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DYNAMICS OF A CANTILEVER BEAM WITH PIEZOELECTRIC SENSOR: EXPERIMENTAL STUDY

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Abstract: *Online and real-time sensing and monitoring of the health state of complex structures, such as aircraft and critical parts of power stations, is an essential part of the research in dynamics. Several types of sensors are used for sensing dynamic responses and monitoring response changes during the operation of critical parts of complex systems. The piezoelectric (PZ) materials belong to one group of electroactive materials, which transform mechanical deformation into an electrical response. For example, PZ ceramics or PVDF foils are employed for online sensing of the time history of mechanical deformation. Experimentally obtained response of a cantilever beam structure with a glued PZ sensor is the case of interest in this contribution. During the transient problem of the beam loaded by suddenly interrupted load due to the weight of a mass at the end of the beam, the time history of normal velocity at a point on the beam surface has been measured by a laser vibrometer and parallely, the output voltage on the PZ sensor has been measured by an electric device. The experimental data in the case of the first eigen-frequency is in good agreement with the value given by the formulae from the theoretical modeling of free vibration of a linear beam.*

Keywords: Dynamics of beam-like structure, Piezo-electric material, Sensing of dynamic response, Structural Health Monitoring, Laser vibrometer measurement.

1. Introduction

Today, structural health monitoring (SHM) plays an important role in sensing and evaluating of state of structures such as aircraft, bridges, power stations, etc., see (Worden, et al.). In these cases, the dynamic responses are sensed over time using periodically sampled response measurements to monitor changes to the material and geometric properties.

Often, smart materials are used to sense mechanical responses, see (Bengisu and Ferrara, 2018). Smart materials, also called intelligent or responsive materials, are designed materials with properties that can be significantly changed in a controlled way by external stimuli, such as stress, electric or magnetic fields, etc. Some examples of smart materials are piezoelectric materials, shape-memory alloys, electroactive polymers, electrostrictive materials, magnetostrictive materials, and others, see the book (Shahinpoor, 2020). These materials and structures made of these materials are used for sensing dynamic events. For example, piezoelectric materials are employed for sensing mechanical events and energy harvesting and are also used for electro-mechanical actuation.

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In this contribution, we study the dynamic response of a beam via the piezoelectric sensor glued on this structure. This study presents initial work oriented on the dynamics of metamaterials made of 3D printed structured, including PZ actuators and sensors.

2. Problem definition

We study a dynamic response of a steel cantilever beam loaded by suddenly interrupted load due to the weight of a mass at the end of the beams. The experimental setup is shown in Fig. 1. A beam structure in the shape of a strip is attached to a robust holder.

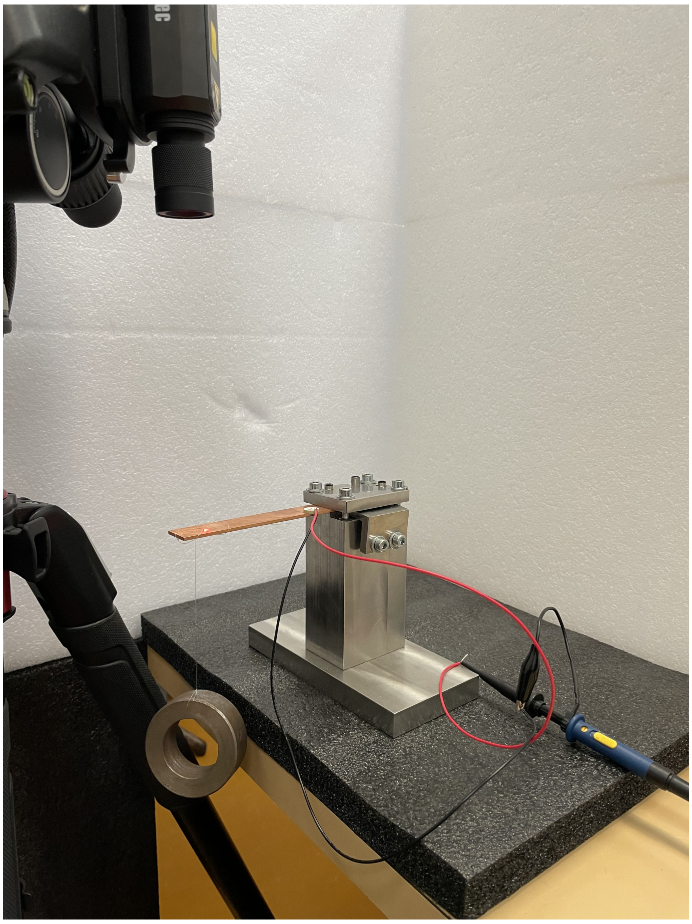

Fig. 1: Experimental setup for sensing of dynamic response of a beam structure on suddenly interrupted load due to the weight of a mass positioned at the end of the beam. A beam structure is attached in a robust holder.

