DEVELOPMENT OF CONTACTLESS RESONANT MEMS FORCE SENSORS IN SOI TECHNOLOGY

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Abstract: In this paper an innovative micromachined resonant force sensor, based on magnetic remote readout and actuation strategy is presented. The device resonance frequency changes in presence of the compressive axial-force to be measured due to changes in the device elastic properties; the sensor is driven to resonance by using externally induced Lorentz forces and the output is then obtained via an inductive pick-up.

Keywords: resonant force sensor, contactless sensor, MEMS.

THE SOI FORCE SENSOR

Load cells and force sensors are generally based on bonded-foil strain gauges or piezo-resistive materials whose resistance changes when an external force is applied. These devices cannot be used in harsh environments and represent an incompatible solution for contactless and not-wired measurement systems. The microsensor presented in this work represents an innovative passive force sensor that can be interrogated adopting a remote sensing strategy: the actuation principle of the architecture proposed is based on the interaction between the eddy currents and the magnetic field generated by an external inductor driven by a sinusoidal signal; the system response (correlated to compressive axial-force) is analyzed adopting a remotely sensing system based on an inductive sensor [1].

THE STRESS SENSOR MODEL

In the following the procedure to obtain the resonant frequency changes, as a function of the applied axial load force (S), is briefly described using the elastic beam theory (Figure 1).

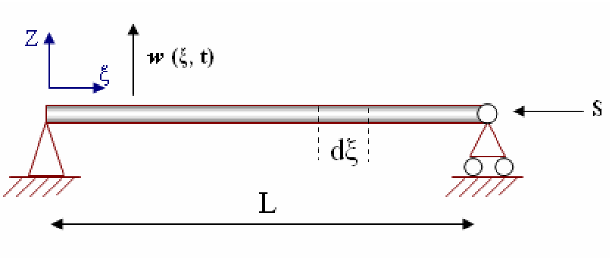


Figure 1. Beam under axial load force.

According to Figure 2 the balance equation along the z-axis, if the higher order terms are neglected, is given by eq. (1):

$$-T - md\xi\frac{\partial^2 w}{\partial t^2} + T + dT - S\sin\varphi_1 + S\sin\varphi_2 = 0 \qquad (1)$$

where the φ_1 , φ_2 are the angles at the initial position ξ and $\xi+d\xi$, respectively, T is the shear force and M is the moment.

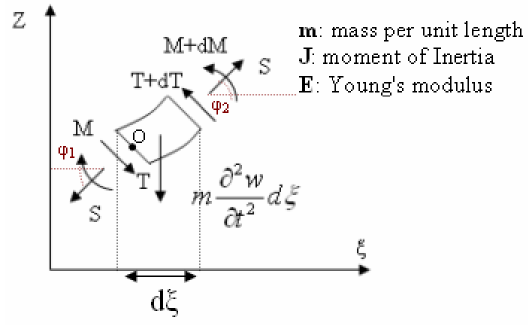


Figure 2. Force analysis.

The linearization at a static equilibrium point allows to define the left and right displacements, respectively:

$$\begin{aligned} w_L(\xi,t) &= w(\xi,t) \\ w_R(\xi,t) &= w(\xi,t) + dw(\xi,t) = w(\xi,t) + \left(\frac{\partial w(\xi,t)}{\partial \xi}\right)d\xi \end{aligned} \qquad (2)$$

where dw represents the incremental displacement as shown in Figure 3.

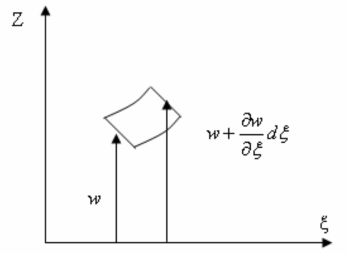


Figure 3. Incremental displacement analysis.

For small displacement (φ_1 and φ_2 are very small), it is possible to write:

$$\begin{aligned}\sin\varphi_1 &\approx \varphi_1 \approx tg\varphi_1 = \frac{\partial w}{\partial \xi}\\ \sin\varphi_2 &\approx \varphi_2 \approx tg\varphi_2 = \frac{\partial}{\partial\xi}\left(w+\frac{\partial w}{\partial\xi}d\xi\right) = \frac{\partial w}{\partial\xi}+\frac{\partial^2 w}{\partial\xi^2}d\xi\end{aligned} \quad (3)$$

that replaced in the expression (1) gives:

$$\frac{\partial T}{\partial \xi}d\xi - m\frac{\partial^2 w}{\partial t^2}d\xi + S\frac{\partial^2 w}{\partial \xi^2}d\xi = 0 \quad (4)$$

