Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 00 (2011) 000–000
Procedia Engineering
www.elsevier.com/locate/procedia

Proc. Eurosensors XXV, September 4-7, 2011, Athens, Greece

A Planar Resonant Structure Sensitive to Out-of-plane Forces

D. Desmaële [a,b,a*], M. Boukallel [a], S. Régnier [b]

[a]*CEA,LIST, Sensory and Ambient Interfaces Laboratory, 18 Route du Panorama, BP6, Fontenay-aux-Roses, F-92265, France*
[b]*Institut des Systèmes Intelligents et de Robotique, Université Pierre et Marie Curie, CNRS – UMR 7222, 4 Place Jussieu, Paris Cedex 05, 75252, France*

Abstract

We present a novel force sensor designed to facilitate force measurement deployment in various applications such as load cells or force sensitive surfaces. This force sensor can indeed inherently sense out-of-plane forces. It is a monolithic structure that integrates two resonators and provides a steady area. If a perpendicular force is applied on this steady area, a frequency shift of the two resonators occurs. The amount of force applied can thus be estimated by monitoring the frequency of the resonators. As a proof of concept, we report the fabrication and experimental characterization of a first prototype. Under atmospheric pressures, our prototype currently offers a quality factor of ~700, and a linear displacement sensitivity of ~5.75 Hz/µm. In addition, we report the implementation of a compact and low-cost optical fiber setup to monitor the resonators' frequency.

Keywords: Mechanical sensor; Triple beam resonator, Out-of-plane force measurement.

1. Introduction

As compared to strain-gauges based sensors, resonant sensors such as double-ended tuning forks (DETF) and triple beam tuning forks (TBTF) allow for higher force sensitivities. For instance, microfabricated DETF can resolve forces in the nN range in vacuum [1]. Nevertheless, DETF and TBTF reported so far can solely measure axial forces applied to their extremities. To measure out-of-plane forces (i.e., forces perpendicular to the sensor's plane), complex configurations [2] or mechanical converters

* Corresponding author. Tel.: +33 1 46 54 89 66; fax: +33 1 46 54 89 80.
E-mail address: denis.desmaele@cea.fr.

must be adopted [3]. To overcome this restriction, we present a force sensor designed to act as a surface that can inherently sense out-of-plane forces.

2. Sensor Description and Sensing Principle

As depicted in Fig. 1a, the proposed force sensor is a monolithic structure that incorporates two rectangular apertures. It is clamped at its extremities and it can thus be viewed as two cantilevers serially linked via three parallel beams, the central beam being wider than the two outer beams. To sense out-of-plane forces, a specific vibration mode is exploited. As illustrated in Fig. 1b, finite element analysis shows that the proposed design provides an antisymmetrical vibration mode where the two outer beams oscillate in antiphase, whereas the central beam remains immovable.

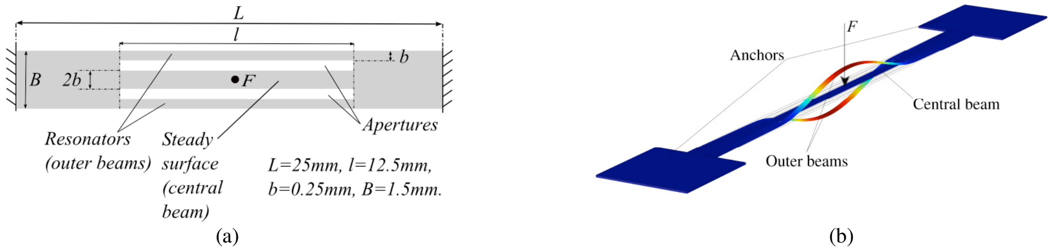


Fig. 1. (a) Top view of the proposed triple beam force sensor; (b) Vibration mode exploited for sensing an out-of-plane force *F*.

