Vibration Energy Harvesting Potential for Turbomachinery Applications

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ABSTRACT

The vibration energy harvesting process represents one of the research directions for increasing power efficiency of electric systems, increasing instrumentation nodes autonomy in hard to reach locations and decreasing total system mass by eliminating cables and higher-power adapters. Research based on the possibility of converting vibration energy into useful electric energy is used to evaluate the potential of its use on turbomachinery applications. Aspects such as the structure and characteristics of piezoelectric generators, harvesting networks, their setup and optimization, are considered. Finally, performance test results are shown using piezoelectric systems on a turbine engine.

KEYWORDS: *turbomachinery, vibration, piezoelectric, energy harvesting*

NOMENCLATURE

ω - Resonant frequency in rad/s
m – Mass in kg
k - Spring constant

1 INTRODUCTION

Energy harvesting is the process of capturing energy from vibration sources, such as rotating machinery, and turning it into electrical energy. Even if the vibration energy of a normally operating machine is low, its use on powering low-consumption electronic devices is considered. This can lead the way to high-end technologies, such as compact control systems or autonomous instrumentation nodes (wireless sensors), as well as an increased overall system power efficiency.
Williams and Yates describe in [1] a micro-harvesting generator and three possible energy conversion mechanisms: piezoelectric, electromagnetic and electrostatic. Generated power depends on the

inertial mass, damping factor, resonant frequency (which needs to be similar to the source vibration frequency), source vibration amplitude and frequency. Piezoelectric generators can provide high voltage; however, the output current is low due to very high impedance, which has a negative impact not only on their efficiency but also on their operation with other electronics [2]. One of the most productive materials used for piezoelectric harvesters is PZT-5A [2][3], but there is a constant interest towards more efficient materials. Although the power density provided is lower in smaller devices, the constraints of smaller dimensions limit the movement and lead to a slightly larger preference towards larger generators.
Existing harvesters on the market, such as MIDE products, can theoretically put up to 60 mW power at 16 V. For higher current, a harvesting network could use multiple harvesters to increase the output. Harvester frequency tuning can be made using a tuning actuator [4]. These actuators can be made active or intermittently active (also called passive) [5], maintaining resonant frequency also during inactive periods. Examples of active actuators are electrostatic elastomers [6], while passive actuators can be various types of bending mechanisms. The role of actuators is to deliver an additional force that varies with displacement (acting on stiffness) or acceleration (acting on mass), but the amplitude of the force also depends on other aspects, such as how the force is applied [5][6].
Main vibration causes in compressor discs or turbines include: variable forces from blades, due to their own vibration or gas pressure variation, variable forces from shaft to disc (deficient balancing, couplings, bending), rotor couplings, bearings, etc.

2 PIEZOELECTRIC DEVICES

When harvesting machinery vibration, most used devices have been based on inertial mass systems [2]. The practical form of piezoelectrical generators is shown in Fig. 1 as a cantilever with a piezoelectric outer layer that is excited into resonance by the vibration source. By the piezoelectric effect, the material generates voltage. In the case of electromagnetic generators. Adjusting the resonant frequency can be done in multiple ways. One is by changing the effective length (l), i.e. adjusting the position of the cantilever at its root. The resonant frequency is inversely proportional with $l^{3/2}$.

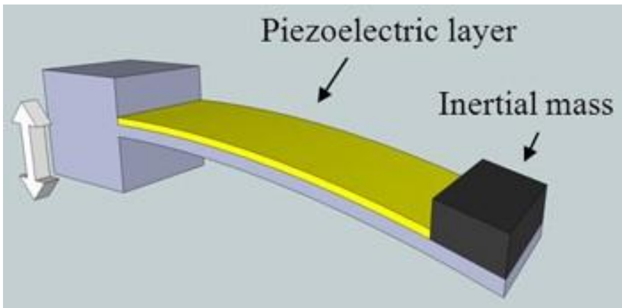

Figure 1: Illustration of piezoelectric generator [8]

A device proposed for shortening was patented in [7] and shown in Fig. 2. The actuator glides the cantilever back and forward so the length of the suspended part is changed.

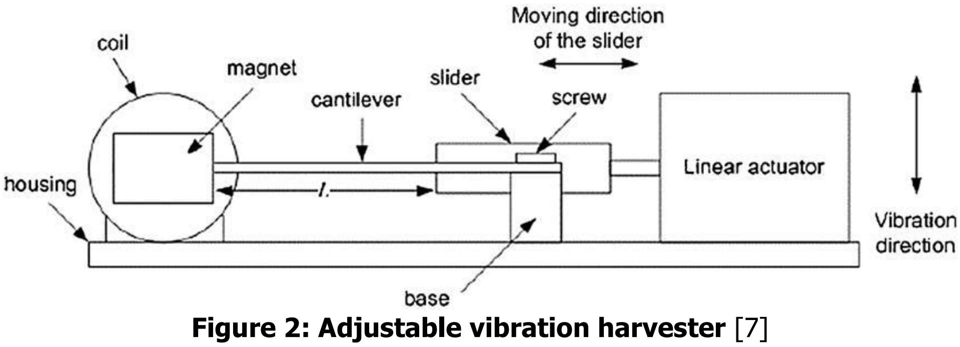

Figure 2: Adjustable vibration harvester [7]

Alternatives include moving the mass's center of gravity. Although this is not very facile after manufacturing the harvester, there are proposed designs. In [9] a piezoelectric harvester prototype

(Fig. 3) is proposed, with a mass (m) consisting of two parts, one that is fixed (m_0) and one that is movable (m_1).