The dynamic rotation around the point *O* can be written as follows:

$$T(\xi,t) = -\left(\frac{\partial M(\xi,t)}{\partial\xi}\right) \Rightarrow \frac{\partial T(\xi,t)}{\partial\xi} = -\frac{\partial^2 M(\xi,t)}{\partial\xi^2} \quad (5)$$

Replacing the expression (5) in the expression (4), the following equation can be obtained:

$$-\left(\frac{\partial^2 M(\xi,t)}{\partial\xi^2}\right)d\xi - m\frac{\partial^2 w(\xi,t)}{\partial t^2}d\xi + S\frac{\partial^2 w(\xi,t)}{\partial\xi^2}d\xi = 0 \quad (6)$$

Taking into consideration the Eulero-Bernoulli beam theory and under the hypothesis of homogeneous beam (*EJ* = constant), a fourth-order differential equation can be obtained to describe the motion beam (*w*) subjected to a static axial load *S*:

$$-EJ\left(\frac{\partial^4 w}{\partial\xi^4}\right) + S\left(\frac{\partial^2 w}{\partial\xi^2}\right) = m\frac{\partial^2 w}{\partial t^2} \quad (7)$$

Assuming a particular integral of the form:

$$w(\xi,t) = \psi_c(\xi)G(t) \quad (8)$$

that replaced in expression (7) gives the following differential equation:

$$EJ\frac{d^4\psi_c(\xi)}{d\xi^4}G(t) - S\frac{d^2\psi_c(\xi)}{d\xi^2}G(t) + m\psi_c(\xi)\frac{d^2G(t)}{dt^2} = 0 \quad (9)$$

Then, it is possible to define two different ordinary differential equations, to obtain *G(t)* and $\psi_c(\xi)$, respectively:

$$\begin{aligned}w(\xi,t) &= \psi_c(\xi)G(t) =\\ &= \left(F_1\sin\gamma_1\xi + F_2\cos\gamma_1\xi + F_3\sinh\gamma_2\xi + F_4\cosh\gamma_2\xi\right)\\ &\left(A\sin\omega t + B\cos\omega t\right)\end{aligned} \quad (10)$$

with:

$$\gamma_1 = \sqrt{-\frac{S-\sqrt{S^2+4EJm\omega^2}}{2EJ}}$$

$$\gamma_2 = \sqrt{\frac{S+\sqrt{S^2+4EJm\omega^2}}{2EJ}} \quad (11)$$

whereas F_1, F_2, F_3, F_4 are strictly related to the boundary conditions and *A, B* correlated to the initial condition of the system at *t*=0; thus, taking into account the Figure 1, they can be expressed as:

$$\begin{aligned}&[w(\xi,t)]_{\xi=0} = 0\\ &[w(\xi,t)]_{\xi=L} = 0\\ &[M]_{\xi=0} = EJ\left[\frac{\partial^2 w}{\partial\xi^2}\right]_{\xi=0} = 0 \qquad \Rightarrow F_2, F_3, F_4 = 0; \quad F_1 = 1\\ &[M]_{\xi=L} = EJ\left[\frac{\partial^2 w}{\partial\xi^2}\right]_{\xi=L} = 0\end{aligned}$$

$$\begin{aligned}&\Rightarrow w(\xi,t) = (\sin\gamma_1\xi)(A\sin\omega t + B\cos\omega t) =\\ &= \left(\sin\frac{\pi}{L}\xi\right)(A\sin\omega t + B\cos\omega t)\end{aligned} \quad (12)$$

Equation (12) represents the beam motion model subjected to an axial load *S*. The frequency response as function of the applied axial load, which is represented in Figure 4, can be expressed adopting equations (11) [2]:

$$\gamma_1^{\,2} = \frac{\pi^2}{L^2} = -\frac{S-\sqrt{S^2+4EJm\omega^2}}{2EJ} \quad (13)$$

$$\Rightarrow f_r \cong \frac{1}{2L}\sqrt{\frac{\left(S+EJ\left(\frac{\pi^2}{L^2}\right)\right)}{m}} \quad (14)$$

