BistableX: Bistable eXploration in Energy Harvesting

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Experimental Setup

The experimental apparatus consists of four main components: a supporting structure, a clamping device, an instrumented piezoelectric beam, and a system of rotatable neodymium magnets.

The **supporting structure** is a lightweight aluminum frame, assembled in two parts, designed to provide a rigid foundation while allowing both linear translation and adjustable rotation of key components. This structure ensures mechanical stability during testing.

A **clamping device** is employed to securely fix one end of the piezoelectric coupled beam, replicating a clamped boundary condition. The device is designed to eliminate any unwanted deflection or slippage at the clamped end, ensuring repeatability and consistency of the measurements.

The core of the system is an **instrumented piezoelectric beam**, composed of a spring steel substrate with dimensions of $145 \times 25.4 \times 0.25$ mm^3. Piezoelectric patches (MIDÉ qp16n) are bonded to both sides of the beam using a high-shear epoxy adhesive (3M DP460N), providing reliable mechanical coupling. The piezoelectric elements are electrically connected in parallel across a load resistor of $R_L = 10^6 \Omega$. To lower the beam's natural frequency and enhance the effects of magnetic interaction, two rigid steel lumped masses are symmetrically attached near the free end.

Nonlinear restoring forces are introduced via **rotatable neodymium magnets**. Two cylindrical permanent magnets are housed in 3D-printed adjustable holders that enable precise control of both the linear position and angular orientation of each magnet relative to the beam. The magnets interact attractively with the steel masses at the beam's free end, establishing stable equilibrium points through magnetoelastic coupling. By independently adjusting the position and rotation of each magnet holder, both symmetric and asymmetric magnetic configurations can be achieved, allowing systematic exploration of different dynamic behaviors.

The supporting structure is mounted on an electromagnetic shaker (TIRA Vib Modal Exciter S 51110-M) equipped with an adjustable base. Three different measurements are employed to characterize the system's dynamic and electrical responses:

Acceleration Measurement: An ICP® miniature accelerometer (PCB model 352A24, sensitivity: 98 mV/g, range: 0.5 g) is attached directly to the base of the piezoelectric coupled beam (clamping device) to measure the input acceleration.

Voltage Measurement: The voltage generated across the load resistor by the piezoelectric bimorph layers is monitored to assess the electrical output of the system.

Velocity Measurement: A single-point laser Doppler vibrometer (Polytec OFV-505) records the absolute velocity at a point near the beam tip. To improve the signal-to-noise ratio, a small reflective tape is affixed to the beam surface. The vibrometer is mounted on a tripod, ensuring a stable line of sight even when the base undergoes rotation.

Figure 1 shows the experimental setup, detailing each component of the system and illustrating various configurations obtained through rotation of the magnets and/or the shaker base.

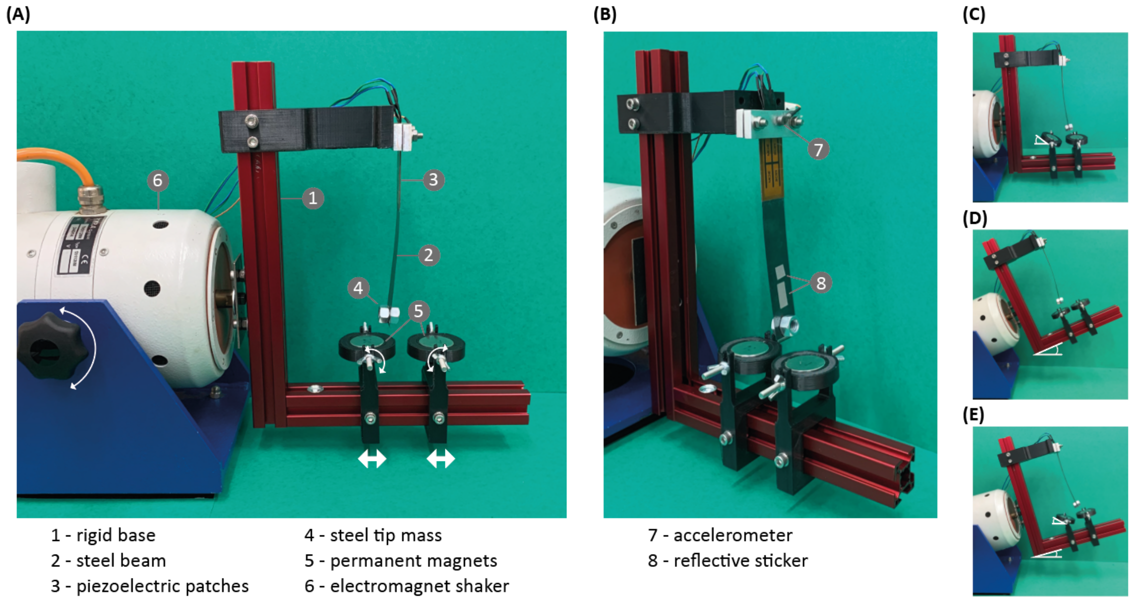

Fig. 1 – Experimental setup of the piezoelectric coupled beam mounted in an electromagnetic shaker to perform vibration testing.

