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A NON-LINEAR PIEZOELECTRIC ENERGY HARVESTING SETUP FOR THE CONTINOUS POWER SUPPLY OF A WIND TURBINE MONITORING SYSTEM

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Abstract. Current work presents the findings of a research project, which objective is the design of an autonomous piezoelectric energy harvesting setup for the uninterrupted power supply of a data acquisition and transmission unit. This system is designed to operate in wind turbine blades providing critical structural condition data. Wind turbine blades are subjected to aerodynamic loads generating oscillations with frequency content below 15Hz. To succeed in such an operational environment, the design of a special nonlinear piezoelectric energy harvester (PEH) is required, based on the post-buckling response of a composite beam with piezoelectric patches connected to harvesting circuits. The components of the PEH system are described and their electromechanical performance is simulated using continuous solid FE. All the required components are manufactured and tested in laboratory conditions to validate simulations and quantify the proposed system energy production performance. Additionally, a laboratory scale demonstrator is built and tested in laboratory environment simulating realistic operational conditions aiming to quantify the overall performance and power autonomy.

Key words: Piezoelectric; energy harvesting; composite beam; bistability; demonstrator; low frequency operation

1 INTRODUCTION

Nonlinear piezoelectric energy harvesters (PEH) attract major attention in the emerging field of self-powered systems in the context of the Internet of Things era. Their superiority compared to linear harvesters is attributed to being highly effective in terms of power output in a much wider frequency range, including low excitation frequencies of 0-20 Hz [1]. Since in typical operation conditions the excitation vibrational energy is distributed over a wide spectrum and may change in spectral density over time, nonlinear energy harvesters provide large deformation in response to a relatively small vibrational energy input [2], [3]. In the present

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configuration, the power harvested through an appropriately tuned circuit is in the mW range and can thus feed batteries to provide energy to transmitters of sensor network data to the cloud. To that end, numerous multi-stable devices have been designed for harvesting energy from vibrations in several application sectors, such as infrastructure [4], [5], medical, wearables to mention a few, while extensive literature reviews provide a detailed overview of the reported research and development in the field [3], [6]. The functional principle of a large part of these nonlinear devices is based on electromagnetic forces acting on a cantilever beam carrying piezoelectric transducers [7] connected to harvesting circuits [8]. Another popular relevant physical concept is the exploitation of the bistable response of a post-buckled piezoelectric beam subjected to base excitation [9]. The PEH presented in this work is based on the latter concept, while designed for powering-up wireless data transfer systems in wind turbine blades [10], as shown in Figure 1.