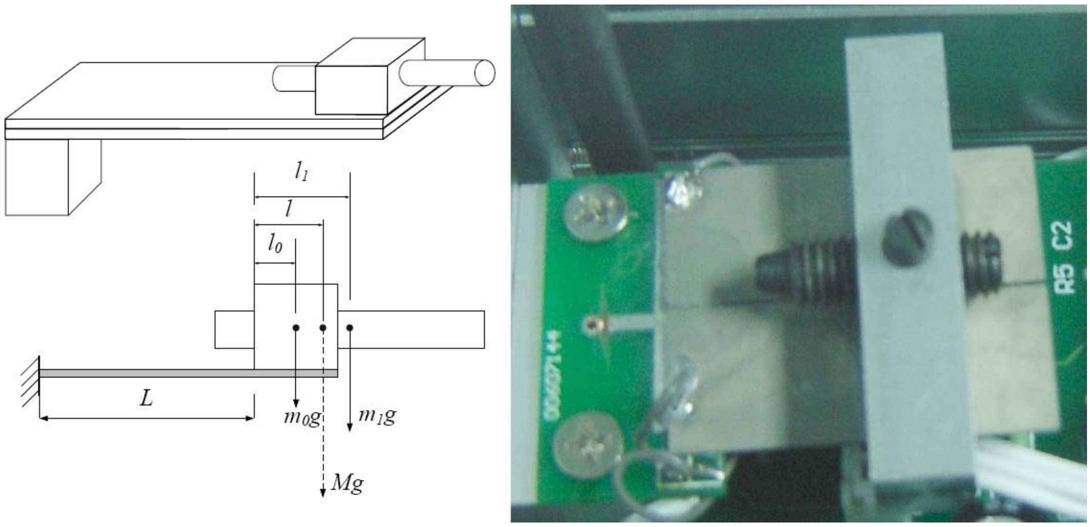

Figure 3: Harvester prototype with adjustable mass position [9]

The position of the movable part is set with a screw along the piezoelectric element, effectively changing the position of the overall center of gravity. Hence, the cantilever's spring constant (k) is changed and thus the resonant frequency results according to Eq. 1:

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

The results showed that the frequency range that was covered is between 130 and 180 Hz. Other mechanical tuning methods may include: tunable resonator [10], magnetic force perpendicular to the cantilever [11], thermal stress applied with a resistor [12], etc. Electrical tuning can also be achieved by varying the load and thus the electrical damping [13].
Without a vast harvesting network, the output electric power generally does not exceed values within the order of milliwatts, depending on the frequency, material and other factors [14][15]. In order to extend the frequency range of harvested vibration, a harvesting network may be used. An example with harvesting devices using various resonant frequencies is shown in Fig. 4. The device has a group of cantilever beams with proof (inertial) masses. In [16] it is shown that the beams and proof masses are of different sizing and were chosen so that the generator would work as a band-pass filter and increase its frequency operating range.

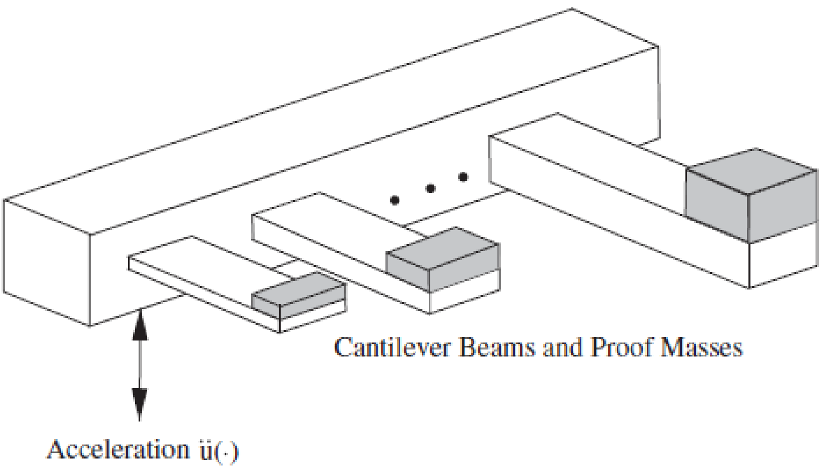

Figure 4: Harvester with multiple resonant frequencies [16]

When a piezo material is stressed, an electrical voltage is generated. The most suited model for representing piezoelectric systems is a voltage generator, with series capacitor and resistor [17]. The conversion efficiency, from mechanical to electrical energy, is an important parameter for developing and optimizing a generating device. In [18] and [19], an analytical formula for the prediction of energy conversion efficiency was determined. When a piezoelectric device is applied to a system, an amount of energy is extracted from the vibrating structure and delivered to electronic components, resulting in a structural damping [20]. Due to the efficiency being defined as the ratio between the power dissipated on the load and the power applied by the external force, one can talk about the electrically induced damping [21].

3 HARVESTING CIRCUITS

The output of piezoelectric harvesters is a low irregular AC current, depending on vibration frequency and amplitude. Compared to battery-powered sensors, which feed on standard and stabilized voltage, sensors based on energy harvesting require an architecture forming an energy harvesting circuit [22]. This needs to rectify the voltage from the harvester into DC. Additionally, a power management subsystem is required in order to store and regulate the energy before delivering it to loads. The regulation is needed because loads require constant DC voltage above a certain threshold, which is not possible via direct connection to the harvester. In [23], a harvesting and conversion circuit was developed and tested to power a thermistor sensor (Fig. 5) and wireless data transmitter.

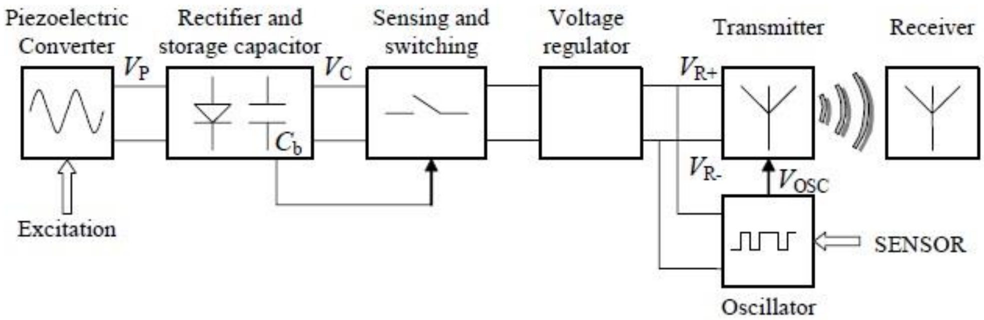

Figure 5: Harvester with multiple resonant frequencies [23]

The piezo generates an AC voltage V_P, which is rectified with Schenkel diodes and stored in the capacitor C_b. With the sensing and switching circuit, most of the energy stored in C_b can be transferred further when the voltage reaches the threshold. Then, the energy is delivered to a voltage regulator to power a sensor and a RF transmitter. On the resonant frequency of 41 Hz, the voltage reached almost 3 V and the power 0.25 µW. A similar harvesting circuit was described in [17], with reported results of 16.3 µW at 100 Hz sine excitation.

