

A Highly Sensitive and Wide-Range Resonant Magnetic Micro-Sensor Based on A Buckled Micro-Beam

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Abstract

We experimentally demonstrate a miniature highly sensitive wide-range resonant magnetic Lorentz-force micro-sensor. The concept is demonstrated based on the detection of the resonance frequency of an in-plane electrothermally heated straight resonator operated near the buckling point. The frequency shift is measured with optical sensing and the device is operating at atmospheric pressure. The magnetometer demonstrates a sensitivity (S) of $33.9/T$, which is very high compared to the state of the art. In addition, the micro-sensor shows a good linearity in wide range and low power consumption around 0.2 mW. The above performances make the proposed micro-sensor promising for various low-cost magnetic applications.

Introduction

In recent years, microelectromechanical systems (MEMS) have increasingly attracted the attention of researchers for various applications, such as filtering¹, signal processing⁹, energy harvesting¹⁰, and environmental sensors including magnetic, pressure²⁻⁴, accelerometer⁵, temperature⁶, flow⁷, and gas⁸. Magnetic field micro-sensors have been explored for various potential applications, such as magnetocardiography (MCG), magnetoencephalography (MEG), biomedical, inertial navigation systems, electronic compasses, telecommunications, and non-destructive testing¹¹⁻¹⁵. These magnetic micro-sensors are mainly based on Lorentz force transduction. In addition to high sensitivity and low power consumption, Lorentz force magnetic MEMS sensors have important advantages, including low fabrication cost, high resolution, and compact size^{14,16-19}.

The intensive demand of MEMS structures has led to magnetic sensors based on Lorentz force MEMS resonators thanks to the high frequency shifting and resonance frequency tunability²⁰⁻²⁴. The frequency shift resonant magnetometer yields high accuracy, high outstanding stability, high sensitivity, low power consumption, and immunity to noise. Exposing heated structures to magnetic field creates uniform distributed forces perpendicular to the test structures affecting their stiffness. Hence, the field strength can be measured by detecting the resonance frequency shift of resonating structures.

Various techniques of magnetic field micro-resonators have been used, such as capacitive, piezoresistive, piezoelectric, and optical sensing techniques^{14,23,25-26}. Despite the intrinsic losses from the device imperfections, optical sensing requires simple read-out electronic circuits, is more robust technique, and presents immunity to electromagnetic interference. In addition, this technique does not demand a vacuum package¹⁴.

The static and dynamic behaviours of electrothermally actuated in-plane micro-beams, have been extensively investigated²⁷⁻³². In a previous work², we exploited the buckling point of heated straight micro-beam to demonstrate highly sensitive and scalable pressure sensor. The concept is based on tracking the frequency shift of the buckled micro-beam upon changing the surrounding air pressure. Based on the same concept, we extended our study to demonstrate highly sensitive gas sensors⁸. The

method is based on the simultaneous recording of the frequencies of the first and second modes while changing the gas concentration and type.

A small and low-cost magnetic sensor with high sensitivity in wide range, which is also simple in fabrication, operation, and sensing scheme, would be highly desirable. In this paper, we aim to realize a highly sensitive and wide range magnetic sensors based on electrothermally heated straight micro-beam operated near the buckling point. The method is based on measuring the frequency shift of the fundamental resonance frequency of micro-beam upon changing the magnetic field. Operating near the buckling point offers significant shifting in frequency, and thus high sensitivity in wide range of magnetic field.

Background And Measurement Method

The concept is illustrated in Fig. 1. First, the variation in the resonant frequency of the first mode is monitored under DC current (I_{Th}). As shown in Fig. 1a, by increasing I_{Th} , the resonant frequency of the micro-beam decreases due to increase in its stiffness until the buckling point where the micro-beam's stiffness is almost zero. After buckling, an increase in the resonant frequency is observed due to the stretching mechanism, which increases the stiffness of the buckled micro-beam. Next, as shown in Fig. 1b, a low DC electrostatic voltage (V_{DC}) induces a static deflection that leads to decrease in the dip of the first resonance frequency. Note here that the straight micro-resonator takes advantage to high frequency shifting by operating around the buckling bifurcation at which the micro-beam is very sensitive to a small stiffness change. By applying a magnetic field while operating around buckling point, it is possible to add a deflection which leads to an increase in the frequency shifting, Fig. 1c. Hence, the concept is based on tracking the fundamental natural frequency of the electrothermally buckled straight micro-beam upon exposing it to a wide range of magnetic field.

