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Design and simulation of resonance based DC current sensor

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Abstract. A novel resonance based proximity DC current sensor is proposed. The sensor consists of a piezo sensed and actuated cantilever beam with a permanent magnet mounted at its free end. When the sensor is placed in proximity to a wire carrying DC current, resonant frequency of the beam changes with change in current. This change in resonant frequency is used to determine the current through the wire. The structure is simulated in micro and meso scale using COMSOL Multi physics software and the sensor is found to be linear with good sensitivity.

Keywords: cantilever beam; resonant sensor; current sensor; proximity sensor; magnetic force.

1. Introduction

Resonant sensors have attracted considerable interest within the research community as they form an excellent device to measure a wide range of parameters such as mass (Uma *et al*. 2008), pressure (Caliano *et al*. 1995), force (Gehin *et al*. 2000), temperature (Franx 1984), humidity (Neshkova *et al*. 1996), liquid viscosity and density (Shih et al. 2001), touch and tactile (Muralikrishna and Rajanna 2004), chemicals (Zhang and Vetelino 2003), gas (Uma *et al*. 2008) and biomedical (Andle and Ryszard 2000). The key element of resonant sensor is its oscillating structure, designed to sense the measurand as a function of the natural frequency. The change in the natural frequency of the vibrating element can be accomplished by means of a change in stress, mass or shape of the resonator. The frequency output of the resonator is less susceptible to electrical noise and independent of the level and degradation of transmitted signals, offering a good long-term stability. Hence frequency output is compatible with digital interfacing and no analogue-to-digital conversion is required, therefore maintaining inherent high accuracy.

The information regarding current flow is required in a wide range of electrical, electronics and instrumentation applications. Precise contactless DC and AC current sensors are required by automobile industry and chemical industry, for measurement of power and many other applications. Various techniques available for current monitoring with their performance and limitations can be seen in (Ziegler *et al*. 2009). In recent years, an integrated systems approach is being developed to

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standardize power electronics components and packaging techniques. Therefore the need for micro current sensors suitable for packaging into integrated power electronics modules and integrated passive power processing units increases (Xiao *et al*. 2003). The experimental and theoretical analysis is used to investigate the out-of-plane resonant characteristics of a cantilevered piezoceramic plate in air and three different kinds of fluid. It is shown that the resonant frequencies of the cantilevered piezoceramic plate in fluid decrease with the increase of the viscosity of fluid (Lin and Ma 2008). The main advantages of integrated sensors are low cost, compatibility, fast response etc. The initial tension and nonlocal stress do play significant roles in the free vibration behavior of a cantilever nanobeam in which the structural stiffness is greatly enhanced (Lim *et al*. 2009). In this paper a micro DC current sensor is proposed, where the DC current is measured in terms of resonant frequency variation of the Piezo laminated cantilever beam. The structure is designed and simulated in meso and micro scale to measure DC current.

2. Measurement system

The measurement system consists of a flexible aluminum beam clamped at one end is shown in Fig. 1. Two piezoceramic patches are surface bonded at the fixed end of the beam, patch bonded on the bottom surface acts as a sensor and the one on the top surface acts as an actuator or vice versa. A cylindrical disc type permanent magnet of flux density 1.2 tesla is mounted on the bottom surface of the free end of the cantilever beam and a copper wire of radius 2 mm is placed under the magnet in proximity. The radial distance between the permanent magnet and the current carrying wire can be as close as possible. The dimensions of the permanent magnet are 6.5 mm × 2 mm and the dimensions and properties of the beam and piezo ceramic patches are given in Table 1 and Table 2

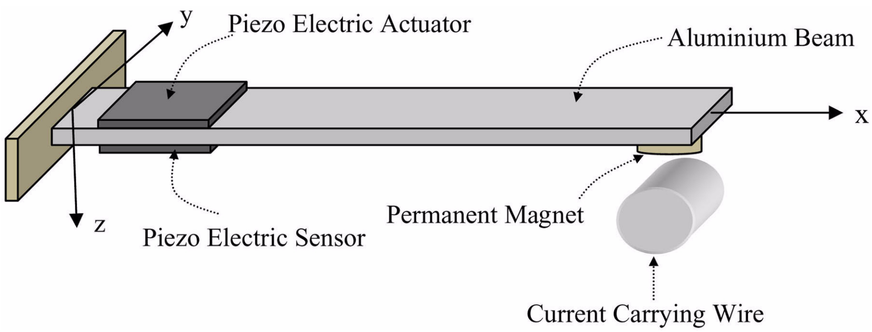


Fig. 1 Piezo actuated cantilever structure with permanent magnet at its tip

Table 1 Properties and dimensions of cantilever beam

Length (m)	l	0.2
Width (m)	b	0.013
Thickness (m)	t_b	0.00127
Young's Modulus (GPa)	E_b	71
Density (kg/m^3)	ρ_b	2700