4 VIBRATION ANALYSIS OF TURBINE ENGINES

In order to perform accurate dimensioning of a harvesting circuit, knowing the vibration spectrum of the engine during operation is needed. The proper harvester has the resonant frequency similar to the vibration frequency of the machine. Also, the vibration amplitude is considered, as the harvester output increases with the amplitude.

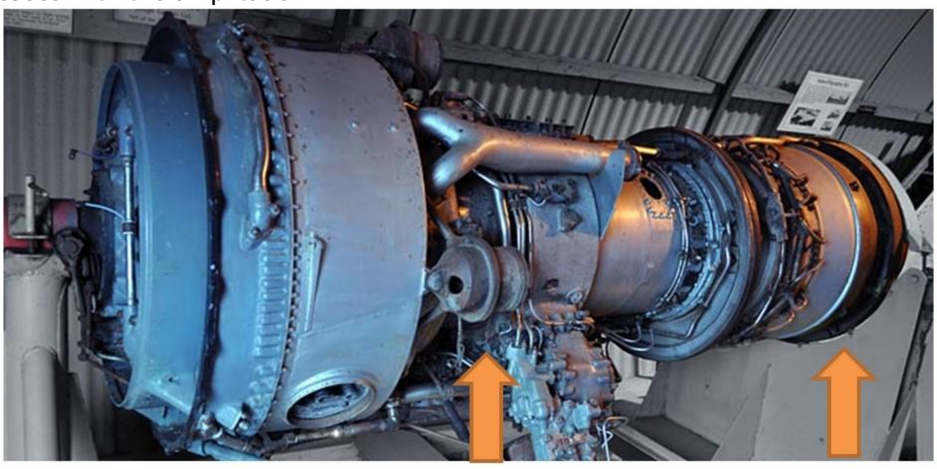

Figure 6: Vibration measurement on the compressor and turbine of the Rolls-Royce Tyne

Below, a vibration analysis is shown for a Rolls-Royce Tyne turboprop engine. The vibration measurements were performed on the compressor in radial direction and on the power turbine, using PCB 352C33 accelerometers, the same as in all the measurements presented in this paper. Their position is shown in Fig. 6.

On the casing near the power turbine the temperature can reach up to 800°C, so this place is not adequate for the proposed system. In the vibration spectra in Fig. 7, two different regimes of the turbine engine are presented based on our tests, separated by a difference of 1200 RPM in engine speed. A range of 0.35 g can be seen on the fundamental of the high-pressure compressor. Within the frequency spectra, the 214 and 190 Hz main components are highlighted, with an amplitude of 0.97 and 0.62 g (RMS), corresponding with the speed of the high-pressure compressor.

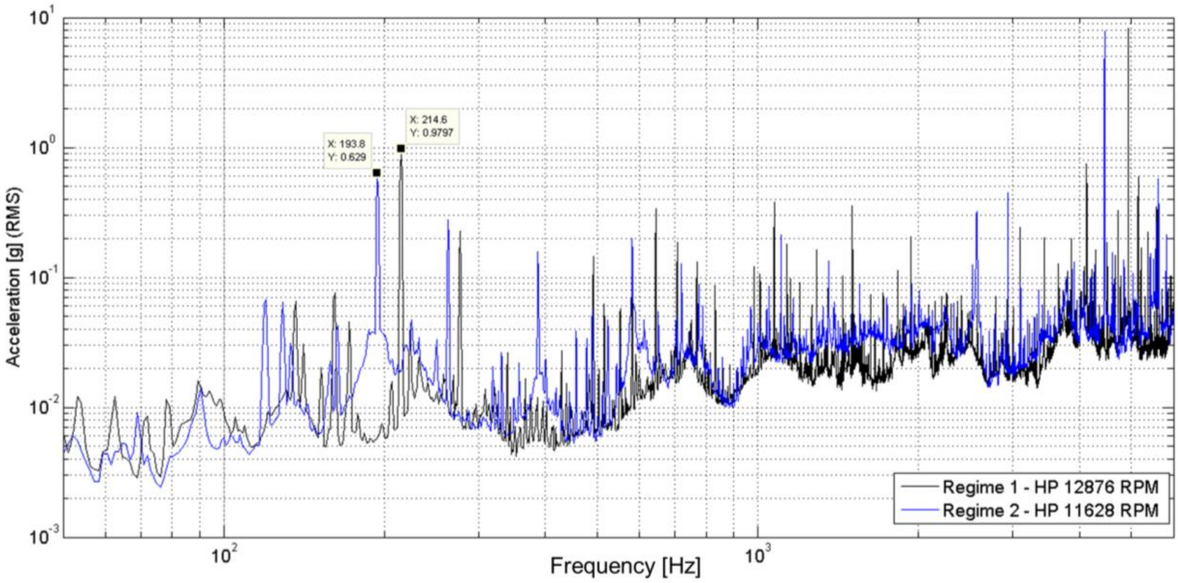

Figure 7: Vibration spectra of the Rolls-Royce Tyne engine

Another example is a Klimov TV2-117 turboshaft engine, which undergoes test bench runs at 10,000 to 14,000 rpm. The vibration measurement location and results are shown in Fig. 8 and 9, respectively. The main component amplitude is 6 m/s^2 (0.6 g) at 175 Hz, a frequency corresponding with the engine speed of 10,500 rpm. Other engines used for either scientific or industrial (e.g. cogeneration) purposes showed similar results.