A schematic of the micro-sensor is shown in Fig 2a. To demonstrate the concept, we utilize a micro-resonator fabricated from a highly doped silicon device layer of silicon-on-insulator (SOI) wafer from MEMSCAP wafer. The micro-beam is of length (L) 800 μm , width (h) 2 μm , 25 μm depth (b), and is separated with two adjacent electrodes of 8 μm gap (g). A schematic of the proposed Lorentz-force magnetic sensor is shown in Fig. 2b. The electrothermal voltage V_{Th} is applied between the two anchors inducing a current I_{Th} flowing through the micro-beam that generates heat. In addition, the straight beam is electrostatically actuated by a DC voltage V_{DC} . As seen in Fig. 2b, with the presence of a magnetic field (B_z) and with a DC current I_{Th} , which flows through the micro-beam, Lorentz-force (F_y) is generated normal to the straight micro-beam in Y-axis.

Schematic of the experimental setup used to test the micro-resonator is shown in Fig. 2c. The resonant frequency shifting is measured using a laser Doppler vibrometer from Polytec³³ (MSA 500) as actuating the straight micro-beam with a white noise signal. The driving electrode of the resonator is electrically connected to a DC and AC harmonic voltage sources provided by the MSA. Also, the micro-beam is electrothermally actuated by a separate DC voltage source V_{Th} . To generate a DC magnetic field in z-axis

(B_z), a Neodymium permanent magnet is positioned above the sensor. All experiments are conducted at pressure atmospheric.

Results And Discussions

Figure 3a shows the variation in the measured fundamental resonance frequency of the micro-beam, while changing the input current I_{Th} and for 0 magnetic field ($B_z = 0$ mT). It can be observed that the resonance frequency decreases with the increase in I_{Th} and reaches a minimum value around 0.27 mA, which corresponds to the buckling point. By increasing I_{Th} , the compressive axial load induced through the micro-beam increases via Joules heating, which also causes decrease in its stiffness. After buckling, a sharp increase in the resonant frequency is observed, which increases the stiffness of the buckled micro-beam. Note here that the buckling bifurcation is utilized since the micro-beam becomes very sensitive to any small stiffness change. A small electrostatic voltage ($V_{DC} = 16$ V) is applied between the lower driving electrode and micro-beam, which creates a small deflection in Y-axis, and thus causes decrease in the dip (above zero) of the first resonance frequency²⁷. Note that the thermal time constant of the proposed magnetic sensor is around $176 \mu s^8$. For faster operation, the micro-sensor needs to be placed in vacuum.

The variation in the resonance frequency, while changing I_{Th} and for varying magnetic field strength (B_z), is shown in Fig. 3b. By increasing B_z , the Lorentz-force (F_y) increases, which also causes increase in initial deflection, and thus increases the resonant frequency of the resonator. The results show that the resonance frequency dip is almost eliminated for high value of B_z (400 mT), which explains that the micro-beam experiences a high perturbed bifurcation due to the existence of magnetic field. In addition, we observe that the frequency responses can be measured with wide range of B_z strengths from 4 mT to 400 mT at atmospheric pressure. However, our proposed micro-sensor can detect a magnetic field lower than 4 mT.

Next, we discuss the sensitivity of the micro-sensor S ($1/T$), which is defined as the relative change in the resonant frequency ($\Delta f/f_0$) over the variation of an input magnetic (∂B_z)²⁰. The frequency shift (Δf) is defined as $(f - f_0)$, where f_0 and f , are respectively, the frequency of the micro-beam at 0 mT and during the measurement with B_z . We first measured Δf with B_z as fixing I_{Th} at 0.14 mA (before buckling) and 0.27 mA (at the buckling point), respectively, Fig. 4a. For both values of I_{Th} , the results show two linear trends, which separate the magnetic strengths in two ranges; low ($B_z \leq 8$ mT) and high range ($B_z \geq 8$ mT). As shown, the frequency shift (resulting from the same field strength) is found higher at $I_{Th} = 0.27$ mA where the micro-beam stiffness reaches almost zero. Hence, operating the resonator near the buckling point maximizes the frequency shift.