Table 2 Properties and dimensions of piezo patch

Length (m)	l_p	0.0765
Width (m)	b	0.013
Thickness (m)	t_p	0.0005
Young's Modulus (GPa)	E_p	47.62
Density (kg/m^3)	ρ_p	7500
Piezoelectric strain constant (mV^{-1})	d_{31}	-247×10^{-12}
Piezoelectric stress constant (VmN^{-1})	g_{31}	-9×10^{-3}
Dielectric constant	K_3^T	3100
Mechanical quality factor	Q_m	65

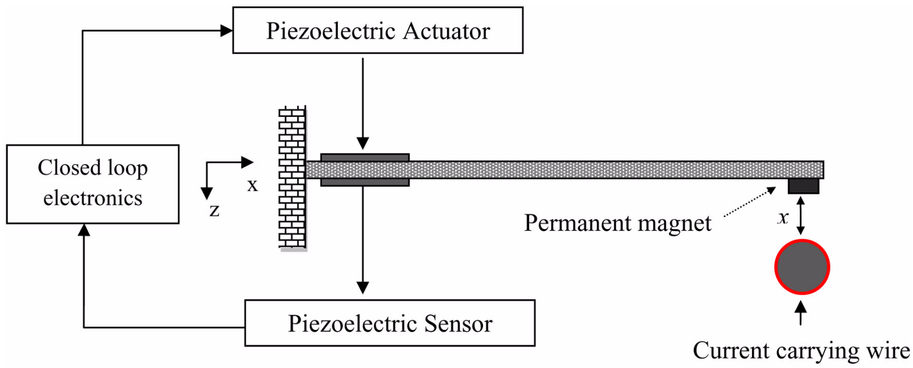


Fig. 2 Measurement system with closed loop electronics

respectively. The dimensions of beam, piezo ceramics and permanent magnet given are for the meso scale structure and for the micro scale structure the dimensions are scaled down by a factor of 10^2.

3. Measurement principle

To measure the DC current, the cantilever structure is placed close to the wire carrying DC current. The force between the permanent magnet and the current carrying wire induces additional stiffness (positive for repulsive force and negative for attractive force) on the structure and hence the resonant frequency of the structure alters. The closed loop electronics adapts to the changes and makes the structure to vibrate at its new resonance frequency, which is shown in Fig. 2. This change in resonant frequency is the measure of the current through the wire.

3.1 Sensing principle

Considering cylindrical permanent magnet Fig. 3, the flux density of the permanent magnet at a distance x is given as

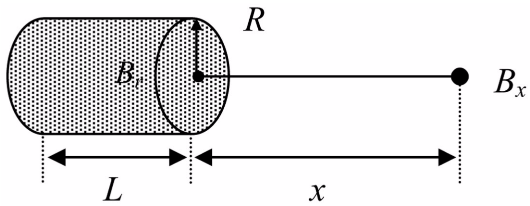


Fig. 3 Magnet flux density at point x

$$B_x = \frac{B_r}{2}\left(\frac{L+x}{\sqrt{R^2+(L+x)^2}} - \frac{x}{\sqrt{R^2+x^2}}\right) \tag{1}$$

where L is the length of the permanent magnet, R is the radius of the permanent magnet and B_r is the flux density of the magnet. Now, the force acting on the current carrying wire placed in the magnetic field is

$$F_{current} = IL_w B_x \tag{2}$$

where I is the DC current through the wire and L_w is the length of the wire under magnetic field. From, Eqs. (1) and (2)

$$F_{current} = IL_w \frac{B_r}{2}\left[\frac{L+x}{\sqrt{R^2+(L+x)^2}} - \frac{x}{\sqrt{R^2+x^2}}\right] \tag{3}$$