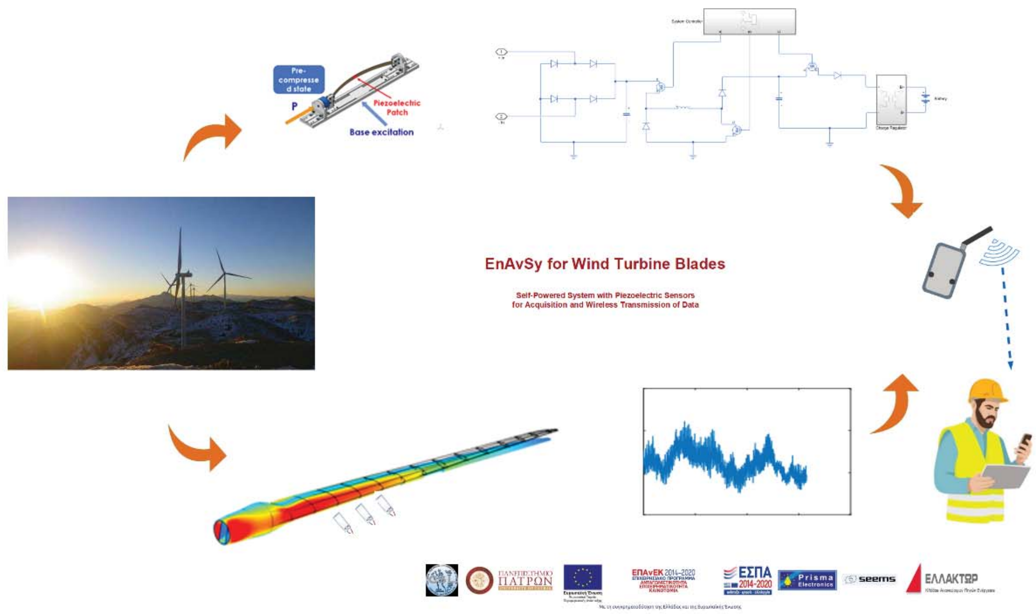

Figure 1 Schematic representation of the potentially autonomous monitoring system[10].

The coupled electromechanical nonlinear dynamic response of a piezoelectric beam subjected to prestress up to post-buckling regime may be tuned in order to achieve maximum harvested power. Various studies have been performed for predicting the response of such beams ([11] - [12]). In most of these works, a resistive electric load has been used to indicate the power harvesting capability of post-buckled piezoelectric beam configurations and its superiority compared to linear devices. Additional effort has been put on the design of the harvesting circuit [13], [14]. Various in-depth studies of the circuit-structure interaction in the case of bistable mechanical vibrations have been reported in the last decade [15], [16], which provide quantitative estimations of harvested power, based on lumped-parameter modeling of the coupled nonlinear electromechanical dynamic system. Finite element-based methodologies have also been used for the design of such systems [17].

The current work presents the findings of a research project, which objective is the design of an autonomous piezoelectric energy harvesting setup for the uninterrupted power supply of a data acquisition and transmission unit to be implemented in wind turbine blades. The more challenging part of the application is the low frequency excitation, which dictates the design of a special nonlinear PEH based on the post-buckling response of a composite beam with piezoelectric patches connected to harvesting circuits. All the required components are manufactured and tested in laboratory conditions to validate simulations and quantify the proposed system energy production performance.

2. SPECIFICATIONS OF THE PEH AND TRANSMISSION SETUP

The PEH setup presented in this work was designed and manufactured for operation in a low frequency oscillation environment i.e., a wind turbine blade. Thus, specific requirements arise from such an implementation perspective with which the developed setup must be harmonized. Wind turbine blades vibrate during operation in a low-frequency excitation range induced by aerodynamic and inertia loads. Depending on the blade configuration, the base excitation of the harvester during operation is expected to lie in a frequency range up to 15 Hz. Consideration of locally added weight constraints should be also considered in the design process, aiming at achieving minimum effect on the response of the blade and preserving safe operation. The objective of applying a PEH in a wind turbine blade is to supply with power an auxiliary unit, which measures the generated dynamic strain from the blade and transmit it to the base acquisition station. To that end, the operational power requirements of the auxiliary unit should be minimum, thus eliminating the need to replace batteries in electronic devices installed in the blade. In this context, the PEH unit should be capable of producing at least 1mW electrical power.

3. DETAILED DESCRIPTION OF THE DEVELOPED PEH, DAQ AND TRANSMISSION SETUP

Current setup is analyzed into four subassemblies: a mechanical part providing the required structural support, an electromechanical for energy conversion, an electrical for the energy harvesting and finally the external unit performing the data acquisition, preprocessing and data transmission. The first three parts, illustrated in Figure 2(a), interact between each other, and their operational scope is to provide the required power for the external unit to operate autonomously.