As we mention above, the measured linear coefficient of the relative change in the resonant frequency as a function of increasing magnetic field can represent the sensitivity (S) of the micro-sensor. Figs. 4b and 4c present $\Delta f/f_0$ measurements against B_z at a bias current of 0.14 mA, away from the buckling point, for

both low and high magnetic field ranges. As shown in Figs. 4(b,c), the sensitivity at low range is 8.46/T, and for high range is 0.35/T. It is observed that, through linear fitting, the micro-sensor shows high linearity for both ranges. We next plot the results for both ranges around the bucking point (0.27 mA), Figs. 4(d,e). The slopes of the plots yield a sensitivity of 33.9 /T for the low range and 2.56/T for the high range. Hence, the device can sense with high sensitivity a wide range of magnetic field. These values are four and seven times larger than the values at 0.14 mA. This confirms well with the concept that by operating at the buckling point, the proposed micro-sensor is very sensitive to any external force including from magnetic fields. The results indicate that the dependence of S on B_z becomes more significant in low range compared to high ranges. The improved high sensitivity at low ranges encourages the efforts toward low cost magnetic sensors applications.

Next, we show the results of S with I_{Th} to have an understanding of the relationship between sensitivity and power consumption. Figs. 5(a,b) plot the sensitivity versus I_{Th} for the two ranges. The results show that S increases as a cubic polynomial with I_{Th} . Increasing the current from 0.1 mA to 0.27 mA (before buckling point), the sensitivity can be further improved by 870 % for the low range and 800 % for the high range. This again confirms that the sensor sensitivity becomes high as operating around the buckling point. It also shows that the operating current point of the magnetic sensor can be tuned to achieve higher sensitivity.

One should mention that the proposed sensor might be promising for some applications, which require high sensitivity. In addition to having high sensitivity, low power consumption is also an important factor. At bucking point (0.27 mA), the sensor consumes power around 0.2 mW due to the electrothermal actuation. This value can be reduced to half by operating at 0.135 mA while there is significant reduction in S (81 %). Hence, with a straight micro-beam, high sensitivity is achieved even for a low input current. However, the power of the device can be improved by reducing the cooling effect between the micro-beam and the surrounding air (e.g., operating at low pressure using vacuumed package).

Note here that the current detection method using optical readout system (laser) does not suffer considerably from noise, electronic circuitry, and weight. In other sensing methods, where resonances are detected electrically, such as capacitive sensing, they suffer from parasitic capacitances and other sources of noise, which can have high impact on the resolution of measurements. Furthermore, the proposed sensing technique does not compensate the environmental temperature variation, which represents one limitation of the frequency based magnetic sensors compared to capacitive technique. Moreover, calibration experiments may be conducted to compensate the variation of ambient temperature.

Table 1 below shows comparison for the performance of the proposed micro-sensor to some recent works on Lorentz force resonant magnetic field micro-sensors. As listed in Table 1, the sensitivity of the device is significantly higher and with smaller dimensions compared with other previously reported magnetic sensors. Also, it is noted that the results show high sensitivity in wide range of magnetic field

strengths. In addition, the proposed micro-sensor is useful to reduce the device power and its size, and thus the cost of the MEMS magnetometer.

Table 1. Summary of the performance of some of the recent MEMS magnetic field sensors based on Lorentz force.

Reference	Magnetic range (mT)	Power (mW)	Surface (mm ²)	Sensitivity (mA ⁻¹ .T ⁻¹)	Sensing method
[Zhang <i>et al.</i> [20]]	≤ 100	40	0.48	33.9 ppm	Capacitive
[Bahreyni <i>et al.</i> [34]]	[2.5-25]	0.1-10	0.27	332.3 ppm	Capacitive
[Herrera-May <i>et al.</i> [35]]	≤ 7	10	0.06	922.7 ppm	Piezoresistive
[Laghi <i>et al.</i> [36]]	[-5 to 5]	10	0.308	2800000 ppm	Capacitive
This work	≤ 8	0.2	0.0144	125000000 ppm	Optical
This work	[8-400]	0.2	0.0144	9500000 ppm	Optical

Conclusions

In this paper, we demonstrated experimentally a highly sensitive in-plane Lorentz-force magnetic micro-sensor by exploiting the buckling point bifurcation of a straight beam. The concept is based on the measured resonance frequency shift of the first mode under different magnetic strengths. The micro-sensor demonstrates high sensitivity compared to reported magnetic sensors. The main advantages of the proposed sensor are the simplicity of fabrication, low-cost, excellent linearity, low power consumption, scalability, and wide range measurements. The high performances above motivate in-depth studies for the implementation of the proposed magnetic micro-sensor in low magnetic fields strengths around μT . In conclusion, we demonstrated that a single electrothermal straight micro-resonator could be potentially used as a magnetic sensor by measuring the frequency shift near the buckling point. Future studies are planned for measurements in vacuum to reduce the power consumption and lower the minimal detectable magnetic fields.

Declarations

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CONFLICT OF INTREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

N.A performed the measurements and analyzed the data. S.B.M. performed the measurements. M.I.Y. supervised the project.

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