers of sensors are to be deployed. The recent development of ultra-low power microelectronic devices and sensors has steered the researchers to the design of passive self-power devices using energy harvesting techniques. Mechanical vibration energy generated via machine and the motion of biological systems is one form of wasted energy that could be harvested. The most popular vibration energy harvesting technique is to capture power from the electrostatic [3-7], electromagnetic [8-12], piezoelectric [13-16], and magnetostrictive [17-20] vibration energy harvesters (VEHs). The most current VEH devices are based on cantilever beam structure which generates continued or intermittent resonance frequency tuning. A typical piezoelectric cantilever beam (PCB) can produce maximum power when its resonance frequency matches the frequency of the vibration source [21]. In a number of cases the vibrations to be harvested consist of a range of frequencies and researchers have proven that the resonance frequency of a PCB can be changed by using a variety of different approaches such as, changing the geometrical PCB structure [22, 23], adding a dynamic magnifier [24-27], using energy harvesting cantilever arrays [28-30], and using external magnetic forces [21, 31-36]. To date, there are a number of researchers that have attempted to capture power from passive tuning by magnetic coupling with a piezoelectric cantilever beam [21, 32-36]. For example, by applying a magnetic force that acts above the PCB it is possible to decrease the spring constant and the resonance frequency of the PCB [21, 31], while applying an attractive magnetic force along the axis of the PCB applies axial tension, and increases the resonance frequency [37].

In a typical vibrational energy harvesting system the mechanical energy, such as the applied external force or acceleration, is converted into mechanical energy in the host harvesting structure. Electrical energy is then produced by use of piezoelectric material that converts strain into an electric charge which is finally transferred to a storage medium for later use. Thus, there are three basic processes in vibration harvesting: (i) conversion of the input vibration energy into mechanical energy (mechanical strain), (ii) electro-mechanical conversion (piezoelectric transduction), and (iii) electric energy transfer. It is worth mentioning that piezoelectric energy harvesters offer a number advantages compared to other transduction mechansims, including high energy conversion, high energy density, high output voltage but low current level, and high output impedance including ease of integration with other systems [38]. The performance of piezoelectric energy harvesting device based on a PCB is evaluated via determination of mainly the resonance frequency of the structure at a variety of electrical and mechanical loads. Thus, measuring input and output voltages, acceleration, displacement, and frequency of vibration are desired practical parameters to fully characterize a piezoelectric energy harvester.

This work presents an automatic measurement station, which is designed and implemented to measure and characterize each part of a vibration-based piezoelectric energy harvesting system separately, as well as the complete system as one module. The designed measurement station allows systematic data acquisition and graphically display in near real-time the characterization data. The system and can be utilized for the measurement and the comparison of different systems, mechanisms, and designs. The automation of measurement station and control of all the peripheral equipment such as measurement instruments and programmable discrete resistor selector is achieved via LabVIEW from National Instruments through USB and RS232 interfaces available in all instruments without the need of a signal going through usual data acquisition (DAQ). The same software (LabVIEW) performs the processing and storage of acquired data including displaying important parameters graphically. This effective approach, makes the characterization processes effective and efficient without operator intervention at every stage.

3. Architecture of a Piezoelectric Energy Harvesting Station

The test station was set up as shown in Figure 1. The experimental set-up consists of a small-mechanical shaker (Bruel and Kjaer Model Type 4810) and function generator (Agilent / Keysight 33500B) to produce a range of vibration frequencies and a high-power amplifier (Bruel and Kjaer Model 2718) to create the cyclic force of the required magnitude and frequency. Accelerometer sensors were employed to measure the vibration acceleration (sensitivity of accelerometer sensor is 100 mV/g). A multimeter (Keithley Model 2110) was used to measure the output voltage from the harvester and a laser displacement meter (MTI Model Microtrack II) to measure the displacement of the cantilever beam. An IET PRS-2000 Programmable Resistance Substituter (PRS) was used to add and electrical load in the harvester circuit. Data acquisition of the acceleration sensors was achieved via a Picoscope (Pico-Technology Model 4224). To avoid any interference from the noise in the surrounding environment, all experiments were performed on an isolated optical bench. When the piezoelectric harvester is subjected to vibrations by the experimental setup it produces an AC electrical output and the output signal from the harvester is connected to a programmable resistance selector or an AC-DC circuit with a capacitive load.