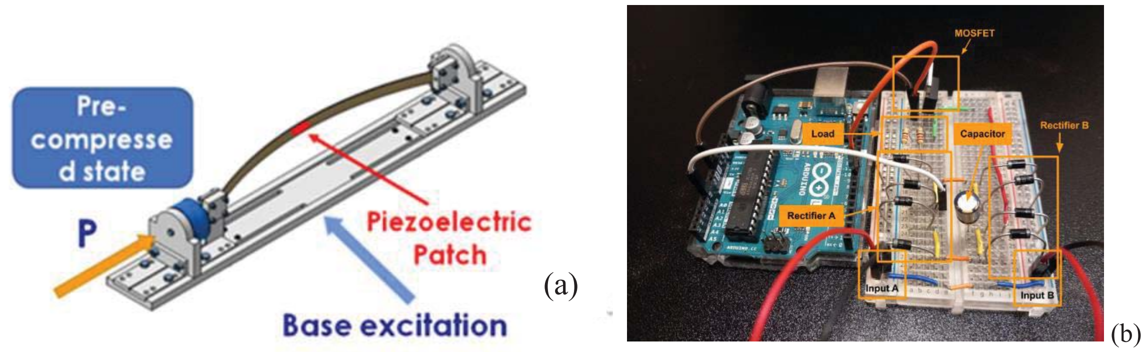

Figure 2 (a) Schematic illustration of the mechanical subassembly (illustrated deformed under axial loading, and (b) the electrical subassembly, which is characterized as the In-house harvesting circuit, and includes a capacitor with Cp=111 μF, a resistor R=100 Ω and a MOSFET [18].

Mechanical subassembly

The mechanical subassembly includes the compression mechanism and its supporting frame. It is critical for the mechanical part to have minimal deformation when the applied axial load to the specimen varies in the range of hundreds of N.

Electromechanical subassembly

The electromechanical subassembly consists of a composite beam, axially loaded in compression up to post buckling, and two piezoelectric transducers, symmetrically placed at center. The used piezoelectric device was the DuraAct P876.A11 and the composite beam dimensions were 368x35x2.5mm^3. Composite material was selected, since it ensures optimal stiffness/weight ratio and linear elastic behavior.

Electric subassembly

The electric subassembly comprises an in-house harvesting circuit (cc-ih), illustrated in Figure 2 (b). This one was selected among other commercial harvesting circuits [19] as the parameters of each individual component were provided by the manufacturers. It includes three main parts: a rectifier, a charging capacitor, and a discharging switch (MOSFET), all connected to the piezoelectric current sources. A resistive load is connected to the MOSFET for ease of harvested power measurement, whereas different kinds of loads, including batteries, can be powered. To simulate the electromechanical response, the piezoelectric composite beam was modeled in COMSOL using layerwise shell finite elements and the analysis was performed in two successive steps: i) A static axial compression by an applied displacement at the free end, and ii) a time-domain solution under a constant base acceleration. Additional details are provided by Plagianakos et.al.[20].

DAQ and Wireless Transmission Unit

The external unit for the acquisition and the wireless data transmission is capable for the simultaneous acquisition of the dynamic strain from four piezopolymer sensors. The custom-made system acquires the data with 16bit resolution, performs a preprocessing, and using a low energy Bluetooth transmits the data to the base unit. It is expected that the results provide critical information for the blade structural condition. Due to the nature of the piezopolymer sensors, a charge amplifier is required to measure the voltage. Also, in order to improve the measuring quality, the external unit is equipped with high pass filter and an antenna to transmit the data. Architecture of this unit is illustrated in Figure 3.

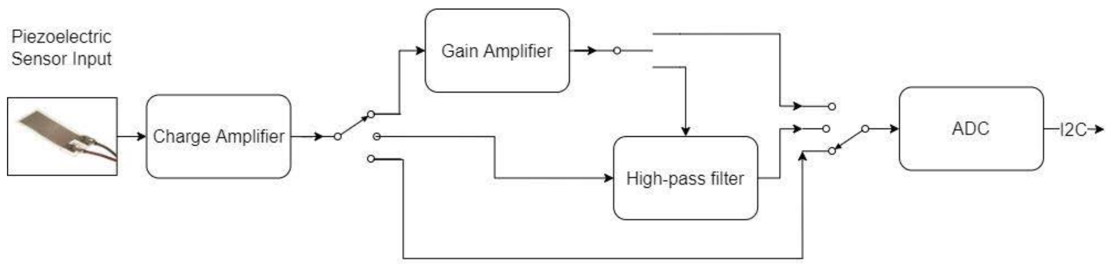

Figure 3 External data acquisition and digitalization unit; schematic illustration for a single input channel.

