Quantum sensors for electromagnetic induction imaging

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***Abstract*— The demonstration of electromagnetic induction imaging with radio-frequency atomic magnetometers has recently opened new avenues for the development of this imaging technique. This paper analyses the state-of-the-art of the technology and identifies directions for future developments.**

***Keywords*— quantum sensors, atomic magnetometers, electromagnetic induction imaging**

I. INTRODUCTION

Electromagnetic induction imaging (EMI) [1] is a contactless technique which relies on the induction of eddy currents in the target object of interest, and the detection of these currents via the measurement of the secondary magnetic field they produce. EMI allows one to image the object of interest in the form of a map of the object passive electromagnetic properties. When supplemented by appropriate inversion algorithms, EMI also displays full tomographic capabilities, and for this reason is often termed magnetic induction tomography (MIT). Despite the wealth of potential applications, from medical imaging to security and surveillance, and industrial monitoring, EMI has not yet become a viable technique. A major factor which prevented EMI deployment in real world scenarios was the lack of sensors with extreme sensitivity at low frequency, as required for the detection of the secondary field produced by the eddy currents. This significant limiting factor was recently overcome by the use of radio-frequency atomic magnetometers (RF-AMs), which exhibit extreme sensitivity at low frequency. This paper analyses the current state of the technology, potential use cases and future developments required for near-future deployment in real world scenarios.

II. CURRENT STATE OF THE TECHNOLOGY

A. Electromagnetic induction imaging

Electromagnetic Induction Imaging (EMI) allows mapping of the electrical and magnetic properties of an object. It relies on the active probing of the conductivity σ, permittivity ε and permeability μ of a target by a small oscillating magnetic field.

In the standard EMI configuration, an induction coil generates a primary magnetic field (B1) at a desired frequency, ω. The primary field induces eddy currents in the sample of interest, which in turn produce a secondary field (B2), oscillating at the same frequency ω. The properties of the secondary field, in particular its amplitude and phase lag, depend on the specimen's electromagnetic properties σ, ε, and μ. Therefore, by measuring the secondary field at different positions, the electromagnetic properties of the sample can be mapped, and an image of the target can thus be created. Measurement of the secondary field is carried out by using a set of coils. In this way, the performance and the imaging capability can be severely limited by the poor response of the coils. Consequently, coil-based EMI has limited sensitivity below 50 MHz. Lack of sensitivity at low frequency has limited the application of EMI to high-conductivity metallic objects and frequencies in the range of several MHz. Thus, EMI has been extensively used only in a very limited set of applications, and mostly for non-destructive evaluation of quality and integrity in industrial processes. Notably, poor sensitivity of induction coil-based sensors has prevented the successful implementation of EMI for biological tissues, which produce very small secondary fields due to their very low conductivity (~1 S/m).

B. EMI with Atomic magnetometers

The fundamental sensitivity limit of atomic magnetometers [2] is frequency-independent and is of the order of a few $fT/Hz^{1/2}$. The significant advantage of the use of atomic magnetometers in EMI systems is thus evident: AMs can efficiently operate from few hundreds Hz to a few MHz, depending on the application area of interest, and this is precisely where induction coil-based systems lose sensitivity while atomic magnetometers' fundamental limit of sensitivity is unchanged. The early demonstrations of EMI with atomic magnetometers (EMI-AM) [3,4] opened up new avenues for the technique, as applications in biomedical imaging, security and surveillance and industrial monitoring suddenly appeared within reach. This stimulated a rapid development of the technology in several different aspects. In terms of absolute performances, the development culminated with the demonstration of imaging of small samples (few mL) of saline solutions with conductivity below 1 S/m [5], thus validating the technique for biomedical applications. On the computational side, the use of machine learning in conjunction with EMI-AM was proved effective for the classification of images [6]. Finally, a compact RF-AM was realized specifically for EMI applications, and it was shown that the sensor could be mechanically translated while taking data, thus enabling its deployment in real world scenario [7]. Finally, a rapid EMI scheme was demonstrated with optical raster-scanned AMs, so to eliminate dead times during the measurements due to mechanical motion [8].