The beam is pre-deformed due to the static force given by the weight of an object with a mass 0.28 [kg], which is tied to the beam by a nylon line at the end of the beam. The force corresponding to the mass object is F = 2.75 [N]. Initially, the nylon line was cut, and the beam vibrated. The dynamic response of the beam is observed via a piezoelectric sensor disc and a laser vibrometer. On the PZ sensor, the voltage on the electrodes is measured, and by laser vibrometer, the normal component of the velocity of a point on the beam surface is measured. The dimensions of the beams and positions of the PZ sensor and laser spots are depicted in Fig. 2.

The material of the beam has been chosen as mild steel. The length of beam structure was 150 [mm], the width $b = 20$ [mm] and thickness $h = 2$ [mm], where the active length of the beam is $L = 102$ [mm]. The figure of the beam structure in the holder is shown in Fig. 1.

3. Experiments

For sensing the dynamic response of the beam, the piezoelectric sensor-disc of diameter 10 mm and thickness 2 mm made of material PIC 181 (company PI, https://www.piceramic.com/) is used. The voltage on

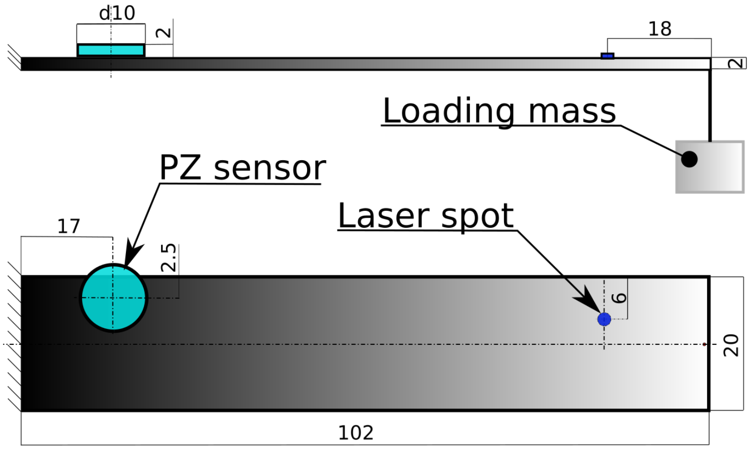

Fig. 2: Scheme of experiment with dimensions and positions of PZ sensor, laser spot and loading mass.

Ag screen-printed electrodes of the PZ sensor was measured by the oscilloscope Picoscope 3404D. PIC 181 is a modified lead zirconate – lead titanate material with an extremely high mechanical quality factor and a high Curie temperature. This material is destined for use in high-power acoustic applications. Furthermore, the good temperature and time stability of its dielectric and elasticity constants make it suitable for resonance-mode ultrasonic applications. It has proved to be particularly successful in piezo-motor drives. Other important parameters of the sensor are the resonant frequency (in the thickness direction) 10.550 [kHz], Resonant frequency (radial mode) 227 [kHz], and Electrical capacitance 0.435 [nF].

For the measurement of velocity, the Polytec CLV-2000 vibrometer with the CLV-700 sensor head was used in this experiment. The laser was attached to a tripod, which was extended above the measured beam. The laser beam was aimed at the beam at a distance of 30 cm. In this case, a reflective label-marked was glued to the beam surface, at the position depicted in Fig. 2, for sufficient reflection of light from the surface, since the material itself did not achieve the quality of reflected light that would be optimal for measurement. The quality of the reflected light was monitored on the input module located on the front of the CLV 2000 unit.

4. Outputs of the experiments

Based on experimental measuring, the time history of the voltage sensed by the PZ sensor is shown in Fig. 3, and the time history of the normal velocity at the laser spot is drawn in Fig. 4. One can also see details of the time histories in these figures. Based on the signal processing of experimental data by the fast Fourier transformation in the software MATLAB, the first eigen-frequency of the structure is obtained as $f_{1,measured} = 159.4\ [Hz]$.