The magnetic force between the permanent magnet and the wire induces an additional stiffness on the vibrating cantilever beam which in turn alters the resonant frequency of the beam. The additional stiffness induced from the magnetic force is positive for repulsive force and negative for attractive force; the attractive force can be represented as a spring under tension and the repulsive force as a spring under compression (Challa *et al.* 2008). Thus, the stiffness due to magnetic force is

$$K_{current} = \frac{dF_{current}}{dx} =$$

$$\frac{IL_w B_r}{2}\left(\frac{\sqrt{R^2+(L+x)^2} - (L+x)^2(R^2+(L+x)^2)}{R^2+(L+x)^2} - \frac{\sqrt{R^2+x^2} - x^2(R^2+x^2)}{(R^2+x^2)}\right) \tag{4}$$

The lumped parameter model of the measurement system is shown in Fig. 4. The stiffness involved in the measurement system is the stiffness of the structure and the stiffness due to magnetic force, which is variable with the current flow through the wire. The effective stiffness of the system for a given current flow would be smaller or greater than the beam stiffness (when no magnetic force is present).

$$K_{eff} = K_{beam} \pm K_{current} \tag{5}$$

$$m_{eff} = m_s + m_{tip} \tag{6}$$

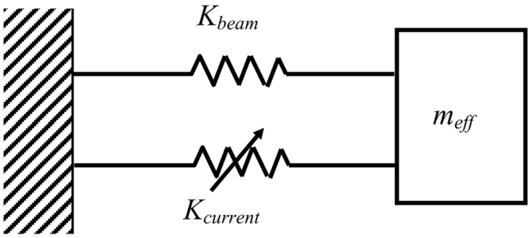


Fig. 4 Lumped parameter model of the system

where, $K_{beam} = 3EI_m/l^3$ is the stiffness of the clamped- free beam, E is the Young's Modulus of the beam, I_m is the moment of inertia of the beam, l is the length of the beam, m_s is the mass of the cantilever beam and m_{tip} is the mass of the permanent magnet placed at the tip of the beam. The natural frequency of the measurement system (ω) with current flow is defined as

$$\omega = \sqrt{\frac{K_{eff}}{m_{eff}}} \tag{7}$$

4. Results and discussion

The structure is built and simulated in COMSOL Multi physics 3.5a version software. The Multi-physics interaction in the measurement system is simulated and analyzed using AC/DC simulator which is a system level simulation module for electromagnetic analysis and MEMS module which is a system level simulation module for piezoelectric and structural mechanics analysis. The MEMS piezo module in COMSOL consists of piezoelectric material database for PZT-2, PZT-4, PZT-4D, PZT-5A, PZT-5H, PZT-5J, PZT-7A, PZT-8. For simulating the measurement system in meso and micro scale the material database of PZT- 5H which is equivalent to NAVY TYPE VI (US DOD MIL STD 1376) in MEMS Piezo module is used. The modal analysis is carried out for the cantilever structure in COMSOL Multi physics and the displacement of the cantilever beam in meso scale and micro scale for the first four modes is shown in Fig. 5 and Fig. 6. It is found that the first mode frequency is 23.1078 Hz for meso scale and 2.31089 kHz for micro scale.

To analyze the force acting between the current carrying wire and the magnet placed on the cantilever beam and to find out the optimal orientation of the magnet with respect to the wire, the AC/DC analysis is carried out. The current passing through wire is varied from 0-200A in meso scale and 0-20mA in micro scale with the magnet placed in horizontal and vertical directions. From the results it is observed that the force acting on the magnet is found to be high in the vertical orientation. Further the distance between the magnet and the wire is varied to analyze the optimal distance of separation; it is observed that the force acting on the beam is high when placing the wire as close as possible to the magnet. The distance between the wire and magnet is optimized to be 1 cm in meso scale and 50 μm in micro scale by considering the tip displacement of the cantilever beam at resonance. The simulation results for horizontal and vertical orientations and the force acting on the beam for a 1cm in meso scale and 50 μm distance in micro scale are shown in Fig. 7 and Fig. 8 respectively.