This central steady beam can hence act as a force sensitive surface. Indeed, if a static force *F* perpendicular to the structure's plane is applied to the half span of the central beam, the whole structure deflects. Consequently, the outer beams are forced to deflect as well. When the outer beams oscillate as illustrated in Fig. 1b, interactions between static and dynamic behaviors occur, and the static deflection imposed by the normal force *F* affects their initial resonance frequency. In fact, even slight static pre-deflection of beam resonators may significantly impact their dynamics [4]. Accordingly, it is possible to estimate the magnitude of the normal force applied upon the central beam by monitoring frequency shifts of the outer beams.

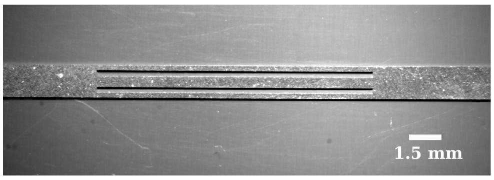
3. Experimental Validation

3.1. Prototype fabrication

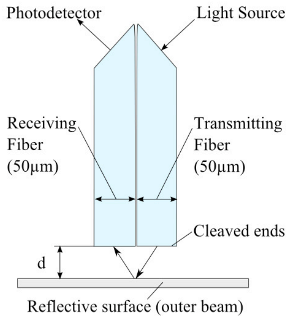
As a proof of concept, we fabricated a first experimental prototype (see Fig. 2a). This first prototype was intended to sense forces in the mN range. It was fabricated from a single sheet of stainless steel using wire cut electric discharge machining. Stainless steel used was 0.1 mm thick. All other dimensions are mentioned in Fig. 1a. Mechanical excitation was provided by a 3 mm long, 2 mm wide and 200 µm thick piezoelectric (PZT) element (Physik Instrumente PIC151) bonded onto the structure.

3.2. Optical fiber displacement probe

To monitor the oscillation frequency of the two outer beams during experiments, we developed an extrinsic optical fiber displacement probe similar to the one reported in [5]. We favored this non-contact measurement technique in order to avoid any alteration of the antisymmetrical mode shown in Fig. 1b. As illustrated in Fig. 2b, the implemented sensing head is made of two optical fibers. One of the fibers serves as a transmitter that guides the light emanating from a light source toward a reflective target. The second fiber is used as a receiver and collects the light reflected by the target. Multimode step index fibers were used (Thorlabs AFS50/125Y). The light source connected to the transmitting fiber was a low-cost VCSEL diode (Honeywell HFE4080-321-XBA) which provided an optical power of 800 µW. At the receiving side, the fiber was connected to a photodetector incorporating a photodiode and a transimpedance amplifier (Thorlabs PDA-10CF). To confirm that our double-fiber probe worked properly, we varied the distance *d* between the fibers' extremities and a reflective target with a micropositioning stage (Physik Instrumente M112-1DG). We thereby verified that fluctuations of light intensity captured by the receiving fiber were in accordance with those reported in [5].



(a)

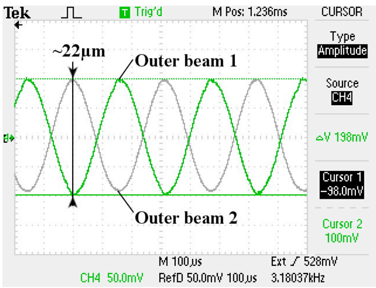


(b)

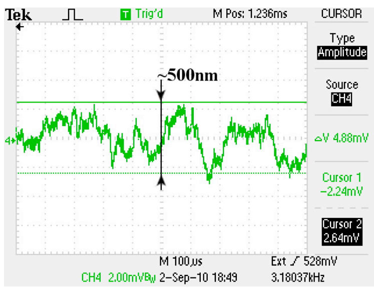
Fig. 2. (a) Close-up of the experimental prototype fabricated (PZT element not visible); (b) Illustration of the double-fiber displacement probe used to measure the oscillation amplitude of the outer beams during experiments.