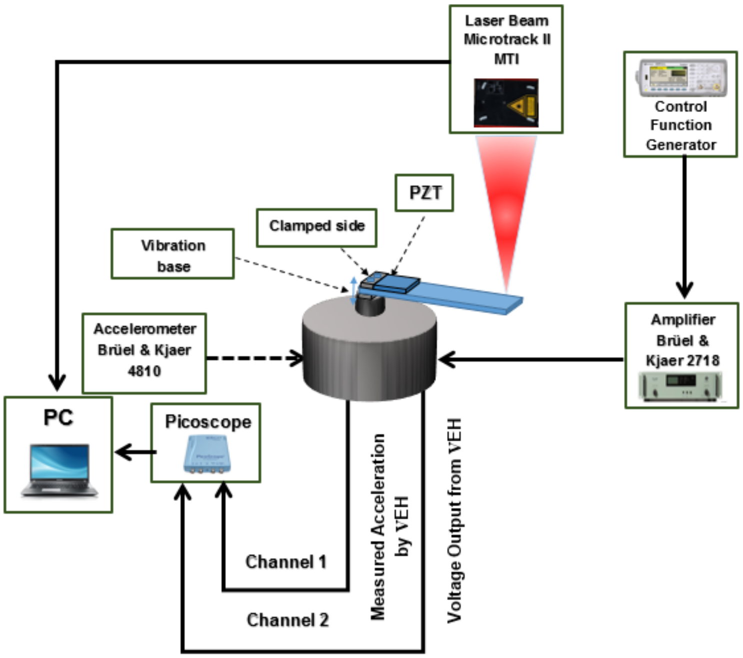

Figure 1. A configuration of the test station for vibration-based energy harvester.

Figure 2. A photograph of the experiment test setup showing all the necessary components.

LabVIEW software (National Instrument Inc.) is installed on the computer and is the controlling center for the system and used to set the exciting frequency to the arbitrary waveform generator, to assign the reading type of the multimeter and to record the data via an USB interface. One end of the cantilever beam is fixed in a fixture attached to the shaker. A small mass can be attached on the other end of the cantilever beam to tailor the resonant frequency of the harvester. A pair of wires are used to conduct the produced current through the programmable resistive load.

4. Procedure for Frequency vs Voltage Measurements

The Test Station setup as shown in Figure 2. After turning on all the measurement instruments and setting up the amplitude of excitation by control of the power amplifier, the LabVIEW software is initiated. The designed front LabVIEW panel screen is illustrated in Figure 3 and LabVIEW is used to perform a series of pre-determined sweeps; each sweep is performed with preselected a resistive load via programmable resistance selector to the piezoelectric energy harvester. Then, following programming order of operations are followed as described below to record vibrating frequency of the cantilever, output AC voltage, and respective resistance:

Figure 3. A screen shot of the control panel of the LabVIEW program

Programming Steps

(1) Enter sample data

(2) Select start resistance (Minimum), end resistance (Maximum), and resistance step. The minimum resistance value allowed is 0 Ω and the maximum resistance allowed is 99,999,999.9 Ω.

(3) Select start frequency (Minimum), end frequency (Maximum) and frequency step.

(4) Select voltage measurement in AC or DC.

(5) Select measurement dwell time.

(6) Select wait time between measurements

(7) Run the program.

(8) The program will ask to find test001.txt file which is located on the desktop.?? What does this do?

(9) All the sample data control strings, date and time control strings are concatenated and written to file.

(10) The Agilent 33500B Arbitrary Waveform Generator (AWG), the IET PRS-2000 Programmable Resistance Substituter (PRS) and Keithley 2011 Digital Multimeter (DMM) are initialized.