III. USE CASES

EMI with atomic magnetometers opens up a wealth of applications. In fact, high sensitivity operation at low frequency enables interesting new regimes for EMI. On the one hand, the possibility to lower the RF-AM operating frequency below the kHz level while retaining extreme sensitivity allows for imaging with deep penetration through barriers. On the other hand, high-sensitivity operation at the MHz level allows for detection and imaging of biological tissues, characterized by very low conductivity. Several use cases where EMI-AM has significant advantages over other techniques have already been identified, with proof-of-concepts recently completed or being carried out. Among recent and ongoing developments, we mention:

(i) Imaging corrosion under insulation (CUI). The demonstration of CUI imaging with atomic magnetometers [9] is of great importance for the Oil and Gas Industry, as RF-AMs allow for low frequency operation, thus enabling imaging also below the surface of the metal pipe of interest. The more recent demonstration of CUI imaging with a mechanically translatable RF-AM [10] further progressed the technology, moving it closer to field deployment.

(ii) Underwater localization. Extreme penetration of barriers can be achieved using oscillating magnetic fields at ultra-low frequency (ULF range, 300 Hz to 3 kHz). Specifically, penetration of over 100 m of sea water can be achieved at 300 Hz. Given the extreme sensitivity of AMs at such a low frequency, their use opens the path to underwater localization applications, of relevance for safe navigation and in security and surveillance. A laboratory proof-of tracking with arrays of RF-AMs in EMI modality validated the approach [11].

(iii) A widespread problem in several manufacturing processes is the anchoring of a metal panel to a support structure. This is the case, for example, in aircraft wing assembly, where the wing outer skin must be fixed to anchoring points on the thick strut. The anchoring process requires the precise identification of the anchoring points without visual access. These anchoring points are often pilot-holes, which are pre-drilled in the thick strut. Through-skin pilot hole detection and localization can be achieved using EMI-AM operating at low frequency, without requiring any visual access to the pilot hole, as demonstrated by a very recent proof-of-concept [12].

(iv) Potential applications in the bio-medical field have also been identified, and several groups worldwide have made progress towards early proof-of-concept. Specifically, AMI-AM was identified [13] as a novel approach to the non-invasive diagnosis of atrial fibrillation. EMI has the potential to generate a non-invasive, space-resolved map of the heart's conductivity, thus directly addressing the presence of permanent conduction anomalies, which are believed to be closely related with the onset and the dynamics of fibrillation. Following the proposal to use EMI-AM for active imaging of the human heart and the diagnosis of atrial fibrillation, progress has been made to improve the sensitivity of EMI-AM [5,14], and sub-S/m EMI was ultimately demonstrated [5], thus matching the requirements for biomedical imaging.

IV. Future developments

Further development of EMI-AM requires progress in several directions. First, the deployment of EMI-AM systems in real world settings requires the AM to retain its sensitivity in a magnetically noisy environment. Low-frequency magnetic noise is particularly detrimental for the operation of the AM. Compensation of the low-frequency noise, as detected by additional fluxgates, was shown to improve the sensitivity of the unshielded AM [15]. Implementation of two-photon transitions further reduces the detrimental effects of the ambient noise [16]. Despite all this progress, the sensitivity of AMs in magnetically noisy environments is still significantly worse than the fundamental limit, so progress is still required. Second, the implementation of EMI full tomographic capabilities requires numerical algorithms which allows for the generation of a 3D map from a finite set of measurements. The standard approach requires the solution of the inverse problem of electromagnetism. Unfortunately, this is an ill-posed problem and, despite decades of work in this area, a general and robust approach is still lacking. An alternative approach is machine learning (ML), which is robust. However, in the context of EMI ML-based image classification was only demonstrated in 2D [5], and further work is required to explore the feasibility of ML applications to three-dimensional EMI. Another approach to tomographic imaging involves the idea of magnetic field synthesis [17], where a set of coils with appropriately tailored currents would allow one to induce eddy currents only in a desired portion of the target. Thus, by sequentially illuminating with the primary field different fractions of the target, it is possible to reconstruct a 3D image of the object.