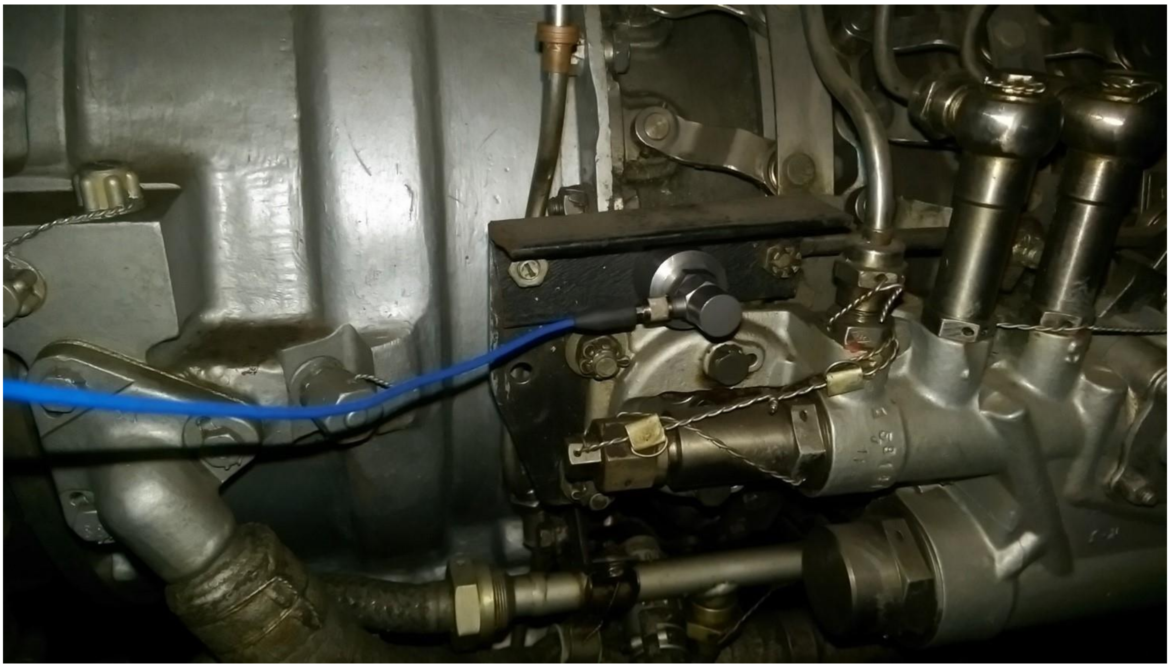

Figure 8: Vibration measurement on the TV2-117 engine

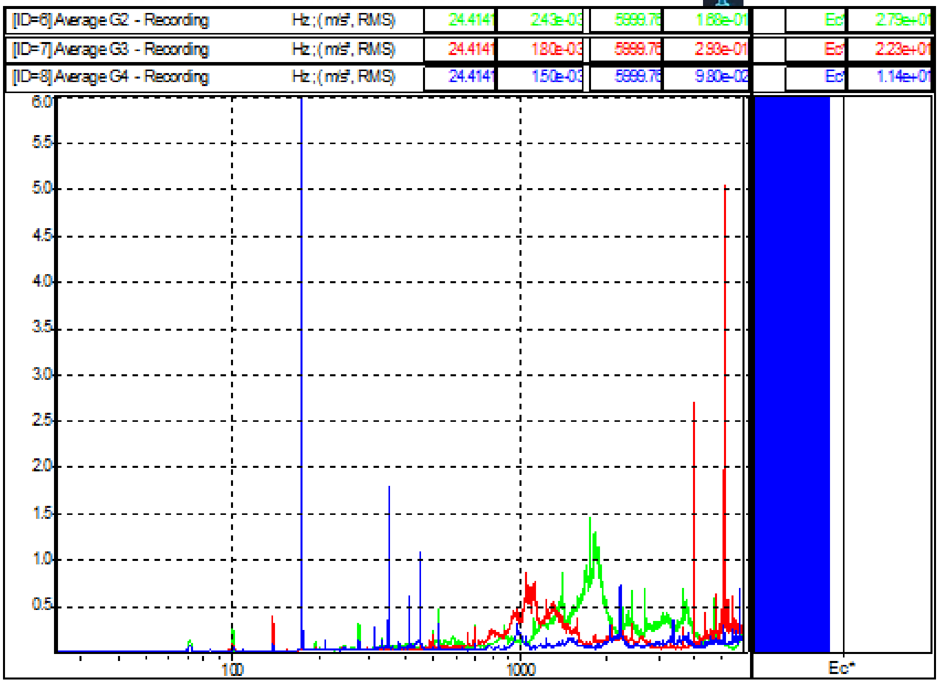

Figure 9: Vibration spectrum of the TV2 engine [m/s² vs Hz]

Within the COMOTI turbine engine laboratory a parallel TV2 study was made. The engines were set to run at the same speed. As can be seen from the figure below, an accelerometer was mounted in vertical direction on each engine.

