A high-resolution fully inkjet printed resonant mass sensor

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Abstract

The rapid prototyping of low cost sensors is assuming a strategic importance in several application fields.

In this paper a fully inkjet printed mass sensor is proposed. The device consists of a PET(poly-ethylene terephthalate) cantilever beam, which is driven to its resonant mode by an electromagnetic actuation mechanism, implemented through the interaction between a current impulse flowing through a planar coil (inkjet printed on the PET beam), and a permanent magnet, facing the actuation coil. Target masses are positioned close to the beam end.

The sensing methodology, based on the relationship between the beam first natural frequency and the target mass, is implemented through a Strain Gauge (inkjet printed across the fixed end of the cantilever).

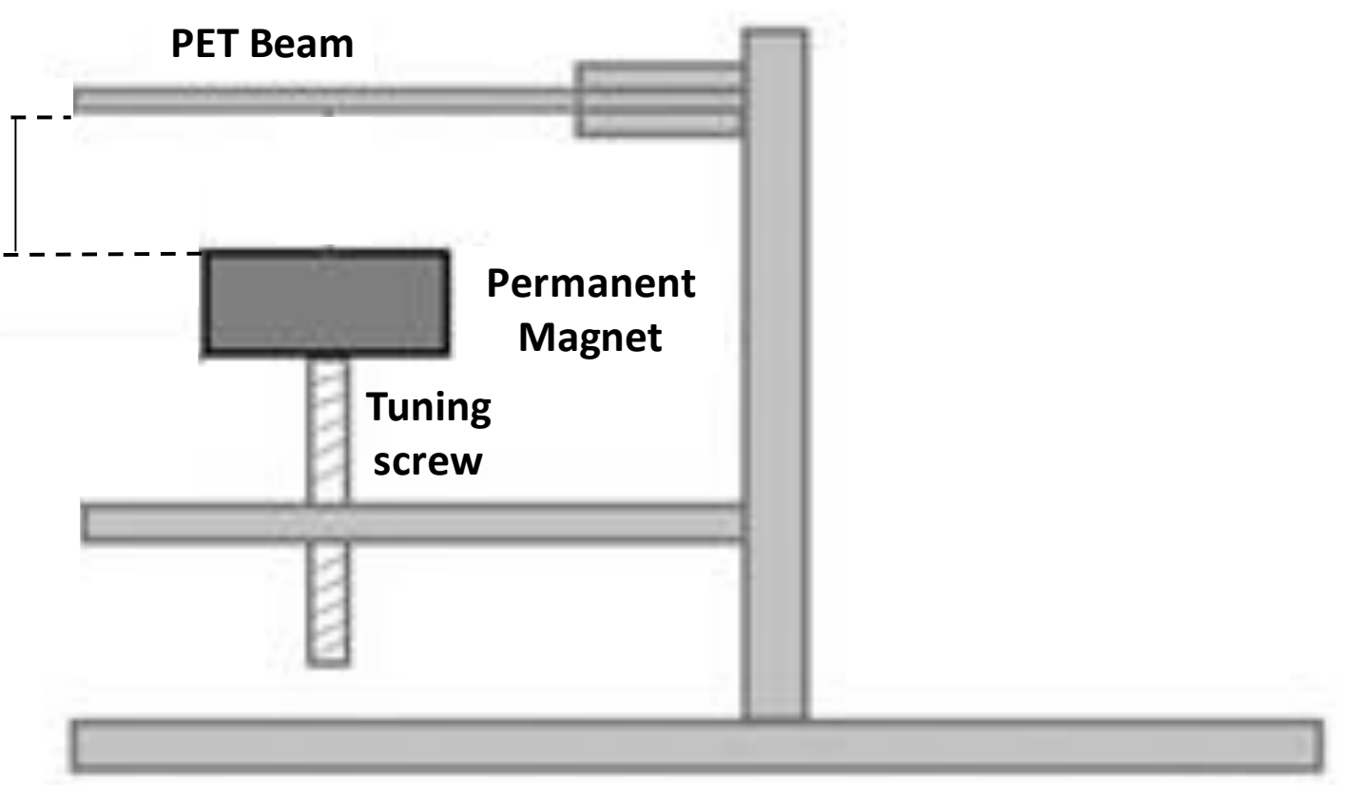
The resonant operating mode of the sensor confers intrinsic robustness against instabilities of the strain sensor structure (e.g. the residual stress of the cantilever beam), the target mass material and the magnet-coil distance. The latter indeed changes as a function of the target mass values. The friction-less actuation mode is another shortcoming of the sensor, as well as the low cost feature arising from the adopted technology. As far as we know, the solution proposed is the first example of a low cost fully printed mass sensor.

