Johan Arbustini*, Johanna Muñoz, Huxi Wang, Eric Elzenheimer, Johannes Hoffmann, Lars Thormählen, Patrick Hayes, Florian Niekiel, Hadi Heidari, Michael Höft, Eckhard Quandt, Gerhard Schmidt, and Andreas Bahr

MEMS Magnetic Field Source for Frequency Conversion Approaches for ME Sensors

https://doi.org/10.1515/cdbme-2022-1079

Abstract: Some magnetoelectric sensors require predefined external magnetic fields to satisfy optimal operation depending on their resonance frequency. While coils commonly generate this external magnetic field, a microelectromechanical systems (MEMS) resonator integrated with permanent magnets could be a possible replacement. In this proof-of-concept study, the interaction of a MEMS resonator and the ME sensor is investigated and compared with the standard approach to achieve the best possible sensor operation in terms of sensitivity. The achievable sensor sensitivity was evaluated experimentally by generating the magnetic excitation signal by a coil or a small-sized MEMS resonator. Moreover, the possibility of using both approaches simultaneously was also analysed. The MEMS resonator operated with $20\,\mathrm{V_{pp}}$ at $1.377\,\mathrm{kHz}$ has achieved a sensor sensitivity of $221.21\,\mathrm{mV/T}$. This sensitivity is comparable with the standard approach, where only a coil for sensor excitation is used. The enhanced sensitivity of $277.0\,\mathrm{mV/T}$ could be identified by generating the excitation signal simultaneously by a coil and the MEMS resonator in parallel. In conclusion, these MEMS resonator methods can potentially increase the sensitivity of the ME sensor even further. The unequal excitation frequency of the MEMS resonator and the resonance frequency of the ME sensor currently limit the performance. Furthermore, the MEMS resonator as a coil replacement also enables the complete sensor system to be scaled down. Therefore, optimizations to match both frequencies even better are under investigation.

***Corresponding author: Johan Arbustini,** Department of Electrical and Information Engineering, Kiel University, Kaiserstraße 2, 24143 Kiel, Germany, e-mail: jrsa@tf.uni-kiel.de
Johanna Muñoz, Mechatronics Engineering Academic Area, Instituto Tecnológico de Costa Rica, Cartago, Costa Rica.
Huxi Wang, Hadi Heidari, James Watt School of Engineering, University of Glasgow, Glasgow, United Kingdom.
Eric Elzenheimer, Johannes Hoffmann, Michael Höft, Gerhard Schmidt, Andreas Bahr, Department of Electrical and Information Engineering, Kiel University, Kiel, Germany.
Lars Thormählen, Patrick Hayes, Eckhard Quandt, Department of Materials Science, Kiel University, Kiel, Germany.
Florian Niekiel, Fraunhofer Institute for Silicon Technology ISIT, Itzehoe, Germany.

Keywords: Magnetic field measurements, MEMS resonator, Magnetoelectric sensor, Frequency conversion.

1 Introduction

This work presents a novel magnetic field (MF) modulation strategy for future magnetic measurements. Bulky coils have significant advantages for resonance adjustment and can be adapted to new applications. The microelectromechanical systems (MEMS) resonator has excellent potential in small-scale applications. Therefore, the effects when MEMS resonator is placed close to a magnetoelectric (ME) sensor should be explored to develop low-noise and small-area alternatives for frequency conversion with ME sensors.

MEMS MF cantilevers consist of piezoelectric resonators that are excited by interactions between integrated permanent micromagnets, thus generating an MF [1]. Nevertheless, similar to the current source required for a statically driven coil, the disadvantage of the MEMS resonator is that a voltage source is required for its operation.

An optimal direct current (DC) bias MF on an ME sensor helps optimize the magnetic operation point of the sensor independent of the resonance frequency [2]. The application of alternating current (AC) signals for frequency conversion (sometimes also referred to as "modulation") exploits the nonlinear behaviour of ME sensors and their improved resonance sensitivity [3]. The presented study compared achievable ME sensor sensitivity values in single modulation by generating an AC magnetic excitation signal using a bulky coil or a MEMS resonator. In addition, how the overlapping magnetic fields impact the sensitivity of the ME sensor using double modulation was examined.