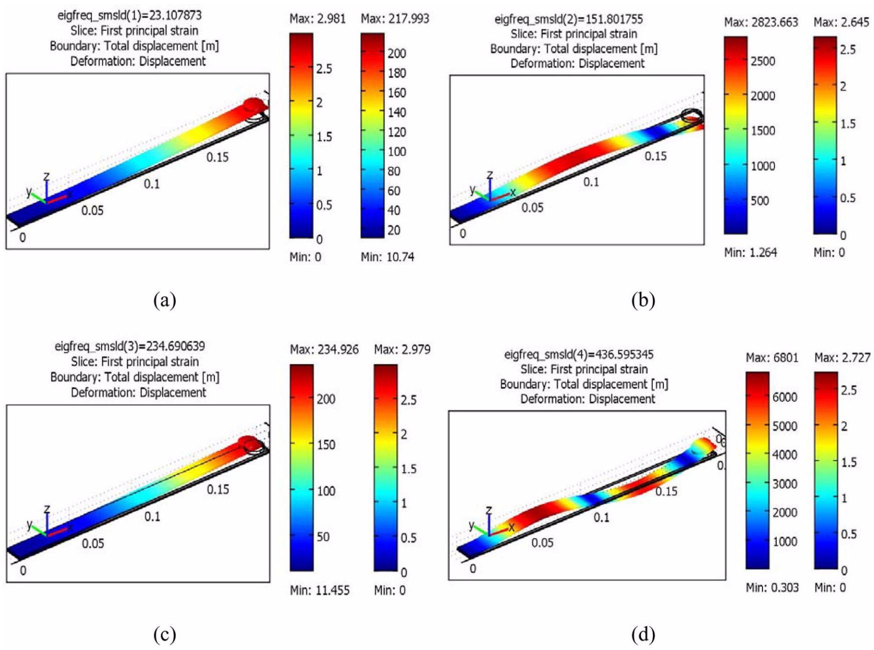


Fig. 5 Simulation model showing modes of vibration : (a) first mode, (b) second mode, (c) third mode, (d) fourth mode

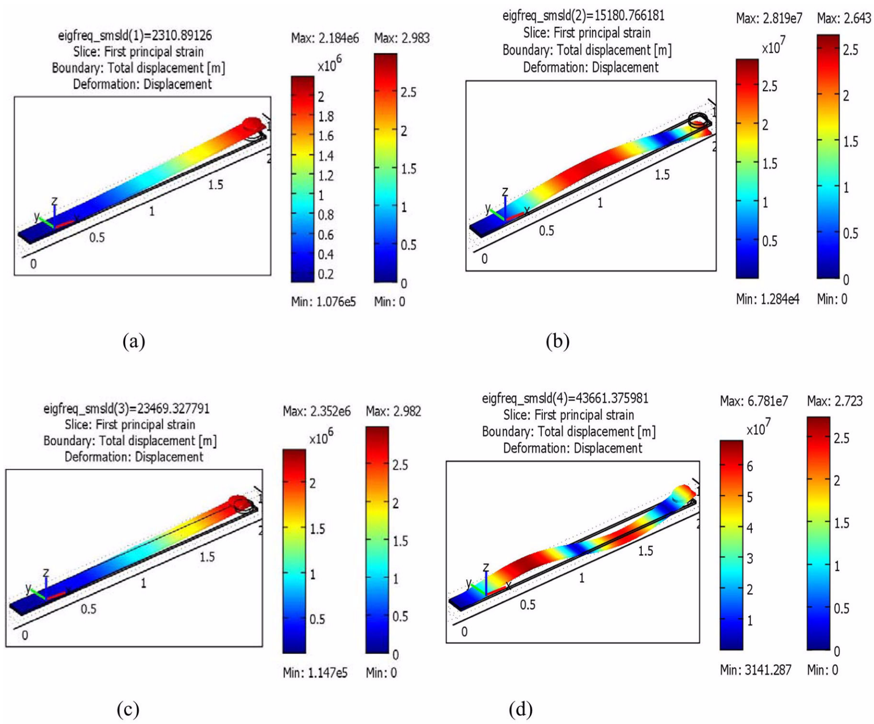
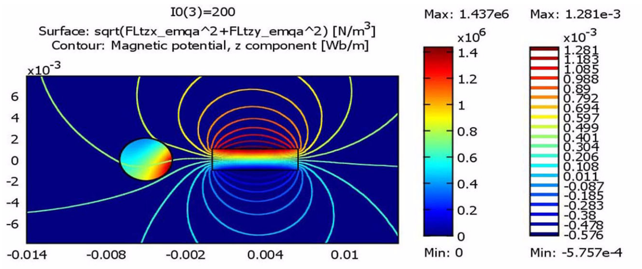
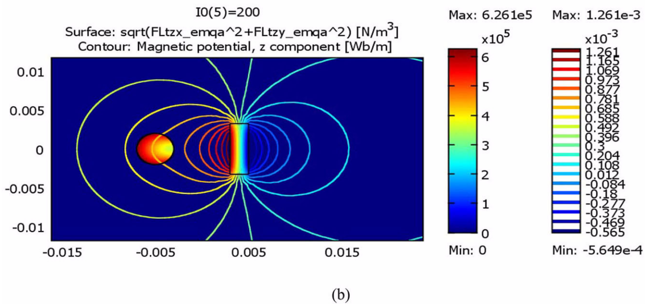