3.3. Characterization of the prototype's performances

For characterizing the prototype, we first sought to evaluate some of its intrinsic performances with no force applied to the central beam. First, we positioned our double-fiber probe at a distance *d* = 250 µm from the reflective surface of the outer beams. At this distance, our double-fiber probe provided a steep linear slope of 9 mV/µm and small oscillatory displacements of the outer beams could be linearly measured. The prototype was then vibrated with the PZT element. The latter was driven with a peak-peak AC signal of 9 V. The antisymmetrical mode of Fig. 1b was found at 3180 Hz. As expected, the outer beams oscillated in antiphase (see Fig. 3a). Potential vibrations of the central beam were also checked. They never exceeded 500 nm (see Fig. 3b), namely ~2% of the outer beams oscillation amplitude.



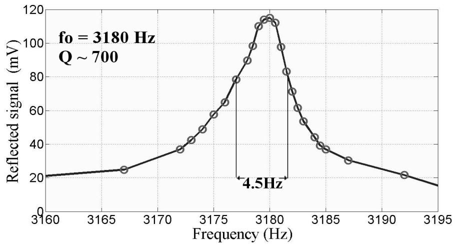
(a)



(b)

Fig. 3. Oscilloscope screenshots showing: (a) The two outer beams oscillating in antiphase with the prototype driven at 3180Hz; (b) Vibrations measured at the half span of the central beam with no force applied.

In addition, we also explored the frequency response of the antisymmetrical mode. In ambient conditions (i.e., in air), a quality factor of 700 was obtained, as illustrated in Fig. 4a.



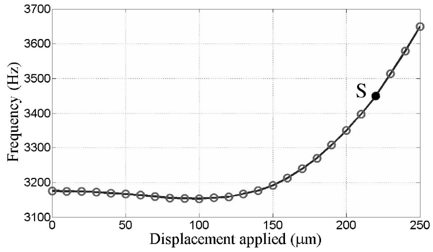


Fig. 4. (a) Experimental quality factor measured in air; (b) Frequency shift measured when controlling the bending of the central beam.

To load the structure, we actually could not apply a calibrated force during experiments. Instead, we bent the central beam with an indenter terminated by a metal bead whose diameter was 500 µm. The indenter was translated by displacement steps of 10 µm via a micropositioning stage (Physik Instrumente M112-1DG). Thanks to the high quality factor of the structure, each displacement increment imposed to the central beam caused drastic amplitude changes in the oscillation amplitude of the resonant outer beams. These easily detectable amplitude changes permitted to recover frequency shifts, as detailed in [2]. The full dynamic range of the prototype was discovered by bending the central beam up to 250 µm. The induced frequency shift is shown in Fig. 4b. The curve exhibits a linear sensitivity of ~5.75 Hz/µm around the point *S*. Although the frequency shift reported varies with respect to a displacement, one can note that the amount of force applied could be recovered via the structure's compliance.

4. Conclusion

This paper has presented a novel type of resonant force sensor that provides a steady area sensitive to forces perpendicular to the sensor's plane. Unlike most reported configurations, no mechanical converter is used. Such a feature may constitute a significant advantage in various applications. A first prototype has been fabricated and characterized. Performance characteristics reported are encouraging. As a next step, improvement of the system for sensing forces in the µN range is presently investigated.

References

[1] Torrents A, Azgin K, Godfrey SW, Topalli ES, Akin T, Valdevit L. MEMS resonant load cells for micro-mechanical test frames: feasibility study and optimal design. *J. Micromech. Microeng.*, 2010; **20**: 125004 (17pp).

[2] Fukuzawa K, Ando T, Shibamoto M, Mitsuya Y, Zhang H. Monolithically fabricated double-ended tuning fork-based force sensor. *J. Appl. Phys.*, 2006; **99**: 094901 (5pp).

[3] Barthod C; Teisseyre Y, Géhin C, Gautier G. Resonant force sensor using a PLL electronic. *Sens. Actuators A*, 2003; **104**: 143-150.

[4] Treyssède F. Prebending effects upon the vibrational modes of thermally prestressed planar beams. *J. Sound Vib.,* 2007; **307**: 295-311.

[5] Binu S, Mahadevan Pillai VP, Chandrasekaran N. Fibre optic displacement sensor for the measurement of amplitude and frequency of vibration. *Opt. Laser Technol.*, 2007; **39**: 1537-1543.