Thus, ME sensors maximize the ME coefficient through output voltage conversion and low-noise preamplifiers, resulting in the lowest possible noise contribution [4]. Although the nonlinear response of ME sensors is still under investigation, frequency conversion and enhanced low-frequency signal driving strategies could be applied to improve the magnetic sensitivity, which is required for some applications [5].

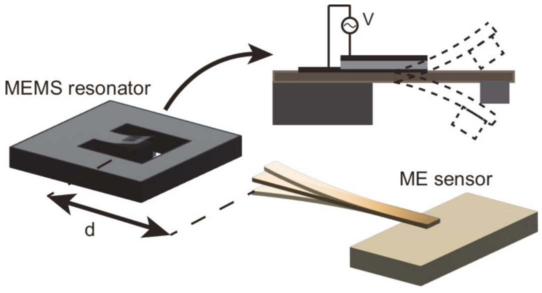

Fig. 1: Proof-of-principle by investigating the interactions between a MEMS resonator and an ME sensor.

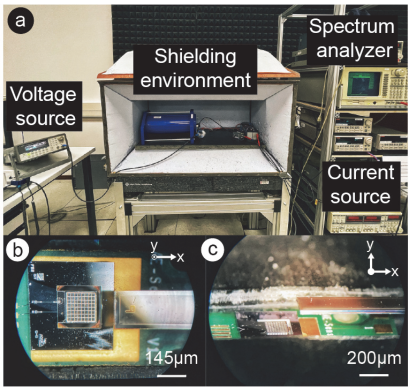

Fig. 2: (**a**) Experimental setup. (**b**) Top and (**c**) side views; the left object is the MEMS resonator (length $0.2\,\mathrm{mm}$) integrated with powder-based permanent magnets (NdFeB), and the right object is the ME sensor (length $20\,\mathrm{mm}$). The height of $2\,\mathrm{mm}$ in the y-axis and the distance of $0\,\mathrm{mm}$ in the x-axis are set by overlapping the top and avoiding mechanical contact.

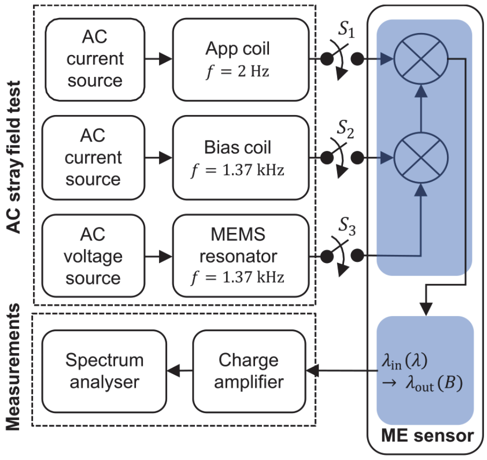

Fig. 3: Testing diagram with switches. Case 1 (SMMR): S_1 and S_3 closed, S_2 open. Case 2 (SMBC): S_1 and S_2 closed, S_3 open. Case 3 (DM): all closed.

2 Methods

As shown in Fig. 1, the alternating position of the magnet placed at the MEMS resonator tip induces a sinusoidal force on the ME sensor operating in the first resonance mode, which can be attributed to the dimensions of the cantilever ME sensor [1, 2, 6]. Thus, the ME sensor deflects and produces voltage signals because of the magnetic sensitivity. The following approximation defines the MF induced in the ME sensor by the MEMS resonator without considering the nonlinearities of the ME sensor or the two-dimensional distance as follows:

$$B(v_{\mathrm{in}}(t), d) \approx \frac{\beta(v_{\mathrm{in}}(t))}{d^3}[T] \qquad (1)$$

The AC excitation voltage ($v_{\mathrm{in}}(t)$) of the MEMS resonator affects the intrinsic constant MF generated by the MEMS resonator (β) and its hysteresis behaviour. The operation principle measures the output signal of the ME sensor while keeping the distance d as small as possible in a known value and maintaining the neglectable deflection angle of the cantilever beams [1]. The ME sensor does not necessarily follow the MEMS resonator deflection directly. Nevertheless, the ME sensor still depends on the MF generated by the MEMS resonator, which affects the magnetostriction of the ME sensor. For the configuration shown in Fig. 2, the x-component and y-component could be influenced by nonlinear behaviours of the ME sensor, even if the sign does not change.

