MEMS LORENTZ FORCE MAGNETIC SENSOR BASED ON A BALANCED TORSIONAL RESONATOR

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ABSTRACT
We demonstrate an x-axis Lorentz force sensor (LFS) for electronic compass applications. The sensor is based on a 30 μm thick torsional resonator fabricated in a process similar to that used in commercial MEMS gyroscopes. The sensor achieved a resolution of 210 nT/√Hz with a DC supply voltage of 2 V and driving power consumption of 1 mW. Bias instability was measured as 60 nT using the minimum Allan deviation. This mechanically-balanced torsional resonator also confers the advantage of low acceleration sensitivity; the measured response to acceleration is below the sensor’s noise level.

KEYWORDS
Magnetometers, compass, Lorentz force actuator, acceleration sensitivity, Allan deviation

INTRODUCTION
Hall-effect sensors and anisotropic magnetoresistance (AMR) sensors are commonly used in portable devices as electric compasses. In comparison, resonant MEMS Lorentz force magnetometers are free from magnetic hysteresis, they do not require magnetic materials and can be monolithically integrated with accelerometers and gyroscopes in the same chip. Unlike the z-axis LFS [1], an x/y-axis LFS requires out-of-plane motion and therefore high magnetic field sensitivity can only be achieved using a torsional resonator when the structural layer is thicker than ~10 μm. Relative to our group’s previous work [2], this LFS reduces the required DC supply voltage from 15 V to 2 V and achieves a resolution of 210 nT/√Hz with a driving power consumption of 1 mW, comparable to commercial Hall-effect sensors [3].

Acceleration sensitivity remains as a problem faced by all resonators. Phase noise from acceleration sensitivity has been widely studied in quartz crystal resonators [4, 5] and MEMS resonators [6]. Similarly, the source of acceleration sensitivity and a method of mitigation in MEMS tuning fork gyroscopes has been recently presented [7]. Although a MEMS resonator functioning both as a magnetometer and an accelerometer had been demonstrated [8], acceleration sensitivity in resonant Lorentz force magnetometers has not been well studied in the past. In this work, we report our theoretical and experimental investigations on acceleration sensitivity in LFS devices.

In the balanced resonator, magnetic fields create torsional motion detected as a differential signal, while motion due to x, y or z-axis acceleration creates a common-mode signal that is rejected by the differential sensing path. The acceleration signal is further reduced by frequency-selective measurement. Experimental results show that the measured response to acceleration falls below the sensor’s noise floor.

DESIGN & MODELING
Sensor Design
The LFS consists of a 1.06 mm by 0.8 mm torsional resonator fabricated out of a 30 μm-thick single-crystal silicon and die-level vacuum-sealed with modest vacuum level. Figure 1 shows the SEM image of the sensor. Excitation current flows through the device structural layer at its torsional resonance frequency of 21.29 kHz and in-plane (x-axis) magnetic field creates an out-of-plane Lorentz force. Figure 2 shows the torsional resonant mode and the out-of-plane common mode in the inset.
Magnetic Sensitivity

Figure 3(a) shows the block diagram for the test setup for magnetic field sensing. The Lorentz force is:

\[ F_L = Li \times B \]  

(1)

An external dc field modulated with the drive current at \( f_n \) generates a Lorentz force at \( f_n \). This force generates displacement amplified by the device’s mechanical quality factor \( Q \):

\[ x_B = \frac{Q \, \frac{\partial i}{\partial t}}{k} \]  

(2)

where \( k \) is the spring stiffness of the resonator.