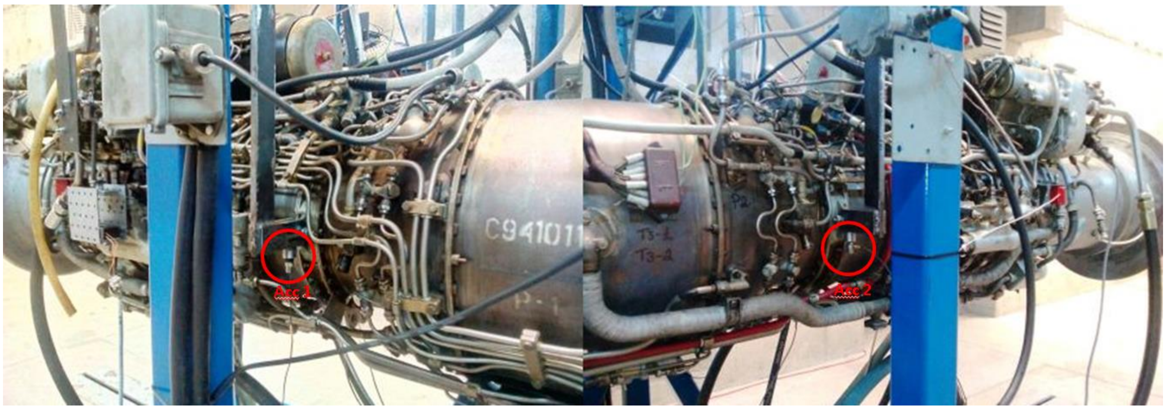

Figure 10: Vibration measurement on two TV2 engines

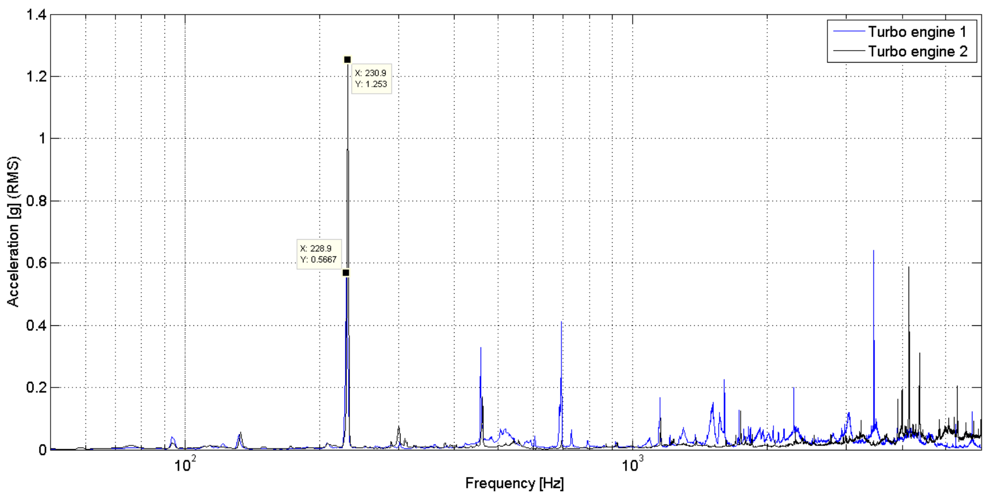

Figure 11: TV2 engines vibration on idling

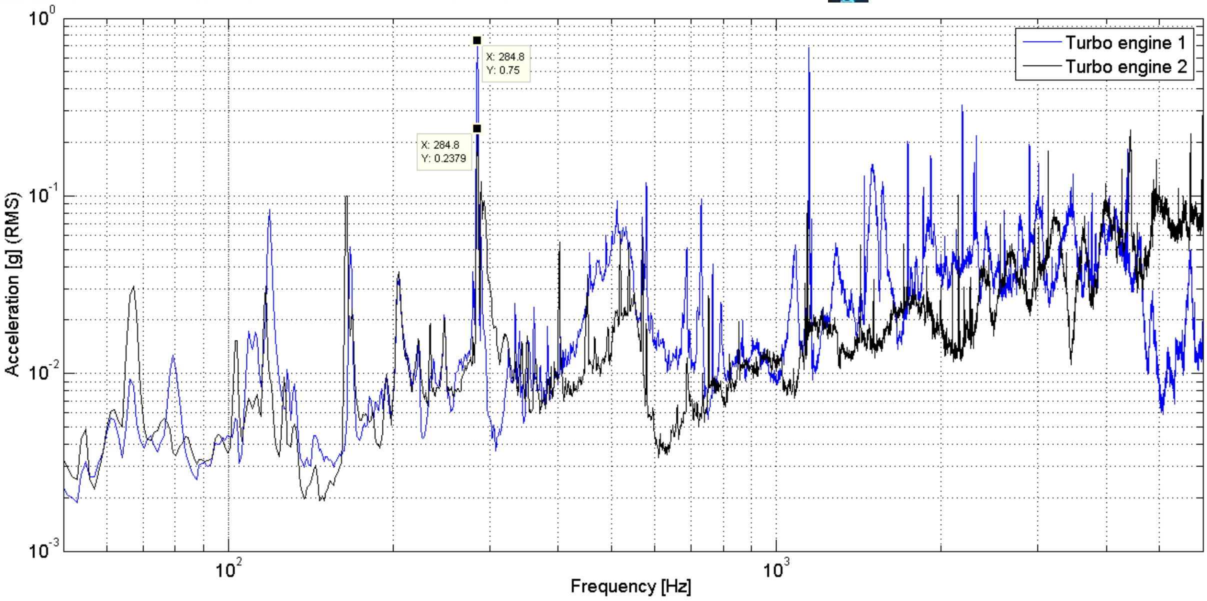

Figure 12: TV2 engines vibration at 17000 RPM

Another example of turbine engines is those from the Cogeneration Plant 2xST 18 – Suplacu de Barcău, where COMOTI completed two cogeneration groups, each being equipped with a ST18 Pratt&Whitney engine. In the Figure below, the position of the accelerometers on a ST18 turbo engine is presented.

Figure 13: Vibration measurement on the ST18 engine

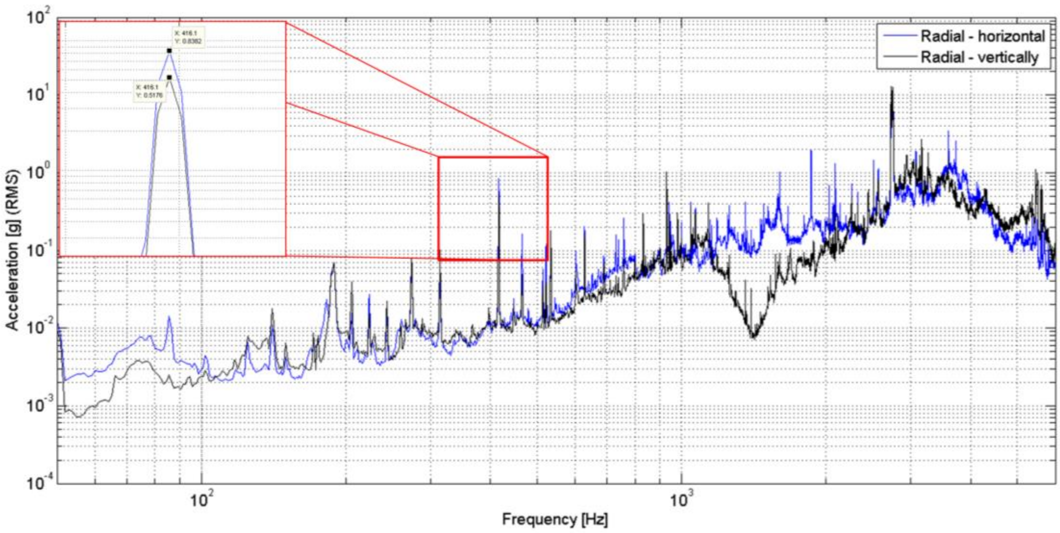

Figure 14: Vibration spectra of the ST18 Pratt&Whitney engine

As can be seen from the vibration spectra the vibration compressor component has on the horizontal direction an amplitude of 0.83 g RMS at an operational speed of 24,966 RPM.

5 PRELIMINARY TESTING

The aim is to develop and test the potential of a harvesting circuit that is most suitable to engine applications similar to those previously showed, mostly, but also targeting perspectives toward aerospace turbomachinery. With these scenarios in mind, the most appropriate harvester type on the market was selected for preliminary testing on a vibration generator. The model MIDE PPA-4011 was selected, which showed the highest output and most options around resonant frequencies similar to those of considered engines. Further resonant frequency adjustments include changing the cantilever effective length, by changing its base position, and/or adding additional proof mass.