4. OPERATION OF THE ELECTROMECHANICAL UNIT

The electromechanical unit is illustrated in Figure 4. The Gl/Epoxy beam equipped with a pair of piezoelectrics and the additional mass bonded at the center are placed in the mechanical frame. The mechanical frame for laboratory testing conditions is mounted on a laterally oscillated base plate, which is excited via an electromechanical shaker.

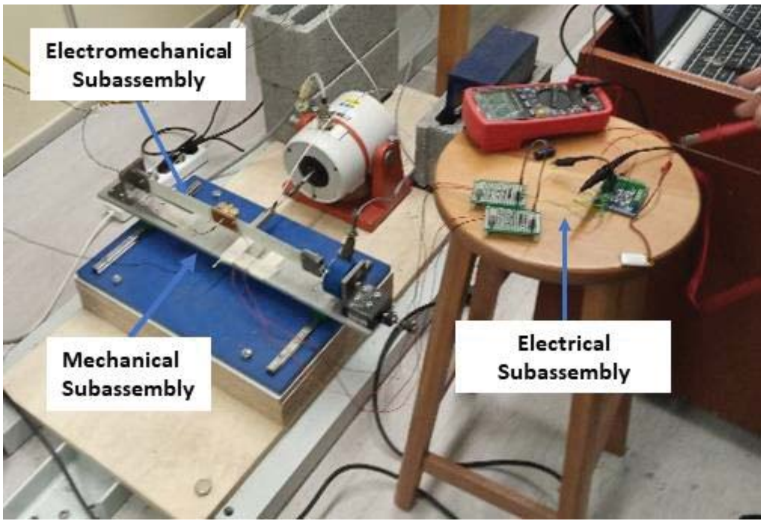

Figure 4 Electromechanical unit and harvesting circuit during laboratory testing

The electromechanical system was equipped with the following sensors for the performance study in laboratory environment; (1) a load cell between the shaker and the base plate, (2) an accelerometer bonded on the specimen to measure the lateral acceleration (3) an accelerometer bonded on the aluminum plate and (4) a non-contact LVDT to measure the static lateral displacement of the beam. As the electromechanical subsystem is operating in the post buckling regime the testing procedure is performed in two steps, based on previous laboratory investigations[21].

- First, the post-buckling regime of the beam was determined by studying its modal frequency, which is affected by the axial compressive load applied. At buckling, the modal frequency is minimal and rises at higher load (post- buckling). The modal frequency was extracted from the measured FRF, where the stimulus signal was the applied force from the shaker on the base plate and the response was the measured acceleration on the specimen. The applied actuation signal was white noise in the frequency range 0-200 Hz. Since no axial displacement or force is measured, the prestress level was measured via an non-contact laser LVDT
- At a second step, which is the step of dynamic response and harvesting, the beam was subjected to a sinusoidal base excitation at 8 Hz and 1g. The values of frequency and acceleration considered are typical for the excitation induced on wind turbine blades in operation.

Figure 5 illustrates measurements of modal frequency versus lateral displacement generated due to the applied axial prestress of the beam for determination of its post-buckling regime. Previous tests performed on a similar composite piezoelectric beam on the same lab configuration[21] indicated that the harvested power is maximal deep in the post-buckling regime, whereas further prestress increase leads to its drastic decrease [20].