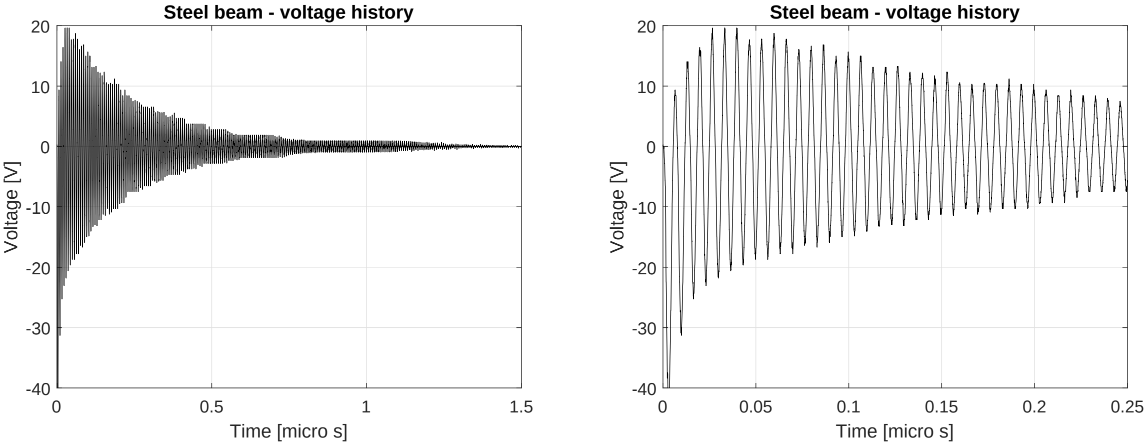

Fig. 3: Time history of the voltage sensed by a PZ sensor.

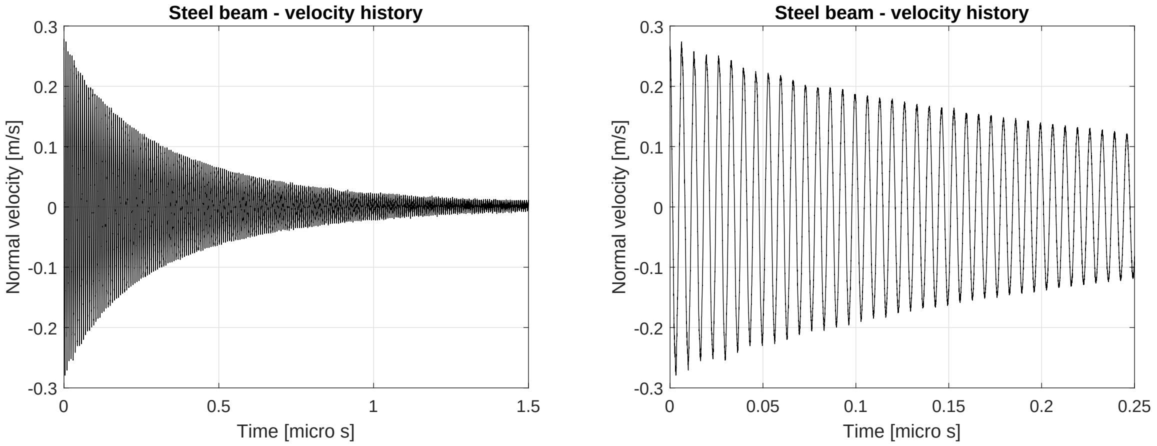

Fig. 4: Time history of the normal velocity at a laser spot.

Also, one can estimate the first eigenfrequency from an analytical model of linear undamped vibration of the cantilever beam from the Bernoulli–Navier hypothesis. The analytical solution to this problem is found in the book of Rao (Rao, 2006), where the value of the first eigen-frequency is computed as

$$f_1 = \frac{1}{2\pi}(\beta_1 l)^2 \sqrt{\frac{EI}{\rho A L^4}}, \tag{1}$$

where $(\beta_1 l) = 1.8751$, the second moment of area $I = \frac{1}{12} b h^3$, the cross area $A = bh$, the mass density of steel $\rho = 7800$ $[kg/m^3]$ and Young's modulus $E = 210$ [GPa]. For that values, the first eigenfrequency is evaluated as $f_{1,\,analytical} = 161.1$ $[Hz]$. The analytical value of the first eigen-frequency is greater than the measured value of the first eigen-frequency around 1.7 [kHz].

5. Conclusions

In the contribution, the electric signal from the PZ sensor of deformation and dynamic response by laser vibrometer have been measured on the experimental stand of the beam-like structure. From that data, the first eigen-frequency has been analyzed. Also, for the structure, we can compute the analytical value of the first eigen-frequency. The experimental result is very close to the analytical value. The difference is given by the damping effect on the experimental side, where the eigen-frequency of the damped system is smaller than the undamped one, see (Rao, 2006). The results agree with the numerical study presented in (Cimrman et al., 2023), where the coupled numerical simulation of the problem of interest is realized.

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