The operating range of the device is [0-0.36]g while its resolution is in the order of 1.0 mg, thus addressing crucial application fields. A Q factor around 35 has been estimated, which confirms the suitable performances of the sensor in term of selectivity and resolution.

Sensing Methodology

The PET cantilever beam is driven to its first natural mode by exploiting the interaction between a permanent magnet, placed at a distance d from the beam, and a coil that has been inkjet printed on the end part of the beam. The magnet position can be modified to investigate the system behavior for different values of the force applied to the beam. Target masses are positioned close to the beam end. The beam is forced with an impulse signal which brings the structure to its oscillating regime. The sensing mechanism is based on the variation of the beam natural frequency (more specifically, its first natural frequency) as a function of the target mass. The beam dynamic is observed by a strain gauge, which has been inkjet printed on the cantilever beam close to the fixed-end.

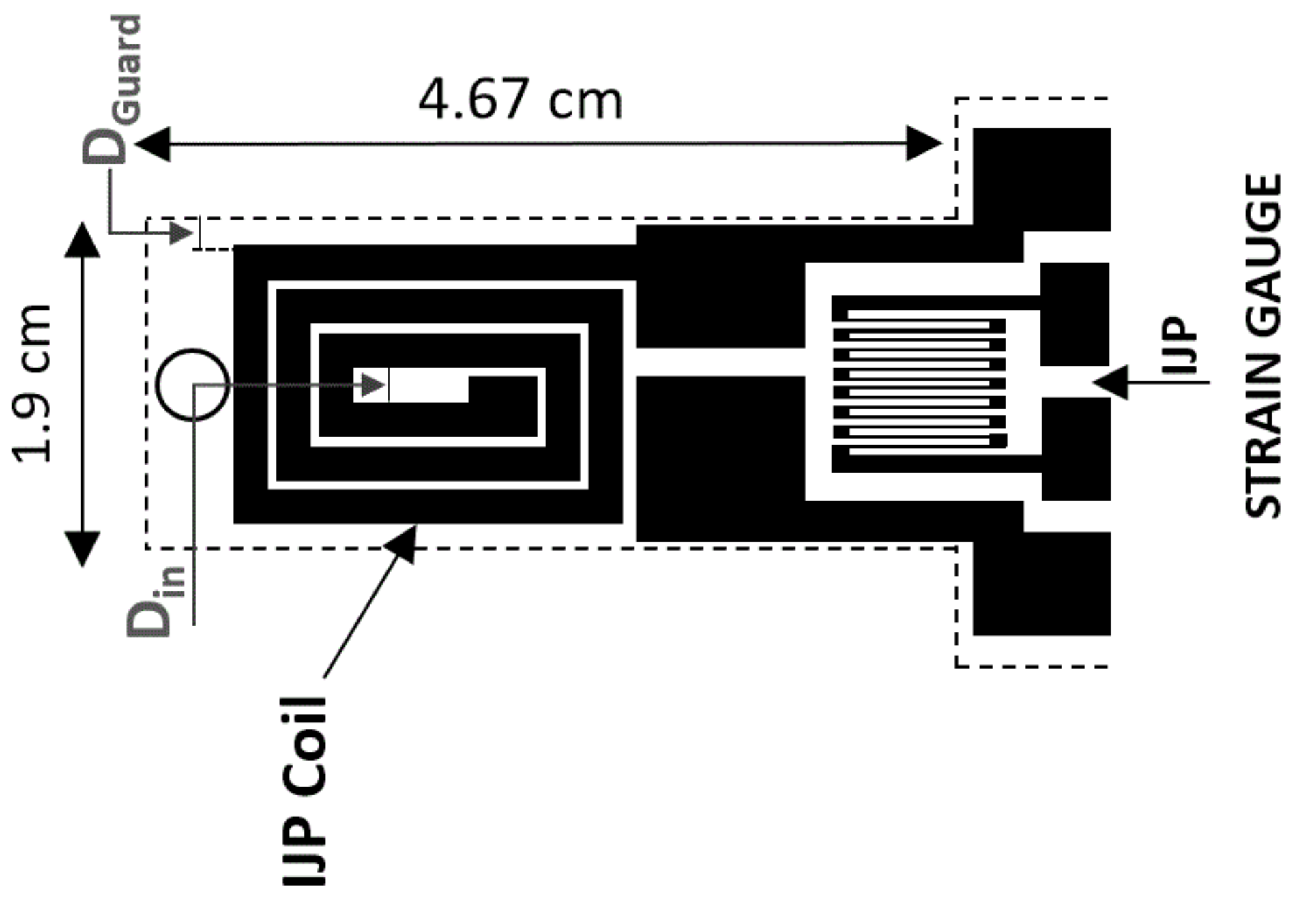
To cope with specific applications requiring accurate measurements of small masses, the operating range of the device has been fixed in the range of tens of milligrams. The beam dimensions have been fixed by the application, as discussed in the next section.