Fig. 6 Simulation model showing modes of vibration in micro scale : (a) first mode, (b) second mode, (c) third mode, (d) fourth mode

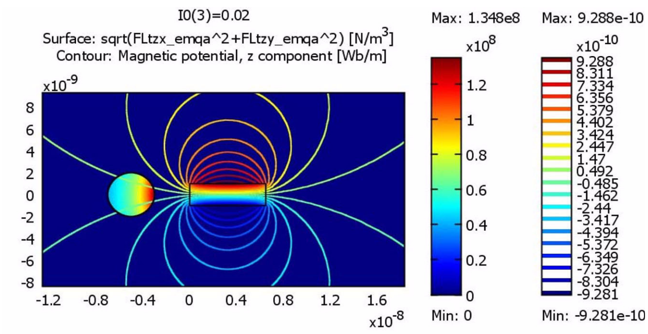


(a)

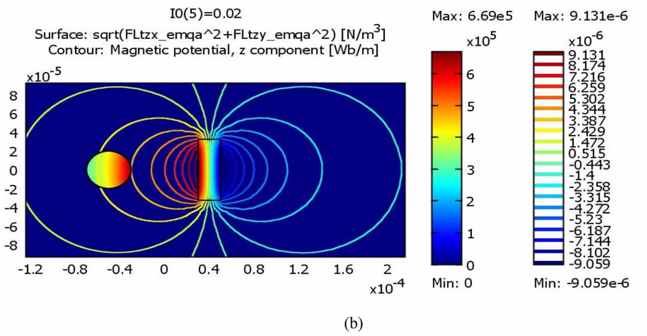


(b)

Fig. 7 Simulation results for force acting on the beam in meso scale : (a) magnet placed horizontal with respect to the wire, (b) magnet placed vertical with respect to the wire

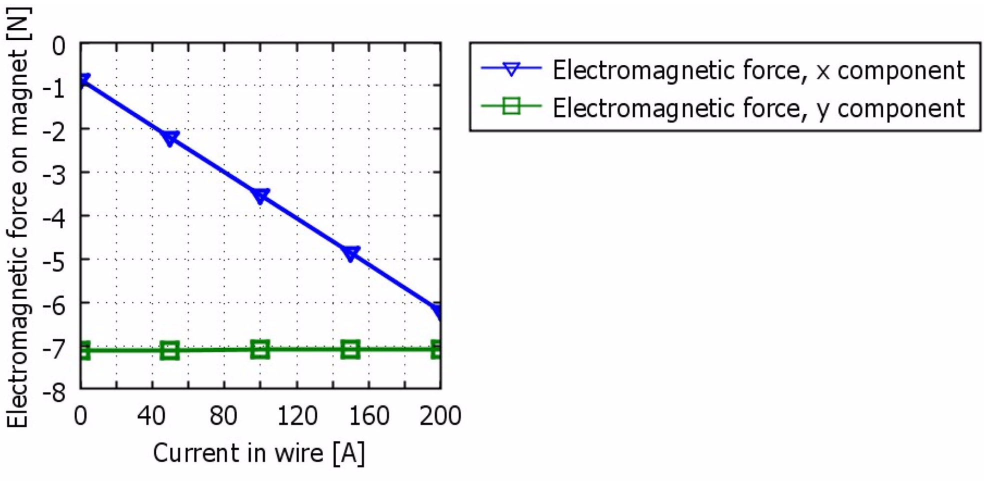


(a)