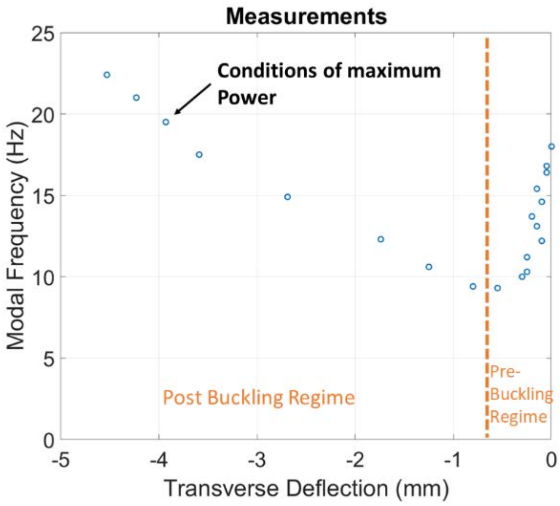

Figure 5 Transverse displacement measured with the laser LVDT versus modal frequency at each loading step.

Dynamic tests were performed on the PEH at the prestress levels identified from the calibration process. At each dynamic test, a sinusoidal base acceleration was applied at a constant excitation frequency below 20 Hz. In Figure 6 typical dynamic response of the harvester is shown by means of deflection and velocity at center, and voltage at piezoelectric patch terminals and circuit capacitor. In the latter case predicted results are compared with measurements.

