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Dynamics identification of a piezoelectric vibrational energy harvester by image analysis with a high speed camera ☆

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A B S T R A C T

This study investigates dynamic responses of a nonlinear vibration energy harvester. The nonlinear mechanical resonator consists of a flexible beam moving like an inverted pendulum between amplitude limiters. It is coupled with a piezoelectric converter, and excited kinematically. Consequently, the mechanical energy input is converted into the electrical power output on the loading resistor included in an electric circuit attached to the piezoelectric electrodes. The curvature of beam mode shapes as well as deflection of the whole beam are examined using a high speed camera. The visual identification results are compared with the voltage output generated by the piezoelectric element for corresponding frequency sweeps and analyzed by the Hilbert transform.

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1. Introduction

Power supply networks for sensors and data transmission are widely used in industrial processes and structural health monitoring. In the conventional approach, wire connections to power supply or battery exchange are required. Since all measuring points must be wired, this approach is expensive. New developments in the field of monitoring include minimization of the number of wires and addressing devices as well as reduction of power consumption [1,2]. An additional difficulty is to maintain connections, which may require the use of an additional equipment. In this context, the use of ambient vibration energy can allow for powering autonomous measuring devices. The source of vibration can be natural processes such as wind and sea level movement; vibration can also be generated by vibrating parts of machines, vehicles and other technical objects. New methods for monitoring conditions in an urbanized environment (industrial processes, road and rail transport) [2] offer a great potential thanks to the implementation of self-powered sensors.

One way to obtain fairly high-density energy converted from the environment is to use piezoelectric elements attached to the elements of deformable continuous objects such as cantilever beams [3]. Other solutions based on electrostatic, electromagnetic or magnetostrictive laws are also considered and tested [3–5]. The performance of piezoelectric harvesters depends on the operating conditions such as the frequency and amplitude of deformation and their mode shapes. Recent studies point to the role of nonlinearities [4,6–8] as a cause of frequency broadening in the vicinity of harvester resonance [9,10]. This phenomenon is forced by inherent variable working ambient conditions (excitation conditions) that are frequently determined as periodic excitations with a modulated frequency and/or amplitude or even random character

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[11,12]. In light of the above, we decided to conduct experimental tests on a flexible nonlinear beam system [13–15] working with a piezoelectric transducer. In our mechanical resonator, which was excited kinematically, we included the vibro-impact system properties [17] and double equilibria with clearance [18]. The results of voltage output are compared with the visual data on the beam bending to account for the appearance of voltage peaks in the final system response.

2. Experimental setup

This study was conducted using an inverted pendulum-like system mounted in a rotary trolley handle, capable of reciprocating movements in the horizontal axis (Fig. 1).

The pendulum movement (beam rotation) was limited by the use of bumpers located at the vicinity of the beam holder with a spacing of $d = 8$ mm. The pendulum was a rectangular cross section of elastic material, with a piezoelectric element placed on its surface, above the contact place with the bumpers. The beam handle was driven by an electric motor controlled by a microprocessor system enabling the programmed reciprocating motion with constant or variable frequency and amplitude. A photograph of the experimental stand is shown in Fig. 1, while the geometrical and mechanical properties of the system are listed in Table 1.

The concept of tracking point trajectories identification by means of a high speed camera is illustrated in Fig. 2. The color image captured during the experiment was processed through recognition markers (tracking points). The tracking algorithm was based on subsequent video frames, where the distinction between the tracking points was important for accurate displacement and shape bending consideration in the time domain. Fig. 2 shows an example of the tracking process by the marker points along the beam. The black-and-white pattern on the left shows the calibrated linear dimensions. The shape of the resulting trajectories depends on the stage of the experiment. At the onset of the experiment, the trolley moves fairly slowly and does not cause the beam to rotate. Consequently, at this stage of the experiment, the tracking lines are horizontal, which reflects horizontal excitation.

The example in Fig. 2 shows another stage of the experiment recorded when the beam was rotating around the handle (this is particularly visible at the end point of the beam). For this reason, the overlapping trajectories form smeared symmetric clusters (denoted as A in Fig. 2). The range of the trajectory of rotation around the end positions of the trolley is shown schematically in the bottom left corner of Fig. 2. The additional narrowing visible in Fig. 2 (denoted as B) is the result of the beam's bending after collision with the amplitude limiters. The marker located at the bottom of the figure indicates a horizontal trajectory reflecting a linear motion of the trolley. The processed images were used to measure the distance between points No. 1 (upper end of the beam) and No. 2 (axis of rotation of the beam holder), which can be called a beam cord.

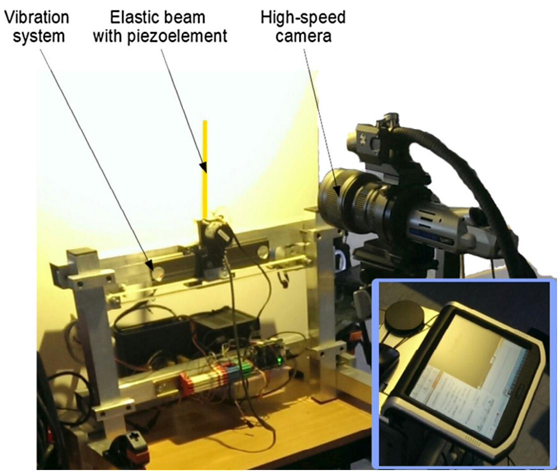

Fig. 1. Energy harvesting system with flexible beams for high-speed video recording. The inset shows an image on the camera.

Table 1
Material and geometrical properties of the beam and piezoelectric component.

Ultimate tensile strength (ASTM D638)	7.5 MPa
Youngs modulus (ASTM D638)	480 MPa
Elongation at break (ASTM D638)	3–5%
Typical parts density	0.85 g/cm^3
Beam dimensions (width × thickness × length)	16.6 × 3.2 × 195 [mm]
Natural vibration of elastic beam	First mode at 9–11 Hz depending on the tip mass
Piezoelectric capacity (MFC M8514-P2)	$C_p = 84.04$ nF

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