Displacement can be sensed by the capacitive pick-off:

\[ C_{S\pm} \approx C_0 (1 \pm \frac{x_B}{g_0} \sin (\omega_n t)) \]  

(3)

where \( g_0 \) is the sense capacitor gap at rest and \( \omega_n \) is the resonant frequency of the magnetometer. The differential current generated from the sense capacitors can be expressed as:

\[ I_{S\pm} = \frac{dQ}{dt} = C_{S\pm} \, \frac{dv}{dt} + V \, \frac{dc_{S\pm}}{dt} \]  

(4)

where \( V \) is the voltage across the sense capacitor between node A and input of the trans-impedance amplifier (TIA):

\[ V = V_b + V_{mis} \cos (\omega_n t) \]  

(5)

where \( V_b \) is the DC bias voltage and \( V_{mis} \) is a voltage which is due to the mismatch between resistors \( R_1 \) and \( R_2 \), representing the resistance of the Si MEMS structure.

Combining (4) and (5), the current generated at \( \omega_n \) is

\[ I_{S\pm\omega n} = -\omega_n C_0 V_{mis} \sin (\omega_n t) \pm \omega_n V_b C_0 \frac{x_B}{g_0} \cos (\omega_n t) \]  

(6)

The first term is common to both pick-offs and can be nulled by differential measurement, leaving only the second term which is proportional to the applied magnetic field. The signal is converted to a voltage by the TIA, then demodulated at \( \omega_n \) for frequency-selective sensing. The magnetic sensitivity can be derived as:

\[ S_B = 2 \, \frac{C_0 \, V_b \, Q \, i}{C_f \, g_0 \, k} \]  

(7)

where \( C_f \) is the feedback capacitance of the trans-impedance amplifier.

Response to Acceleration

The mode shape of the motion due to z-axis acceleration is shown in the inset of Figure 2. Whereas Lorentz force creates differential response, acceleration causes both sense capacitances, \( C_{S+} \) and \( C_{S-} \), to vary in the same direction. Similar to the derivation of the magnetic sensitivity, the response to acceleration can be modeled by adding a common-mode displacement \( x_a \) to both \( C_{S+} \) and \( C_{S-} \).

\[ C_{S\pm} \approx C_0 (1 \pm \frac{x_a}{g_0} \sin (\omega_n t) + \frac{x_a}{g_0}) \]  

(8)

The acceleration-induced change in capacitance modifies the first term in (6), producing:

\[ I_{S\pm\omega n} = -\omega_n C_0 \left( 1 + \frac{x_a}{g_0} \right) V_{mis} \sin (\omega_n t) \]

\[ \pm \omega_n V_b C_0 \frac{x_a}{g_0} \cos (\omega_n t) \]  

(9)

We note that the first term now contains an acceleration-dependent component at \( \omega_n \), which could produce acceleration sensitivity in the magnetic sensor’s output. However, since this term is a common-mode current on both pick-offs, it is cancelled (to first-order) by differential measurement (Figure 3). In addition, the amplitude of the common-mode current relative to the differential (magnetic field-induced) current is small because \( V_{mis} \) is a small fraction of \( V_b \).

EXPERIMENTAL RESULTS

Frequency Response

Motion resulting from the Lorentz force is measured using differential capacitive sensing electrodes on a silicon cap chip bonded above the structural layer. The signal is acquired using a trans-impedance amplifier (TIA) connected to a digital lock-in amplifier (Zurich Instruments HF2LI). The resonator’s frequency response, shown in Figure 4, exhibits a 3 dB bandwidth of 69 Hz and a mechanical quality factor \( Q \) of 154.

![Figure 4: Frequency response for the magnetic sensor. A second-order transfer function fit to the measurement shows \( Q \) of 154 and a 3 dB bandwidth of \( f_n/2Q = 69 \text{ Hz} \).](image-url)
Magnetic Sensitivity

Magnetic field sensitivity was measured by varying the field strength of a 10 Hz ac magnetic field and recording the demodulated output amplitude. Figure 5 shows the measured sensitivity of 10.3 V/T. The sensor response is linear over 450 μT. Applied magnetic field is limited to 450 μT which is restricted by the test equipment. Figure 6 shows the output spectral density for a 10 Hz, 44 μT input (similar in amplitude to Earth’s field). The Lorentz force appears as sidebands ±10 Hz from the centered drive frequency. The noise floor is ~40 dB lower than the input magnetic signal. The total system noise of 210 nT/√Hz is dominated by Brownian noise which is marked by the red dashed line. A larger magnetic sensitivity and lower electronic noise allow this result to be achieved at 2 V dc bias in comparison with 15 V used in our earlier work [2]; the lower bias voltage is more compatible with CMOS processes.