Figure 15: Preliminary testing setup

The testing setup is shown in Fig. 15, with the block diagram illustrated in Fig. 16. It shows: a function generator, that generates a variable frequency signal; a controllable amplifier, that amplifies the signal to the vibration generator using variable amplitude; the vibration generator, that generates vibration based on the frequency and amplitude of the signal received; the piezoelectric harvester (PZT), attached to the vibration generator; a 5 kΩ test load; an oscilloscope to read voltage output; an accelerometer attached to the vibration generator to read vibration values, based on the voltage read from the load amplifier.

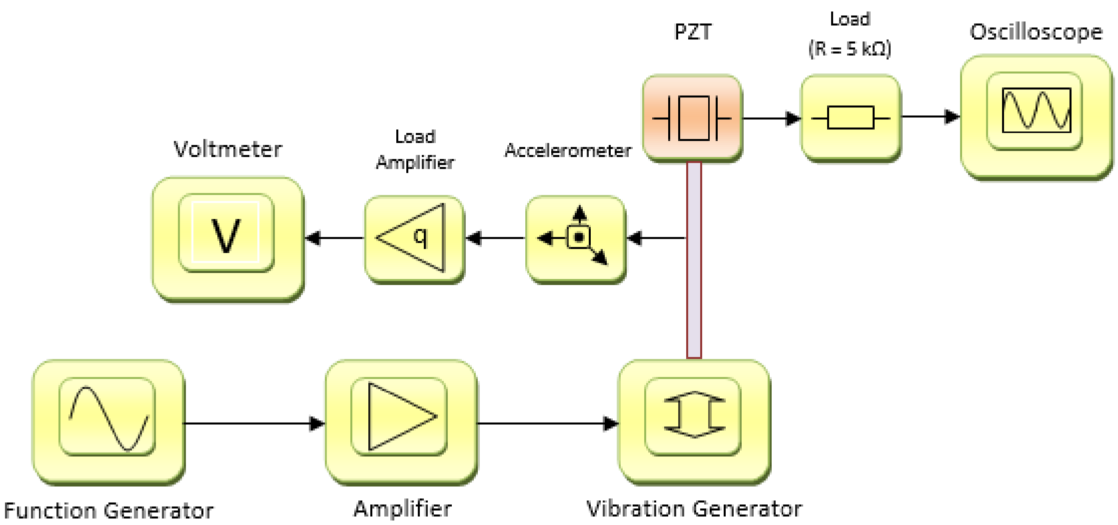

Figure 16: Preliminary testing setup – block diagram

The resulting AC output in terms of voltage and power is shown in Fig. 17 and varies from 2.8 V (1.57 mW) at 205 Hz, 0.5 g, to 12.6 V (31.75 mW) at 190 Hz, 3 g. For most lower amplitudes, it showed a resonant frequency of around 205 Hz. That means on an engine it would normally generate the highest voltage at 12,300 rpm. With this expectation, the following step is to further test a harvesting circuit on a real turbine engine with a less than perfect vibration frequency spectrum.

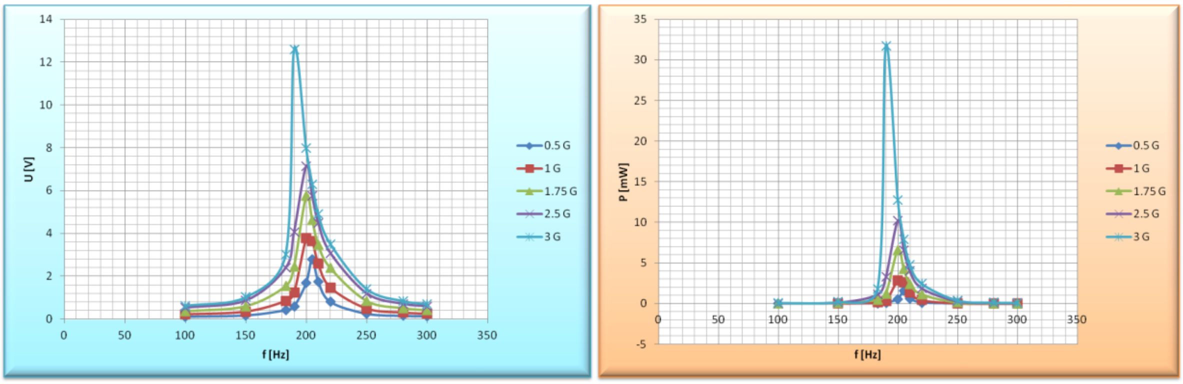

Figure 17: Harvester output results

6 FINAL TESTING

The final testing consists of attaching the harvester on the side of a TV2 turbine engine, connecting it to a harvesting demo board and measuring its output during the operation of the engine. The mounting site of the harvester is shown in Fig. 18. In the measurement campaign, four accelerometers were mounted on the casing of the turbine engine. Two accelerometers were mounted near the harvester in horizontal and vertical position, in order to observe the vibration in both directions (Fig. 19). The third was placed at the end of the compressor and the beginning of the combustion chamber. The forth accelerometer was placed on the starter/alternator casing in axial direction.

Figure 18: Position of the harvester

The engine ran between 10,500 and 12,000 rpm, maintained on various regimes, while voltage, speed (frequency) and vibration data was permanently monitored. The rectified output of the harvester demo board was measured along with associated vibration. The results are shown and discussed below.

Figure 19: Position of the harvester and accelerometers

Figure 20: Position of the harvester and accelerometers along the engine: (1) axial-horizontal near the harvester, (2) axial-vertical near the harvester, (3) at the end of the compressor, (4) on the engine starter

7 RESULTS AND DISCUSSION

The vibration and voltage measurements were performed on the entire engine running time using 01dB Orchestra multichannel acquisition system. The measurements were performed in order to test and observe the response in real conditions of the harvesting system, and the analysis of the vibration signals to observe the influence of vibrations on the generated voltage. For the vibration signal, a FFT function was applied from which only the spectral component of the compressor was subtracted. In Fig. 21, the vibration spectral component of the compressor from each accelerometer is presented. As can be seen in the vertical direction, the same as the harvesting direction, the vibration of the compressor reaches the highest level.
The regimes are shown in Fig. 22, with the red line being the vibration amplitude (in *g*) near the position and direction of the harvester. A nearly 0.9 g vibration was measured at the frequency of 190 Hz (11,400 rpm). The vibration measured by the other accelerometers is also shown in blue (axial-horizontal near the harvester), green and violet the other two downstream the engine. At the resonant frequency, the voltage showed between 3 and 3.5 V (Fig. 22, 23), which is higher than a small-sized battery.