Fig. 2(a) shows the experimental setup when both cantilevers are placed in the centre of the coil, which results in a precise and reproducible test MF [4]. The equipment includes one current source per coil (Keithley 6221), while the MEMS resonator is powered by a voltage source (Agilent 33250A). The ME sensor is connected to an electrically shielded low-noise charge amplifier (aluminium box) that is powered by batteries to amplify the output voltage signal. The cantilevers and coils are placed in a shielded environment, namely, a wooden box equipped with acoustic absorbers and a highly conductive mat, for electrostatic shielding and to prevent mechanical vibrations. Two unique holders were 3D ABS printed, one for the MEMS resonator and another for the ME sensor. Additionally, foam was added to improve the stability of the holders and ensure that the cantilevers were mechanically decoupled. The preamplified signal was measured using a signal analyser (model SR785) that acquired five root mean square (RMS) average measurements and 400 fast Fourier transform (FFT) lines with a span of $12.5\,\mathrm{Hz}$. Sections (b) and (c) represent the positions of the ISIT MEMS resonator and the ME sensor [1, 2].

The evaluation of a sensor system with ME sensors typically requires two coils because static and dynamic test fields must be generated (reproducible magnetic flux density) [1, 7, 8]. As presented in Fig. 3, the nonlinear response of the ME effect is sufficient for frequency conversion. Hence, three

MF sources were considered: the application (app) coil as an input MF test signal, the bias coil for a single modulation bulk coil (SMBC), and the MEMS resonator field for a single modulation MEMS resonator (SMMR). Test cases define whether the ME sensor operates with single or double modulation. A double modulation technique (DM) uses the SMBC and the SMMR simultaneously to modulate the input signal. Sensitivity and limit-of-detection (LOD) disadvantages arise because the employed cantilevers have different resonance frequencies, limiting the performance. Preliminary experiments have analysed potential improvements in signal detection by DM.

3 Results

The MEMS resonator behaviour was verified by changing its AC excitation voltage from $0\,\mathrm{V_{pp}}$ to $20\,\mathrm{V_{pp}}$ at a resonance frequency of $1.377\,\mathrm{kHz}$. An FM 302 teslameter (uniaxial probe AS-LAP) connected to the SR785 was used to measure the MF at $d = 0\,\mathrm{mm}$. Fig. 4 shows the hysteresis curve for the MEMS resonator, and the hysteresis effect is noticeable for input excitation voltages between $5\,\mathrm{V_{pp}}$ and $8\,\mathrm{V_{pp}}$.

Then, the results when d was varied between $0\,\mathrm{mm}$ and $9\,\mathrm{mm}$ are displayed in Fig.5. The figure illustrates model deviations because of the assumptions in the mathematical approximation and that the MF had the greatest magnitude near the tip of the MEMS resonator. Thus, the subsequent tests maintain the ME sensor at $d = 0\,\mathrm{mm}$ to ensure that both the MEMS resonator and the ME sensor are covered.

The coils used for modulation and MF generation were characterized using an FM 302 teslameter and the steps described by Durdaut et al. [4]. The bias coil was excited at $1.377\,\mathrm{kHz}$ and the current source was set to $46\,\mathrm{mA_p}$, yielding $296.4\,\mathrm{\mu T_{rms}}$. Similarly, for the application coil, the frequency of the current source was set to $2\,\mathrm{Hz}$ and the current amplitude was $5\,\mathrm{mA_p}$, yielding $66.05\,\mathrm{\mu T_{rms}}$.