Figure 2 illustrates the signal flow diagram. The DAQ system (LMS SCADAS Mobile) generates the excitation signal, which is fed into a TIRA BAA 500 power amplifier and subsequently delivered to the shaker. Simultaneously, the DAQ system acquires data from the accelerometer, the piezoelectric voltage output (measured using 10× attenuation probes), and the vibrometer (after signal conditioning through the Polytec OFV-5000 control unit). The base acceleration signal is routed to the DAQ's reference channel via ICP coupling. All signals are synchronized and recorded through a computer running LMS Testlab software, which interfaces directly with the DAQ system.

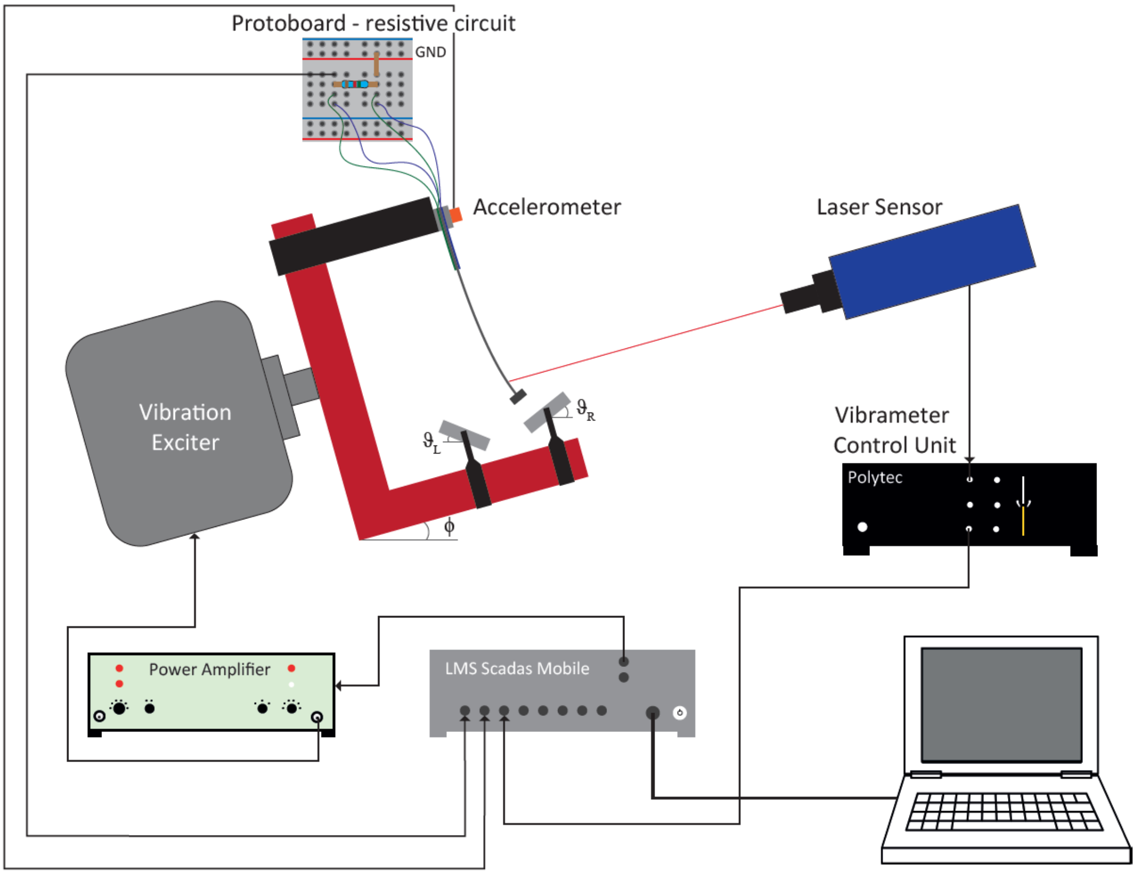

Fig. 2 Schematic diagram of the experimental setup and signal flow.