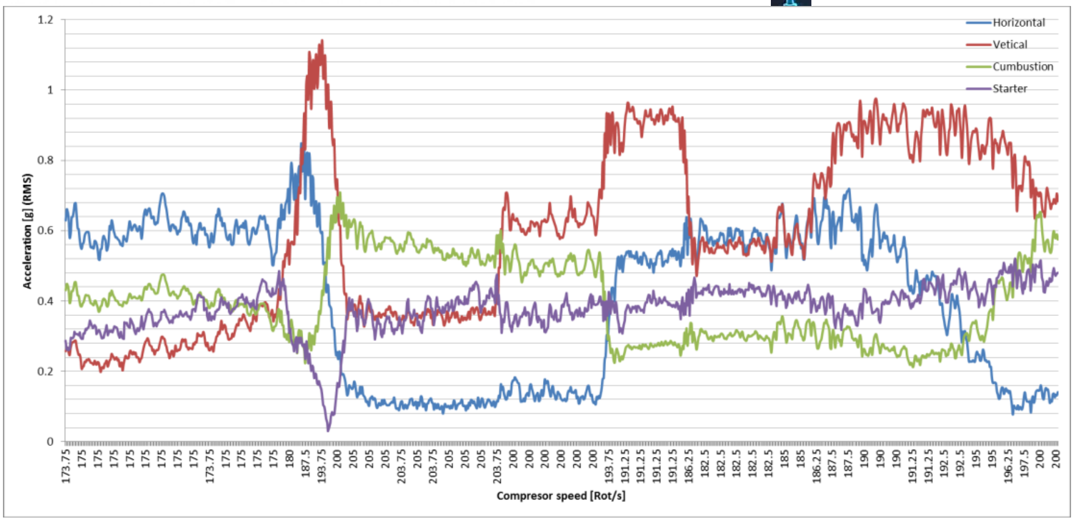

Figure 21: Vibration amplitude

The generated voltage in respect with the compressor speed is showed in Fig. 22, where it can be seen that in transient regime a value of 4 V is obtained at 190 Hz.

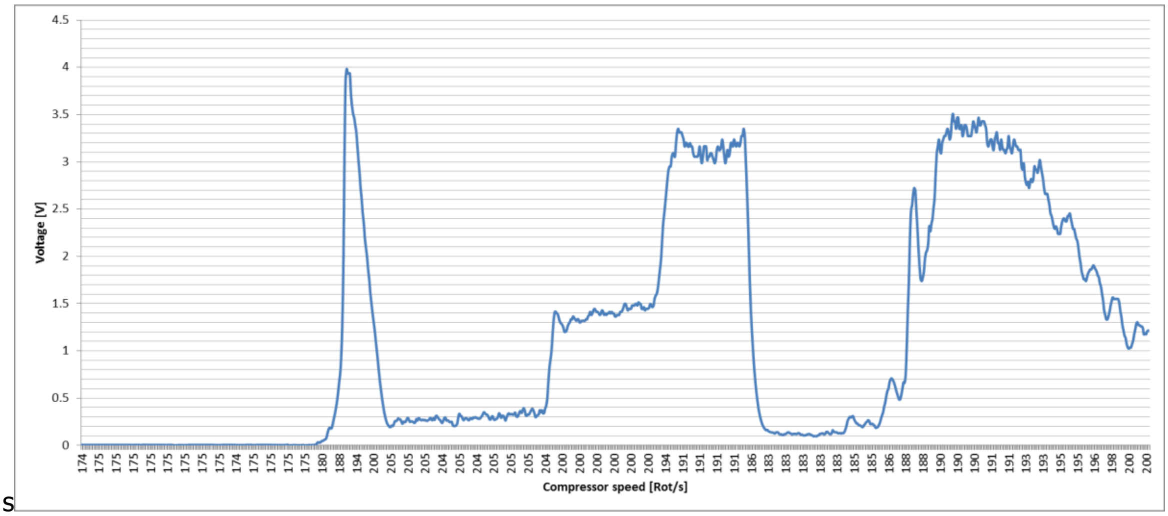

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Figure 22: Voltage in respect with compressor speed