(11) The software executes a series of nested do loops:

   a. Level 1 Do Loop: Resistance value is sent to the programmable resistance. The value is iterated until the maximum value is encountered then a "False" Boolean is generated and the do loop stops.
   b. Level 2 Do Loop: Frequency value is sent to the waveform generator. The value is iterated until the maximum value is encountered then a "False" Boolean is generated and the do loop stops.
   c. Level 3 Do Loop: Voltage is measured from the digital multimeter.
      i. Resistance, Frequency & Voltage are written to file.
      ii. Data is updated on the front panel.
         1. Resistance is displayed on the digital read out
         2. Frequency is displayed on the digital read out and meter
         3. Voltage is displayed on the digital read out
         4. Frequency and Voltage are plotted on an XY Graph.

iii. Voltage measurement continues until timeout is encountered then a “False” Boolean is generated whereby the do loop stops and the program jumps to the Level 1 Do Loop.

(12) When the nested do loops stop, commands are sent to:

a. Turn off the AWG output.

b. Reset the PRS and program it to 0 Ω.

(13) The user should then locate file Test001.txt and rename it.

After obtaining the resonance frequency as above, optimum load/resistance is obtained at which the output voltage is miximum; for this purpose the designed front LabVIEW panel screen is utilized as illustrated in Figure 4.

5. Procedure for obtaining Resistance vs Voltage Measurements.

The Test Station is setup as shown in photograph in Figure 2. After turning on all the measurement instruments and setting up the amplitude of excitation manually using the control on the power amplifier, the LabVIEW software is initiated. The designed front LabVIEW panel screen is illustrated in Figure 4. LabVIEW is used to perform a series of pre-determined sweeps; each sweep is performed with preselected resistive load via programmable resistance selector to piezoelectric energy harvester. Then, following programming order of operations are followed as described below to record vibrating frequency of the cantilever, output AC voltage, and respective resistance:

Figure 4. A screen shot of the control panel of the LabVIEW program

Programming Steps

(1) Enter sample data

(2) Select start resistance (Minimum), end resistance (Maximum), and resistance step. The minimum resistance value allowed is 0 Ω and the maximum resistance allowed is 99,999,999.9 Ω.

(3) Ensure that start Frequency (Minimum), end frequency (Maximum) and frequency are the same value such that the system only collects data at one frequency.

(4) Select voltage measurement in AC or DC.

(5) Select measurement dwell time

(6) Select wait time between measurements

(7) Run the program.

(8) The program will ask to find test001.txt file which is located on the desktop. [??]

(9) All the sample data control strings, date and time control strings are concatenated and written to file.

(10) The Agilent 33500B Arbitrary Waveform Generator (AWG), the IET PRS-2000 Programmable Resistance Substituter (PRS) and Keithley 2011 Digital Multimeter (DMM) are initialized.

(11) The software will execute a series of nested do loops:

- a. Level 1 Do Loop: Resistance value is sent to the PRS. The value is iterated until the maximum value is encountered then a “False” Boolean is generated and the do loop stops.
- b. Level 2 Do Loop: Frequency value is sent to the AWG. The value executed then a “False” Boolean is generated and the do loop stops.
- c. Level 3 Do Loop: Voltage is measured from the DMM.
  - i. Resistance, Frequency & Voltage are written to file.
  - ii. Data is updated on the front panel.
    - 1. Resistance is displayed on the digital read out
    - 2. Frequency is displayed on the digital read out and meter
    - 3. Voltage is displayed on the digital read out
    - 4. Resistance and Voltage are plotted on an XY Graph.
  - iii. Voltage measurement continues until timeout is encountered then a “False” Boolean is generated whereby the do loop stops and the program jumps to the Level 1 Do Loop.

(12) When the nested do loops stop, commands are sent to:

- a. Turn off the AWG output.
- b. Reset the PRS and program it to 0 Ω.