![Figure 5: Measured magnetic field transfer characteristic. The sensor response is linear over a 450 μT range and the measured sensitivity is 10.3 V/T.](image)

Noise and Stability

The LFS sensor output must have low bias drift to achieve accurate compass readings. The bias drift, measured from the minimum of the sensor’s Allan deviation, is 60 nT with 28 s averaging time, as shown in Figure 7. Using $R_e = 10 \mu T$ as a conservative estimate of Earth’s field, this bias drift is equivalent to a maximum heading error of 0.34°, approximately 10x lower than a similar sensor operated at 10 V bias [9] and is attributable to the reduced up-conversion of the 1/f noise from the 2 V dc supply. Allan deviation also shows the resolution of 210 nT/√Hz at 1 s averaging time, which is consistent with our measurement from Figure 6.

![Figure 7: Allan Deviation measurement. The sensor has a bias drift of 60 nT with 28 s averaging time.](image)

Acceleration Test

Figure 8 shows a plot of the sensor output versus the input acceleration measured with 20 Hz bandwidth. The acceleration sensitivity was measured using a commercial accelerometer mounted next to the magnetic sensor. The sensor board was shaken by hand to avoid magnetic interference that would be created by an electromagnetic shaker. For an acceleration ranging from -0.5 g to 0.5 g, the sensor’s output shows an RMS variation of 900 nT, equal to the sensor’s noise floor with no acceleration input.

![Figure 8: LFS output versus input acceleration. The RMS variation of the output is $\sigma = 900$ nT, equal to the sensor’s noise floor and shows negligible sensitivity to acceleration.](image)

Another experiment was performed to measure the common-mode acceleration signal and to show that it can be nulled by taking differential measurements. From (9), the common-mode current induced by acceleration is proportional to $V_{mum}$, which is less than 50 mV assuming a maximum mismatch of 10% for $R_1$ and $R_2$, making the common-mode acceleration signal too small to measure. Thus we modified the detection electronics to a setup...
analogous to the one used in a conventional accelerometer (Figure 9) and intentionally increased $V_{\text{bias}}$ tenfold to 500 mV to increase the acceleration signal to a measurable level. No drive current was injected in order to null the magnetic field sensitivity. Figure 10 shows the output signal resulting from acceleration when measurements are taken both differentially and single-ended. The single-ended measurement shows acceleration sensitivity of 71 μV/g but the differential measurement shows no measurable response to acceleration.

![Figure 9](image1)  
**Figure 9:** Block diagram of the test setup to measure the common-mode acceleration signal.

![Figure 10](image2)  
**Figure 10:** Sensor output when tested using setup from Figure 9 showing no measurable response to acceleration. Inset: Single-ended measurement shows acceleration sensitivity of 71 μV/g.

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>DC bias voltage</td>
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<td>Natural frequency</td>
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### Table 1: Sensor parameters.

CONCLUSION

This work demonstrates a MEMS Lorentz force magnetic sensor based on a torsional resonator. Table 1 is a summary of the key parameters of the sensor. The sensor detects x-axis magnetic field and has a sensitivity of 10.3 V/T. This sensor requires lower bias voltage and lower power consumption compared to our previous work. It also shows better resolution and bias drift. Acceleration sensitivity in Lorentz force magnetic sensor is analyzed and measured in this work. The mechanically-balanced torsional resonator reduces the acceleration sensitivity to a level below sensor’s noise floor.

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REFERENCES


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