The MEMS resonator was supplied with a power of $20\,\mathrm{V_{pp}}$, generating an MF of approximately $27.16\,\mathrm{\mu T_{rms}}$. The noise density shown in Fig. 6 was predominantly due to the ME sensor, which was connected to the charge amplifier and limited by the unmatched resonance frequencies. The frequencies near the carrier ($1.377\,\mathrm{kHz}$) were set to $\pm\,2\,\mathrm{Hz}$ based on the frequency of the application coil. The noise density was $2.87\,\mathrm{\mu V_{rms}}/\sqrt{\mathrm{Hz}}$ when a modulation was employed, similar to all the cases. Despite the high noise density, the application input signal led to an output signal of $15.26\,\mathrm{\mu V_{rms}}$; however, there was an LOD of approximately $10.6\,\mathrm{\mu T_{rms}}/\sqrt{\mathrm{Hz}}$.

Case 2 in Fig.7 depicts the SMBC, and case 3 shows the DM. These results present output magnitude responses similar to the input amplitude at $2\,\mathrm{Hz}$. Case 2 (SMBC) includes a symmetrical response at $\pm\,2\,\mathrm{Hz}$; however, case 1 (SMMR) or case 3 (DM) affects the maximum value achieved by the carrier, which becomes larger and wider. Additionally, at $2\,\mathrm{Hz}$, the responses of the two cases are similar, but a nonlinear effect is observed at $-2\,\mathrm{Hz}$, which could be related to the MF distribution. Finally, the ME sensor sensitivity shown in Fig. 8 represents the relationship between the ME sensor output voltage and the applied MF. In case 1 (SMMR), the sensitivity increases as the MEMS input AC voltage amplitude increases; however, in case 3 (DM), the sensitivity tends to be stable and independent because of the bias coil MF, similar to case 2 (SMBC). After the voltage reaches $18\,\mathrm{V_{pp}}$ in case 3 (DM), the MEMS resonator MF overwhelms the sensitivity, similar to case 1; this effect reduces the noise and causes the sensitivity to increase slightly to $277.0\,\mathrm{mV/T}$.

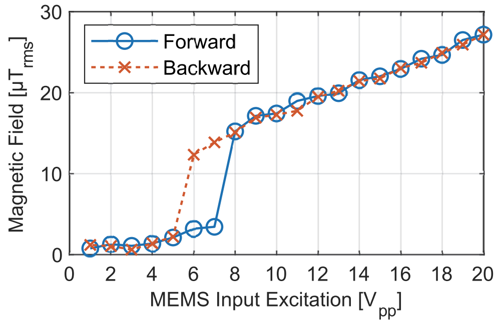

Fig. 4: MEMS resonator hysteresis curve for forwards to backwards input excitation at $d \approx 0\,\mathrm{mm}$.

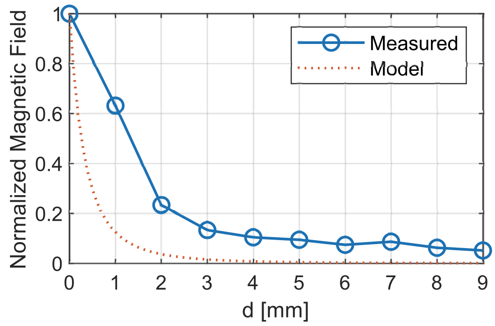

Fig. 5: MEMS resonator calibration, showing the normalized MF versus d.

4 Conclusions and Outlook

The capability of the MEMS resonator to serve as a single modulation was tested with an ME sensor, achieving a readable value of $66.05\,\mathrm{\mu T_{rms}}$ and a noise density of $2.87\,\mathrm{\mu V_{rms}}/\sqrt{\mathrm{Hz}}$ near the carrier.

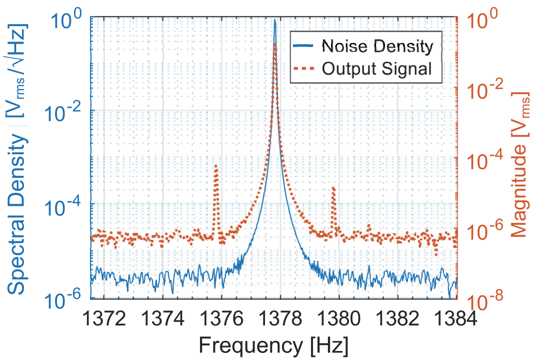

Fig. 6: Noise density and output signal of the ME sensor using the SMMR.