6. Example of Measurement Results

From the acquired data, the following graphs were plotted for a cantilever piezoelectric energy harvester [details needed?]. Figure 5 shows the measured output voltages of the piezoelectric energy harvester as a function of frequency and with various electrical loads, ranging from 10kΩ to 45kΩ; the vibration amplitude was fixed at. ?.

From Figure 5, it can be observed that maximum output voltage (occurring at resonance) increases slightly with the increase in resistive load value. Figure 6 shows the variation calculated power as a function of frequency and these results agree with the available literature [39-40].

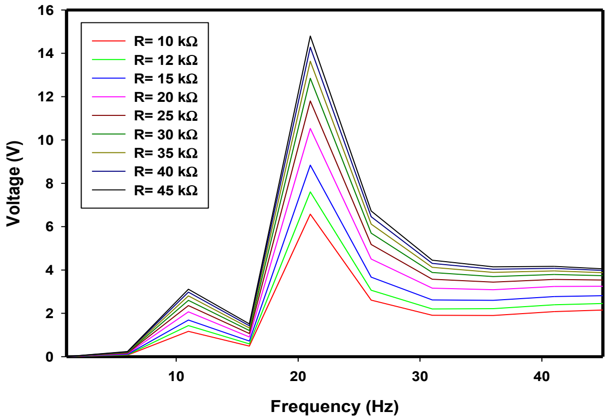

Figure 5. Output voltage versus frequency at different values of load resistance.

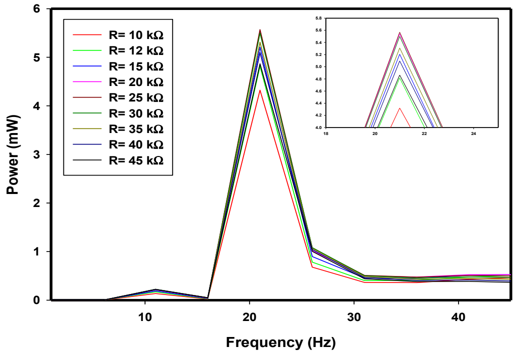

Figure 6: Output power versus frequency at different values of load resistance and an enlarged view around the first vibration mode.

Figure 7 shows the voltage measured across the load resistor and power dissipated by it at resonance frequency extracted from Figure 5 at the peak of the curve. A maximum output power of around 6 mW was generated into a resistive load of 0.25MΩ at the operating frequency of 21 Hz. (You can also measure I from V=IR and plot that too – that will be max at low R and fall with increasing R, opposite to V and peak will peak max VI).

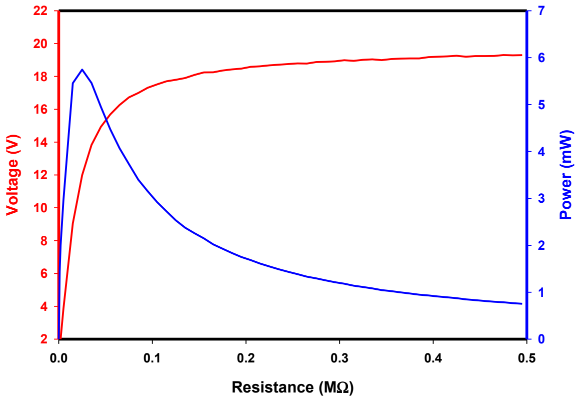

Figure 7. Output voltage and Output power versus load resistance.

6 Conclusions

In conclusion, the electric output performance of a vibration-based harvester directly connected to resistive load has been investigated utilizing a developed novel configuration for an automated measurement station for piezoelectric energy harvesting system based on cantilever structure. The measurement procedure for a complete characterization of the performance of a vibration-based energy harvesting system, either as a whole or separately as in different modules is described. Typical results illustrating the important capabilities of the proposed automated measurements configuration are provided for an effective and efficiently characterization and comparison with various piezoelectric energy harvesting systems in different applications, including derivation of other important parameters. While a cantilever system has been examined here it could be applied to other vibration harvesters such as..

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