V. Conclusions

The potential of electromagnetic induction imaging has never been fulfilled because of the lack of sensors with extreme sensitivity at low frequency, and lack of numerical algorithms and procedures enabling the robust generation of tomographic images. This paper discusses how the use of atomic magnetometers overcame the sensitivity issues, thus opening the path to a wide range of applications, with many proof-of-concepts for different use cases already produced. Possible strategies for the generation of tomographic images are also outlined.

References

[1] H. Griffiths, "Magnetic induction tomography", Meas. Sci. Technol., vol. 12, no. 8, pp. 1126-1131, 2001.

[2] D. Budker and M. Romalis, "Optical magnetometry", Nature Phys., vol. 3, no. 4, pp. 227-234, Apr. 2007.

[3] A. Wickenbrock, S. Jurgilas, A. Dow, L. Marmugi, F. Renzoni, "Magnetic induction tomography using an all-optical 87Rb atomic magnetometer," Opt. Lett. 39, 6367 (2014).

[4] C. Deans, L. Marmugi, S. Hussain, F. Renzoni, "Electromagnetic Induction Imaging with a Radio-Frequency Atomic Magnetometer", Appl. Phys. Lett., vol 108, 103503 (2016).

[5] C. Deans, L. Marmugi, and F. Renzoni, "Sub-Sm-1 electromagnetic induction imaging with an unshielded atomic magnetometer", Appl. Phys. Lett., vol 116, 133501 (2020).

[6] C. Deans, L.D. Griffin, L. Marmugi, and F. Renzoni, "Machine learning based localization and classification with atomic magnetometers", Phys. Rev. Lett. , vol 120, 033204 (2018).

[7] C. Deans, Y. Cohen, H. Yao, B. Maddox, A. Vigilante and F. Renzoni, "Electromagnetic induction imaging with a scanning radio frequency atomic magnetometer", Appl. Phys. Lett., vol. 119, 014001, Jul. 2021.

[8] B. Maddox, C. Deans, H. Yao, Y. Cohen and F. Renzoni, "Rapid Electromagnetic Induction Imaging with an Optically Raster-Scanned Atomic Magnetometer", IEEE Trans. Instrum. Meas., vol 72, 4503105, (2023).

[9] P. Bevington, R. Gartman, W. Chalupczak, C. Deans, L. Marmugi and F. Renzoni, "Non-destructive structural imaging of steelwork with atomic magnetometers", Appl. Phys. Lett., vol. 113, no. 6, Aug. 2018.

[10] B. Maddox, Y. Cohen and F. Renzoni, "Imaging corrosion under insulation with a mechanically-translatable atomic magnetometer", Proc. IEEE Int. Workshop Metrology Ind. 4.0 IoT (MetroInd4.0&IoT), pp. 104-108, Jun. 2022.

[11] C. Deans, L. Marmugi and F. Renzoni, "Active underwater detection with an array of atomic magnetometers", Appl. Opt., vol. 57, no. 10, pp. 2346-2351, 2018.

[12] B. Maddox, Y. Cohen, and F. Renzoni, "Through-Skin Pilot-Hole Detection and Localisation with a Mechanically-Translatable Atomic Magnetometer", Appl. Phys. Lett., vol 120, 014002 (2022).

[13] L. Marmugi and F. Renzoni, "Optical magnetic induction tomography of the heart", Sci. Rep., vol. 6, no. 1, pp. 23962, Apr. 2016.

[14] K. Jensen, M. Zugenmaier, J. Arnbak, H. Staerkind, M. V. Balabas, and E. S. Polzik, “Detection of low-conductivity objects using eddy current measurements with an optical magnetometer,” Phys. Rev. Res., vol 1(3), 033087 (2019).

[15] H. Yao, B. Maddox, and F. Renzoni, “High-sensitivity operation of an unshielded single cell radio-frequency atomic magnetometer”, Opt. Express, vol 30, 42015 (2022).

[16] B. Maddox, and F. Renzoni, “Two-photon Electromagnetic Induction Imaging with an Atomic Magnetometer”, Appl. Phys. Lett., vol 122, 144001 (2023).

[17] D. Cubero, L. Marmugi, and F. Renzoni, “Exploring the limits of magnetic field focusing: simple planar geometries”, Results Phys., vol 19, 103562 (2020).