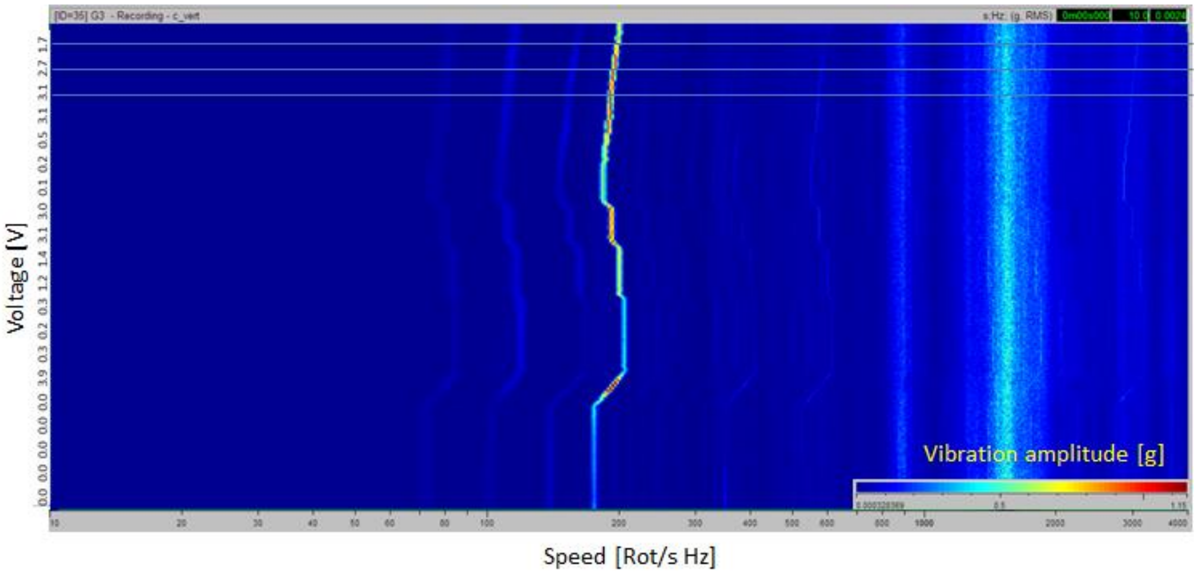

Figure 23: Voltage associated with speed and vibration amplitude

8 CONCLUSION

This paper showed an experiment in real conditions in order to evaluate the potential of vibration energy harvesting. Further investigation will continue, however, after further tests which will involve: multiple harvester networks, various electronic conditioning typologies, different engines and engine regimes, or various types of loads. With the potential of an energy storage and conditioning circuit, it was showed that a high enough voltage to power wireless instrumentation can be achieved. It was also showed that the harvester can be tuned in such way to match the fundamental frequency of vibration given by the rotational speed of the main shaft of the gas turbine. In this way, the energy provided by the harvesting device can be maximized for certain regimes where it is most needed.

REFERENCES

1. C.B. Williams, R.B. Yates; 1996; "Analysis of a micro-electric generator for microsystems"; *Sensors and Actuators A: Physical*; **52**; pp. 8 - 11
2. D. Zhu; 2011; "Vibration Energy Harvesting: Machinery Vibration, Human Movement and Flow Induced Vibration"; Editor Y.K. Tan; *Sustainable Energy Harvesting Technologies - Past, Present and Future*; First edition; **1**; InTech; Rijeka; pp. 25 - 54
3. D. Zhu, S. Beeby, J. Tudor, N. Harris; 2011; "A credit card sized self powered smart sensor node"; *Sensors and Actuators A: Physical*; **169**(2); pp. 317 - 325
4. S. Roundy, Y. Zhang; 2005; "Toward self-tuning adaptive vibration-based micro-generators"; *Smart Structures, Devices, and Systems II, Proceedings of SPIE*; **5649**, Bellingham, WA, pp. 373 - 384
5. D. Zhu, M.J. Tudor, S.P. Beeby; 2010; "Strategies for increasing the operating frequency range of vibration energy harvesters: a review"; *Measurement Science and Technology*; **21**(2)
6. S.G. Adams, F.M. Bertsch, K.A. Shaw, P.G. Hartwell, F.C. Moon, N.C. MacDonald; 1997; "Capacitance Based Tunable Resonators"; *Journal of Micromechanics and Microengineering*; **8**(1)
7. J.F. Gieras, M. Huzmezan, J.H. Oh, H.S. Sane; 2007; "Electromechanical energy harvesting system"; Patent WO 2007070022 A2, WO 2007070022 A3
8. M. Stewart; 2017; "Vibration energy harvesting"; www.npl.co.uk/science-technology/functional-materials/research/vibrational-energy-harvesting
9. X. Wu, J. Liu, S. Kato, K. Zhang, T. Ren, L. Liu; 2008; "A Frequency Adjustable Vibration Energy Harvester"; *Proceedings of PowerMEMS 2008+ microEMS2008*; Sendai, Japan; pp. 245 - 248
10. C. Peters, D. Maurath, W. Schock, Y. Manoli; 2008; "Novel Electrically Tunable Mechanical Resonator for Energy Harvesting"; *Proceedings of PowerMEMS 2008+ microEMS2008*; Sendai, Japan; pp. 253 - 256
11. V.R. Challa, M. Prasad, Y. Shi, F.T. Fisher; 2008; "A vibration energy harvesting devices with bidirectional resonance frequency tunability"; *Smart Materials and Structures*; **17**(1)
12. T. Remtema, L. Lin; 2001; "Active frequency tuning for micro resonators by localized thermal stressing effects"; *Sensors and Actuators A: Physical*; **91**(1); pp. 326 - 332
13. D. Charnegie; 2007; "Frequency Tuning Concepts for Piezoelectric Cantilever Beams and Plates for Energy Harvesting"; *M.Sc. Thesis*; University of Pittsburgh; PA, USA
14. MIDE Technology – PPA Products Datasheet; 2016; Rev. No. 002
15. H. Madinei, H.H. Khodoparast, S. Adhikari, M.I. Friswell, M. Fazeli; 2015; "Adaptive tuned piezoelectric MEMS vibration energy harvester using an electrostatic device"; *The European Physical Journal Special Topics*; **224**(14); pp. 2703 - 2717
16. S.M. Shahruz; 2006; "Design of mechanical band-pass filters with large frequency bands for energy scavenging"; *Journal of Sound and Vibration*; **16**(9); pp. 523 - 531
17. T.H. Ng, W.H. Liao; 2005; "Sensitivity Analysis and Energy Harvesting for a Self-Powered Piezoelectric Sensor"; *Journal of Intelligent Material Systems and Structures*; **16**(10); pp. 785 - 797
18. C.D. Richards, M.K. Anderson, D.F. Bahr, R.F. Richards; 2004; "Efficiency of Energy Conversion for Devices Containing a Piezoelectric Component"; *Journal of Micromechanics and Microengineering*; **14**(5); pp. 717 - 721
19. J.H. Cho, R.F. Richards, D.F. Bahr, C.D. Richards, M.J. Anderson; 2006; "Efficiency of Energy Conversion by Piezoelectrics"; *Applied Physics Letter 89: 104107*

20. H.A. Sodano, D.J. Inman, G. Park; 2004; "A Review of Power Harvesting from Vibration Using Piezoelectric Materials"; *The Shock and Vibration Digest*; **36**(3); pp. 197 - 205
21. Y.C. Shu; 2009; "Performance Evaluation of Vibration-Based Piezoelectric Energy Scavengers"; Editors S. Priya, D.J. Inman; *Energy Harvesting Technologies*; Springer; Boston, MA; pp. 79 - 105
22. L. Wang; 2008; "Vibration Energy Harvesting by Magnetostrictive Material for Powering Wireless Sensors"; *Ph. D. Thesis*; North Carolina State University; Raleigh, NC
23. M. Ferrari, V. Ferrari, D. Marioli, A. Taroni; 2008; "Piezoelectric multifrequency energy converter for power harvesting in autonomous microsystems"; Sensors and Actuators A Physical **142**(1); pp. 329 - 335