Schematization of the mass sensor architecture

Technology

The device has been realized on a PET substrate, with a thickness of 120 µm, by using a low-cost EPSON piezo inkjet printer and the silver nano-particle solution "Metalon® JS-B15P" by Novacentrix. Curing post-processing has been performed at 90°C for 1 hour. Dimensions of the beam are given in the figure. The beam's width, *Wb*, is fixed to cope with the needs of properly fixing the target mass on the sensing area and to design a suitable strain sensor. The cantilever length, *Lb*, has been fixed to allow the realization of both the strain sensor and the actuation coil, according to constraint provided by the adopted IJP technology.



The layout of the inkjet printed components.

The sensor design: simulation results

The strain sensor has been designed to capture the main curvature area of the beam. The track spacing and width adopted for the SG realization are the minima allowed by the adopted technology, 300 µm and 200 µm, respectively. The GF and the resistance of the IJP SG are 1,68 and Ro=226Ω, respectively.

The coil design, in terms of the number of turns and the coil track width, *Wc*, is strictly constrained by:

- the beam dimensions, with particular regards to the actuation section of the beam (close to the beam free end);
- the required current to produce, in the whole range of the sensor operation (tens of milligrams), a suitable beam deflection.

To such aim, the behavior of the actuation system has been simulated for different values of the driving current *I* and *B*.

The magnetic force, F_m, acting on the beam structure is given by: $F_m = k * I * L_{tot} * B$

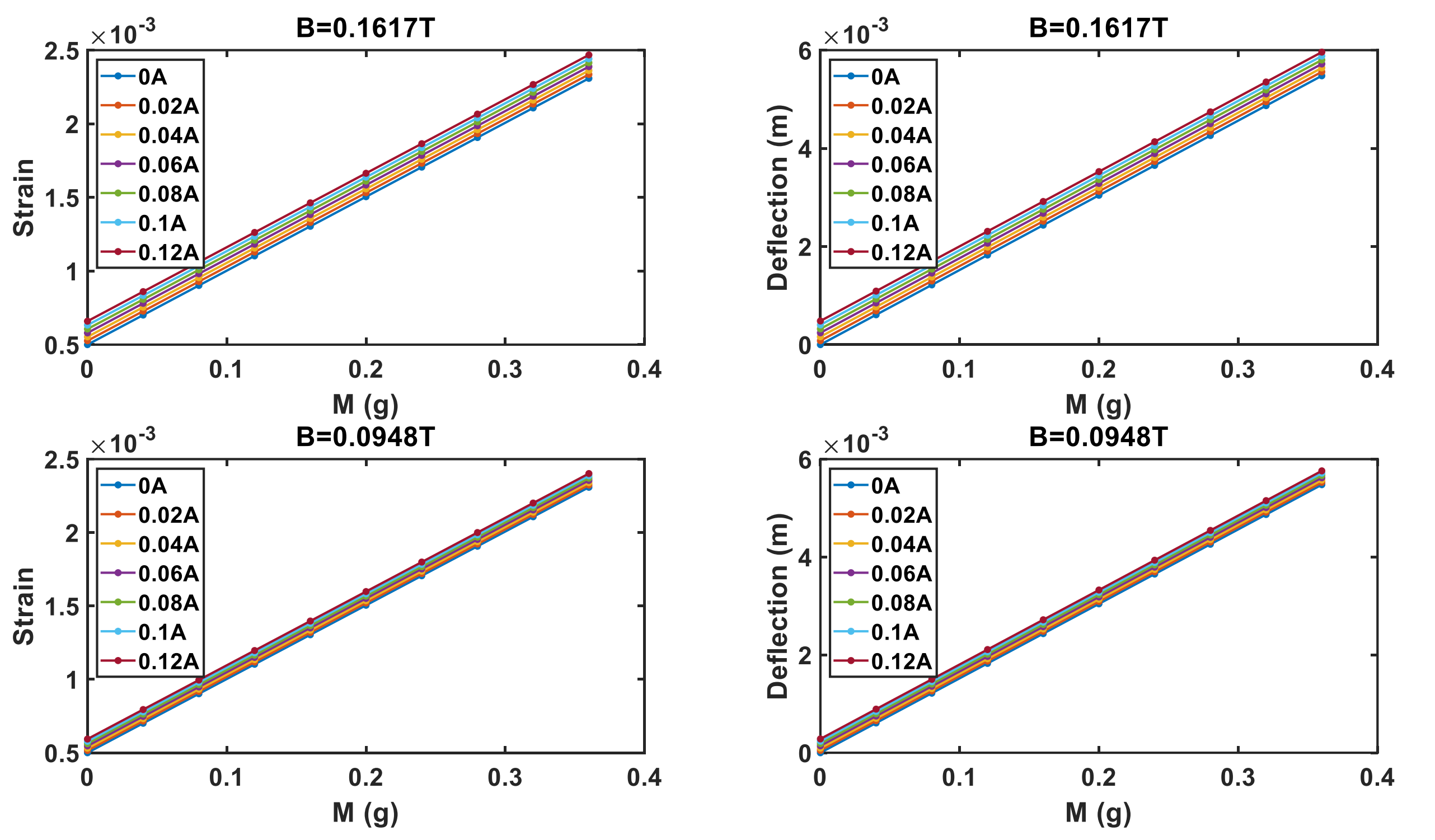
where: I_d is the driving current flowing through the coil; *B* is the magnetic field; L_{tot} is the total coil length, *k* is a fitting parameter taking into account the non-ideal coupling between *B* and *I*.