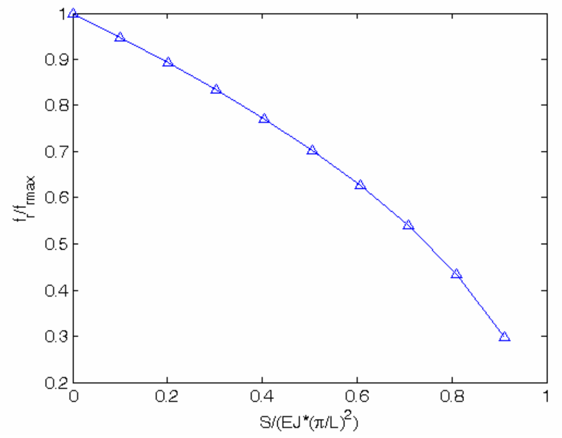
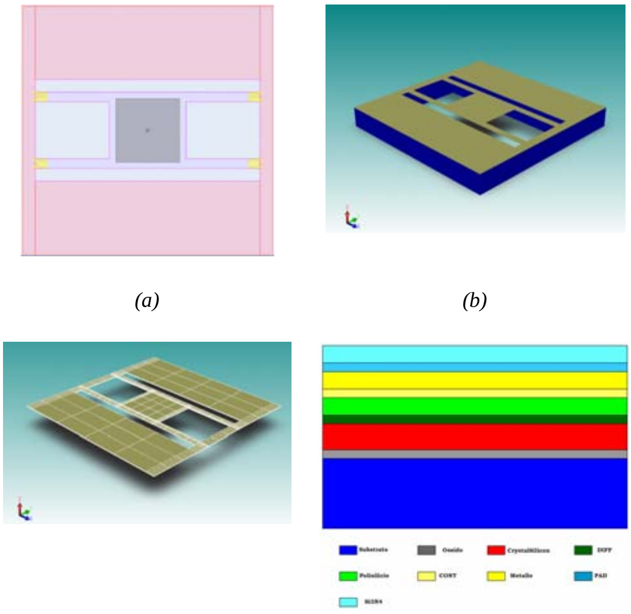


Figure 4. Frequency response as a function of the applied axial load (S).

THE SOI DESIGN PROTOTYPE

The force sensor has been developed by adopting a BESOI (Bulk and Etch Silicon on Insulator) technology, thus releasing a symmetric device (with aluminium surface) supported by four beams (Figure 5(a)). In order to simulate the physical behaviour of the micromachined device, CoventorWare$^{©}$ MemMech tool, based on a FEM method has been used (Figure 5(b) and 5(c)).



(a) *(b)*

(c) *(d)*

Figure 5. a) Force sensor layout in SOI technology, b) 3D model device, c) CoventorWare$^{©}$ mesh model, d) Silicon on Insulator stack materials.

A custom MEMS process has been adopted: SOI-based bulk micromachining (Figure 5(d)). This technology is based on a 450 μm thick carrier silicon substrate, separated from a 15 μm thick c-Si layer by a 2 μm thick buried oxide.

The etching operations of Silicon from both the front side and the bottom side can be summarized as follow:

- a RIE etching on the front-side is used to remove 15 μm of Silicon;
- a DRIE etching of Silicon on the back-side is adopted, in order to remove the 450 μm of silicon;
- a RIE etching of buried SiO_2 from the backside is used to remove the 2 μm of oxide.

Table 1 summarizes the process characteristics.

Substrate (silicon)	450 μm
Oxide	2 μm
Silicon	15 μm
Oxide	0.1 μm
Polysilicon	0.48 μm
Oxide	0.73 μm
Metal	1 μm
Oxide	0.5 μm
Nitride	2 μm

Table 1. Feature of the custom SOI foundry process.

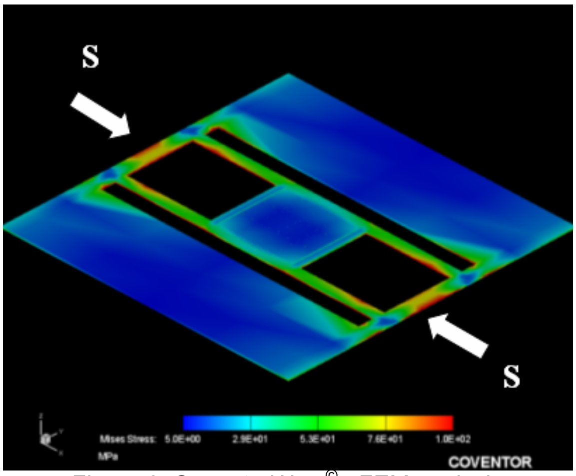


Figure 6. CoventorWare$^{©}$ - FEM analysis. The colour map shows the stress distribution.

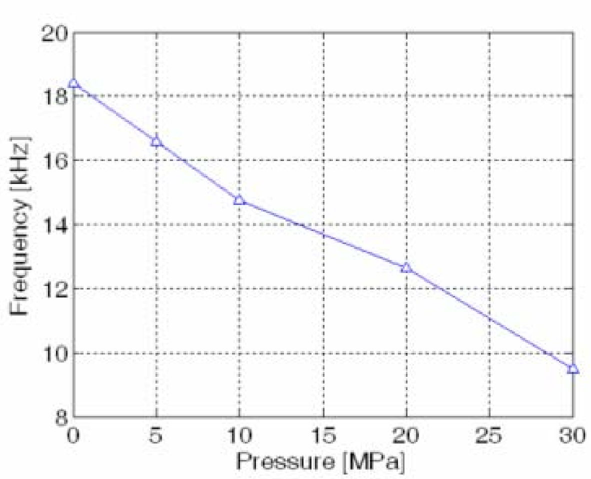


Figure 7. CoventorWare$^{©}$ FEM-analysis: resonant frequency as function of the axial load pressure.