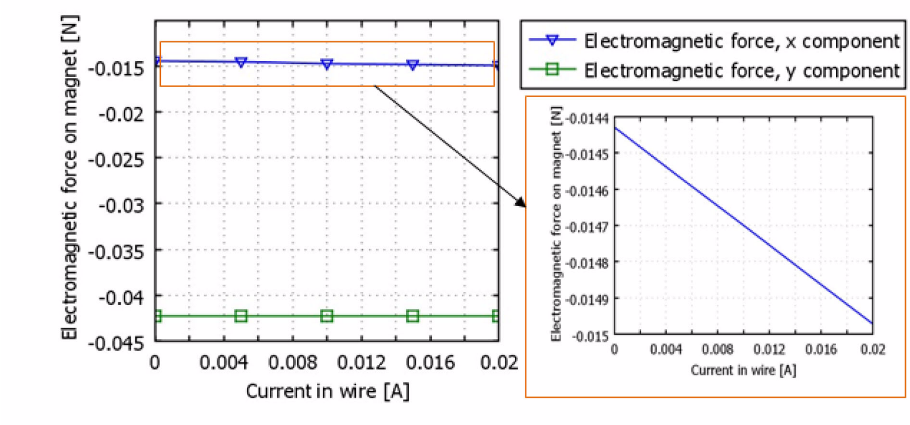


(b)

Fig. 8 Simulation results for force acting on the beam in micro scale : (a) magnet placed horizontal with respect to wire, (b) magnet placed vertical with respect to wire



(a)



(b)

Fig. 9 Force acting on the cantilever structure versus current : (a) in meso scale, (b) in micro scale

The resultant force acting on the cantilever beam in the x-direction and the y-direction with the varying current passing through the wire are shown in Fig. 9 for the cantilever structure in meso scale and micro scale. The force acting in x-direction is zoomed for convenience in Fig. 9(b).

The applicability of the cantilever based resonant structure for current sensing is tested by applying the force corresponding to the current at the tip of cantilever beam. A shift in resonant frequency of the structure was observed when the structure is simulated in MEMS structural mechanics module of COMSOL multiphysics. It is noted that the shift in resonant frequency of the structure is from 23.1078 Hz to 21.0087 Hz for a current of 0-200A in meso domain and 2.31089 kHz to 2.0295 kHz for the current ranging from 0-20mA in micro domain as shown in Fig. 10(a) and Fig. 10(b) respectively.

In the measurement system, non-linearity in input-output characteristics can arise from two sources namely from the cantilever structure and from the magnetic flux distribution. The

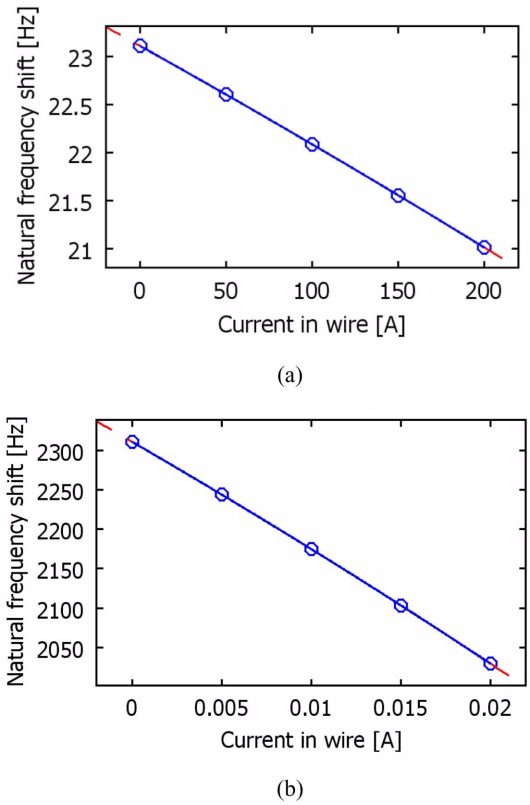


Fig. 10 Shift in the natural frequency of the cantilever structure versus current : (a) in meso scale, (b) in micro scale.

measurement system will exhibit nonlinear input-output characteristics for large structural deformation and with distance between the magnet and current carrying wire as the magnetic flux distribution is not linear with distance. These nonlinearities can be reduced by restricting the structural deformation to be small in magnitude and maintaining the distance between the magnet and current carrying wire to accomplish the linear magnetic flux distribution.

5. Conclusions

A novel proximity based DC current sensor is designed and simulated in COMSOL Multi physics software for micro and meso scale. As the force on the permanent magnet is found to depend on the distance between the magnet and current carrying wire, it is recommended that the cantilever structure has to be as close as possible to the current carrying wire and, the strength of the magnet should be as high as possible. The sensor is found to have good linearity and the sensitivity is found to be 12.8 Hz/mA in micro scale and 10.49 mHz/A in meso scale. Hence, the measurement system suites well for DC current measurement in micro scale devices. The proposed system is simple in design and can be easily fabricated in micro scale to measure DC current of various ranges.

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