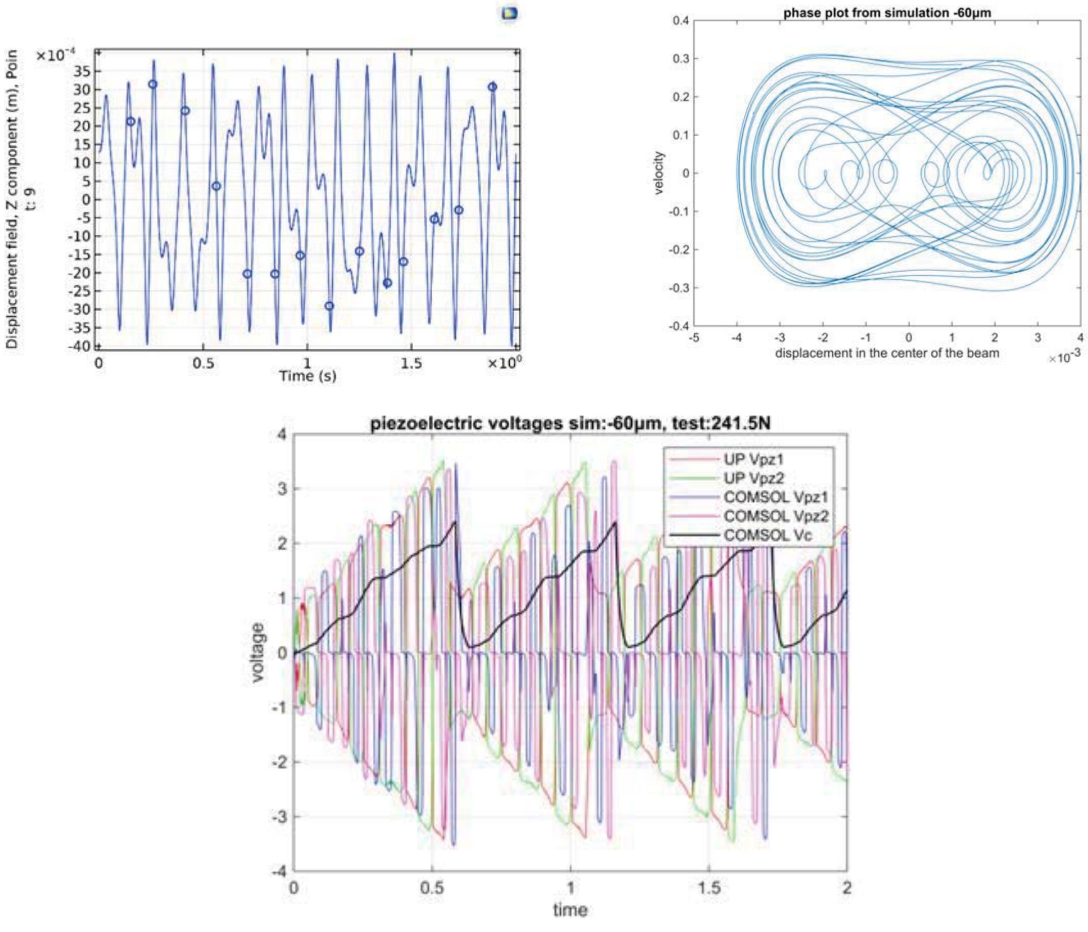

Figure 6 Typical bistable dynamic response of the PEH at a high-power post-buckling regime [20].

The harvested power from the PEH circuit is calculated using the energy guided to the output of the discharging subcircuit between two timestamps as,

$$P(t)=\frac{\int_{t_1}^{t_2}V(t)I(t)dt}{t_2-t_1} \tag{1}$$

where V and I indicate voltage and current in the capacitor discharging subcircuit [19]. Figure 7 illustrates measured and FE predicted power for a time range of 0-2s, indicating a similar increasing trend with increasing prestress in simulation and test up to a certain prestress level, where there is a sudden drop in harvested power as well as the beam oscillatory stroke.

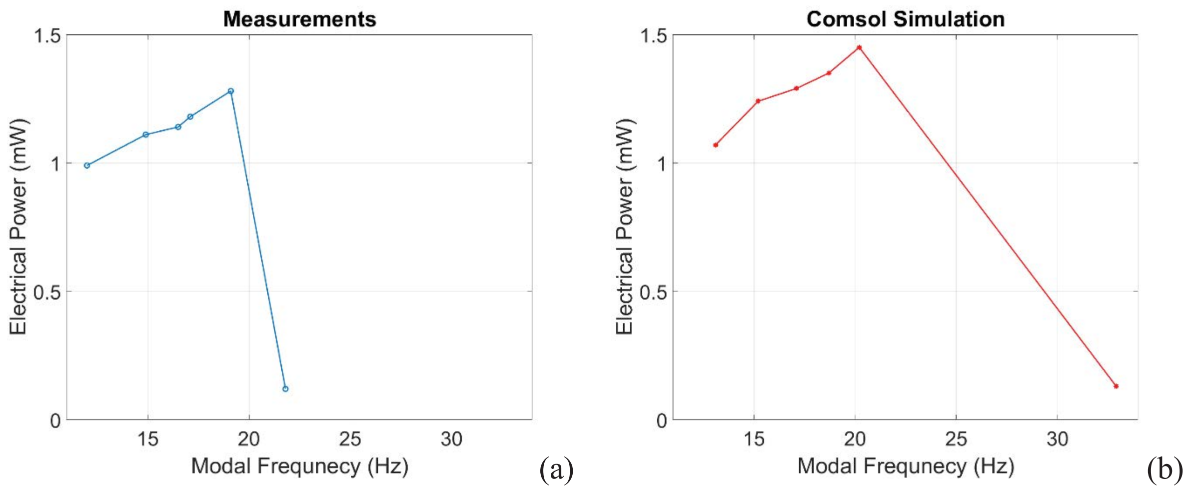

Figure 7 Produced electrical power as a function of the electromechanical subassembly 1st bending modal frequency (a) Measured data and (b) COMSOL simulations

6 CONCLUSIONS

A potentially power autonomous setup for the uninterrupted structural monitoring of a wind turbine blade was presented. The system is composed from a PEH unit, which power supplied the external dynamic strain data acquisition and transmission unit. Investigation of the performance of the PEH unit indicated that prestress calibration by means of modal frequency is essential, providing the appropriate post buckling condition and thus maximizing power harvesting. At post-buckling, the harvested power increases with prestress up to a transition point and after this point the power drops off drastically. The FE model accurately captures the gradual increase of the harvested power; however, it overestimates the transition point due to deviations with respect to the physical boundary conditions.

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