THE CONTACTLESS STRATEGY

The contactless working principle is based on Lorentz force actuation system, and a differential dual-coil inductor to measure the device resonance oscillations [3, 4]. Moreover, the interaction between the eddy currents and the magnetic field, generated by an external inductor onto the conductive mass (exerted by a sinusoidal signal) are exploited for the actuation. Furthermore, the system response (strongly depending on the applied external force) is analyzed adopting a remotely sensing based on an inductive sensor.

The actuation/sensing process can be summarized as follows:

1) a sinusoidal bias signal, having a frequency of $f_r/2$ (f_r: resonance frequency of the mechanical structure), is used to excite the elastic structure;
2) a sinusoidal signal at 80 kHz is used to bias the primary coil of the sensing inductor;
3) the conditioning circuit output represents the displacement information (AM signal, modulated by the device motion);
4) the device frequency response (related to the axial force) can be analyzed using an amplitude demodulator.

In Figure 8 the contactless readout strategy is sketched:

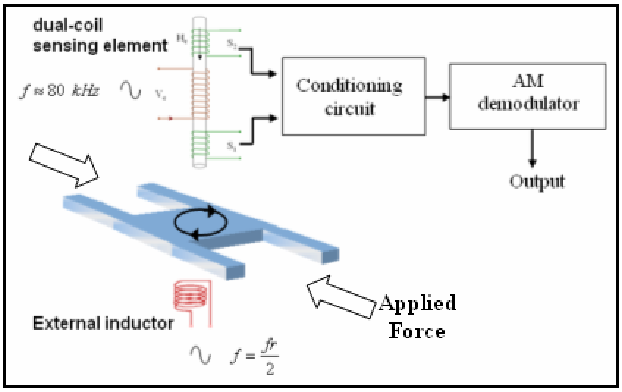
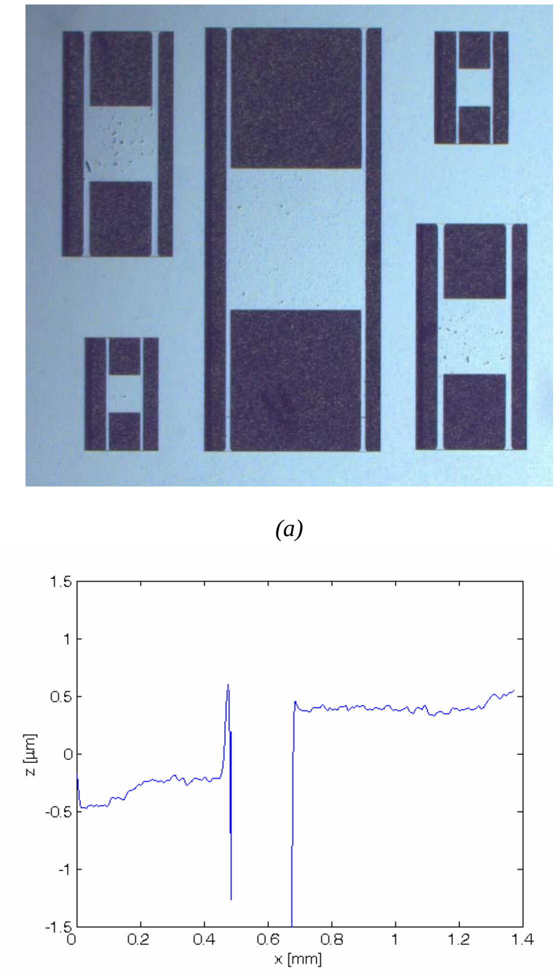


Figure 8. Contactless electromagnetic readout strategy.

The Figure 9(a) shows a microscope picture of a set of SOI force sensors while Figure 9(b) the output of a profile experimental analysis (performed through a confocal microscope).



(a)

(b)

Figure 9. a) SOI force sensor prototypes, b) profile analysis of the central pictured device.

CONCLUSIONS

The development of a novel force sensor for contactless measurements has been described in this work.

A cantilever beam subjected to an axial load has been modeled and the frequency response, as a function of the applied axial load, has been obtained.

The developed force sensor (mainly composed by a central square area supported by four beams) has been simulated using the CoventorWare© MemMech solver, based on a FEM method.

The SOI prototypes have been realized adopting a custom MEMS process.

Future activities will include the contactless characterization of the devices, performed by using a Lorentz force actuation principle, and a sensing inductor to measure the system resonance frequency variation as consequence of the external applied axial load.

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