The deflection, *D*, and the strain, *S*, at the free end of the cantilever beam are: $D = \frac{F * L_b^3}{3 * E * J}$ $\quad S = \frac{6 * F * L_b}{E * W_b * T_b^2} + S_0$

where:
E=2.0 10^9 N/m^2 is the Elastic module of the PET beam;
T_b=120.0 µm, is the PET thickness;
L_b is the cantilever length;
F=Mg, being *M* the target mass and *g* the gravity acceleration;
S_0=500 µε is the offset strain measured at the free beam end in case of null *I*, *B* and *M*;

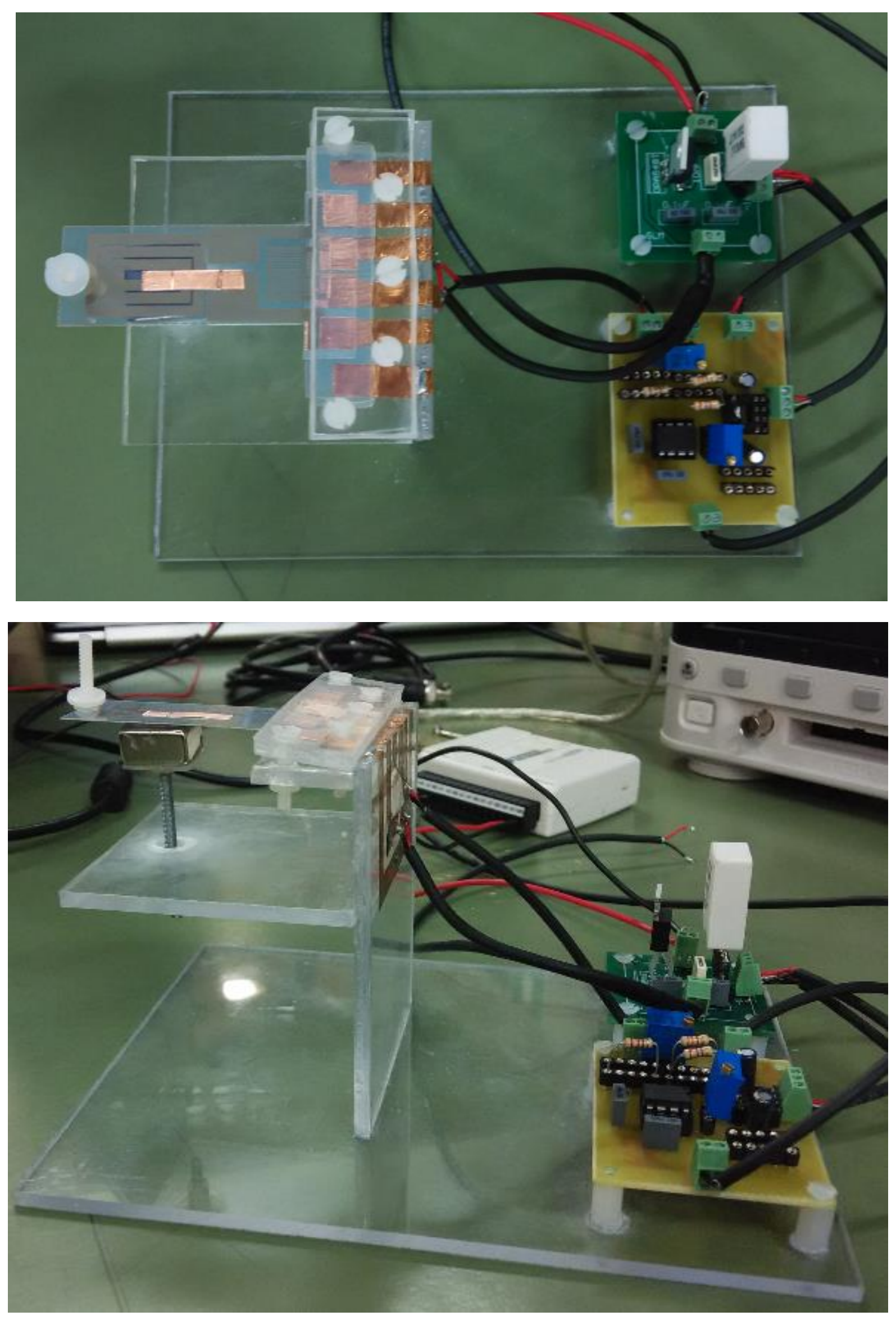
$J = \frac{W_b T_b^3}{3}$ is the moment of inertia.

Simulation results have shown that a coil track width of 2 mm is the minimum assuring a good compromise between the desired driving force intensity (producing a substantial readable strain of the beam and a deflection compliant with the structure geometry) and the possibility to investigate the sensor behavior for driving current values up to 100 mA.