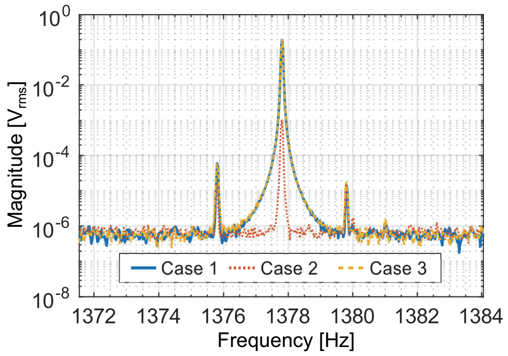

Fig. 7: Effects of the carrier generator on the modulation. Case 1 (SMMR). Case 2 (SMBC). Case 3 (DM).

For the double modulation, once the MEMS resonator excitation voltage reaches a dominant value, it enhances the sensitivity due to interactions with the bias coil, but this effect is limited by the increased carrier magnitude because of the MEMS resonator.

As the sensitivity also depends on mechanical resonance, future work should optimize the cantilever dimensions to obtain the resonance frequencies in a desirable range of compatibility and work with more reliable magnetic field measurements. Thus, if the resonance frequencies are matched, the limit-of-detection and sensitivity should approach state-of-the-art ME sensors and allow finding possible applications based on quantitative measures.

Acknowledgment: We thank Björn Gojdka and Torben Dankwort from the Fraunhofer Institute for Silicon Technology ISIT, Itzehoe, Germany for their support.

Author Statement

Research funding: This work was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) through the Collaborative Research Centre CRC

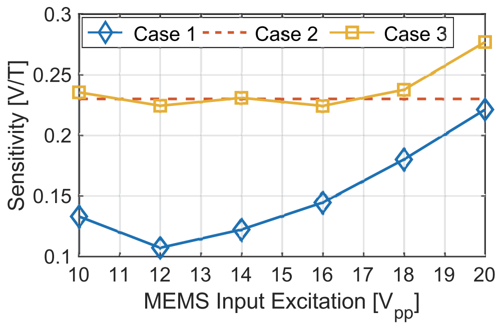

Fig. 8: ME sensor sensitivity versus the MEMS resonator excitation voltage outside the hysteresis region.

1261 "Magnetoelectric Sensors: From Composite Materials to Biomagnetic Diagnostics". Conflict of interest: The authors declare no conflicts of interest. Informed consent: Informed consent was obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations and institutional policies and was performed in accordance with the tenets of the Helsinki Declaration and approved by the author's institutional review board or equivalent committee.

References

[1] F. Niekiel *et al.*, "Highly sensitive mems magnetic field sensors with integrated powder-based permanent magnets," *Sensors and Actuators A: Physical*, 2019.
[2] R. Jahns *et al.*, "Magnetoelectric sensors for biomagnetic measurements," in *2011 IEEE International Symposium on Medical Measurements and Applications*, 2011.
[3] S. Salzer *et al.*, "Comparison of frequency conversion techniques for magnetoelectric sensors," *Procedia Engineering*, vol. 120, 2015.
[4] P. Durdaut *et al.*, "Low-frequency magnetic noise in statically-driven solenoid for biasing magnetic field sensors," *arXiv: Instrumentation and Detectors*, 2020.
[5] G. Schmidt *et al.*, *Magnetoelectric Sensor Systems and Applications.* MDPI Sensors, 2022.
[6] M. Korsa *et al.*, "Optimizing piezoelectric cantilever design for electronic nose applications," *Chemosensors*, 2020.
[7] E. Elzenheimer *et al.*, "Quantitative evaluation for magnetoelectric sensor systems in biomagnetic diagnostics," *Sensors*, 2022.
[8] P. Durdaut *et al.*, "Fundamental noise limits and sensitivity of piezoelectrically driven magnetoelastic cantilevers," *Journal of Microelectromechanical Systems*, 2020.