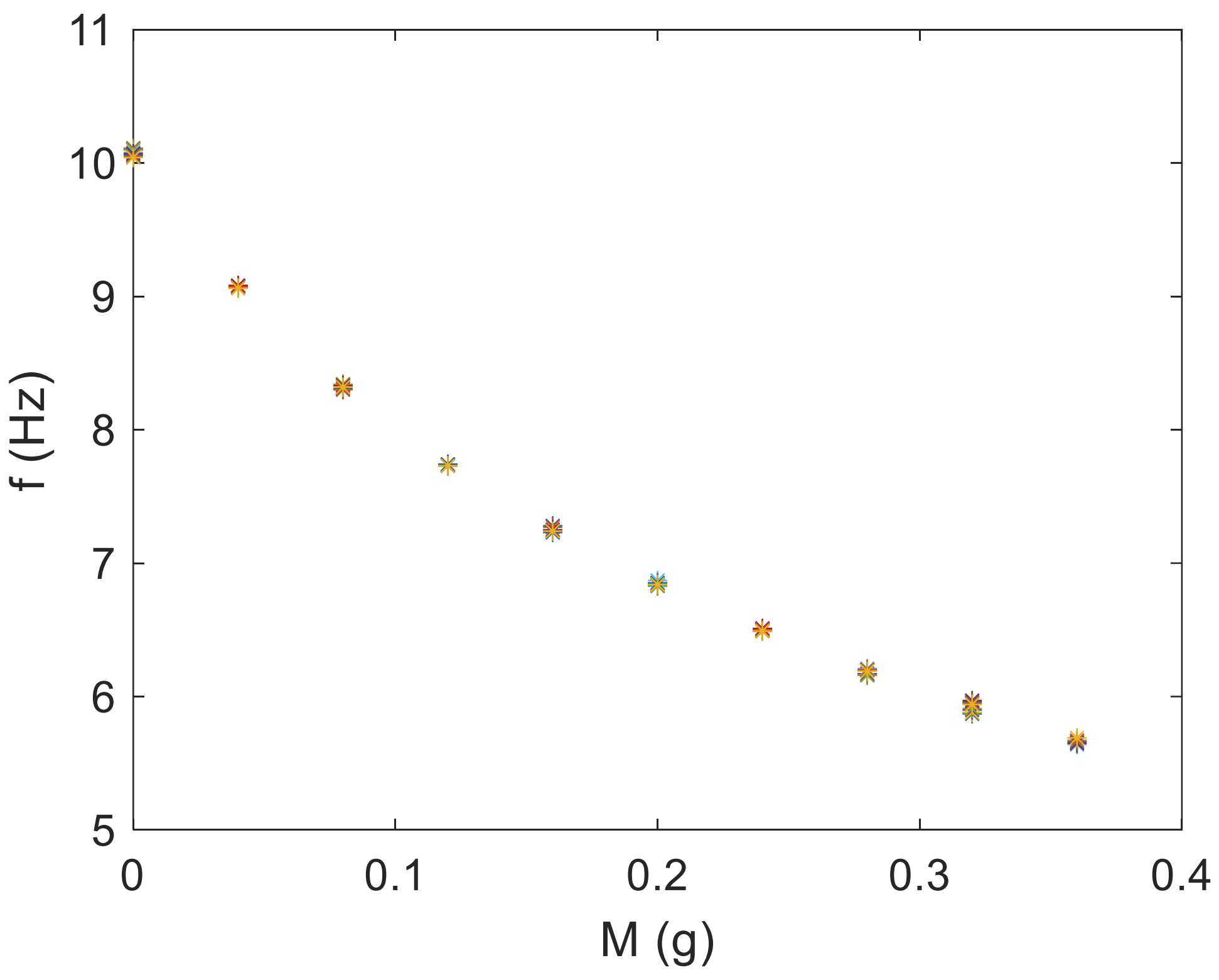
The beam strain and deflection in case of a track width of 2 mm, as a function of the target mass, for different values of I and the two values of B.

Experimental Results

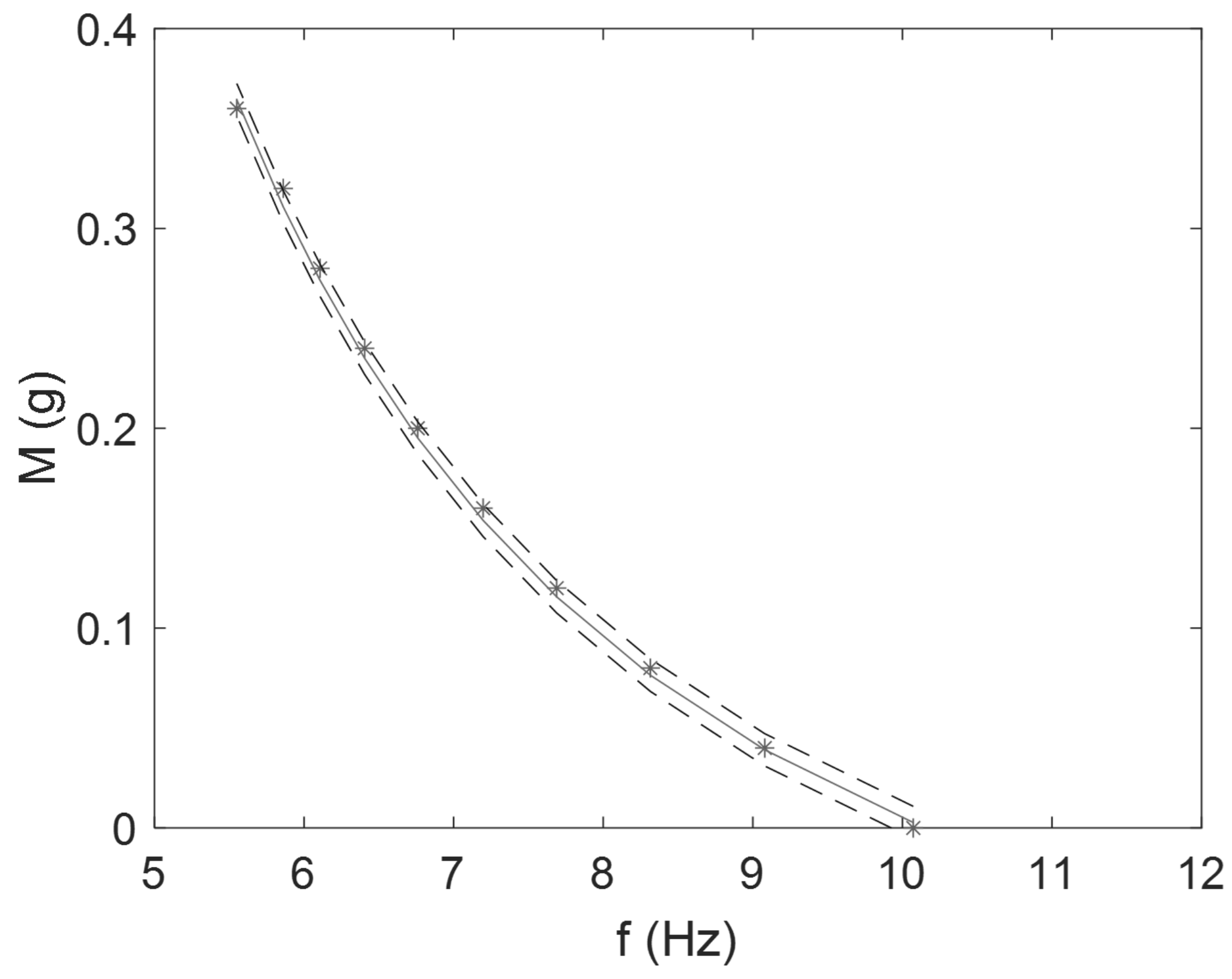


The real device and the adopted experimental set-up.

It has been observed that the sensor response, in terms of natural frequency, is practically insensitive to the different operating conditions (magnetic field and driving current).
Based on the observed behavior, the most convenient actuation mode is the one exploiting the lowest magnetic field (allowing for a wider operating range) and current, being 0.0948 T and 20 mA, respectively.



The behavior of the sensor for different values of the driving current and two values of the magnetic field.

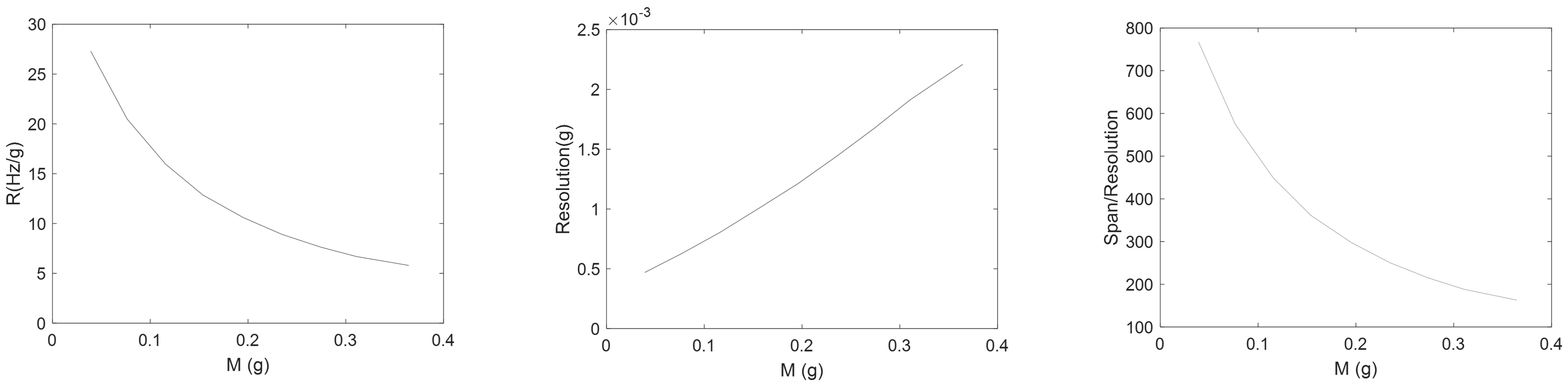


The sensor calibration diagram in the operating conditions B=0.0948 T and I=20 mA.

The following model has been used to interpolate the observed behavior of the beam natural frequency:

$$f_{beam}^{mod} = \alpha \sqrt{\frac{1}{M + m_0}}$$

α takes into account the beam properties;
m_0 is the cantilever mass;
M is the target mass.



The responsivity, the resolution and the span-to-resolution of the sensor, in the operating conditions B=0.0948 T and I=20 mA.

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