PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Electromagnetic imaging with atomic magnetometers: applications in security and surveillance

Ferruccio Renzoni

Ferruccio Renzoni, "Electromagnetic imaging with atomic magnetometers: applications in security and surveillance," Proc. SPIE 12274, Emerging Imaging and Sensing Technologies for Security and Defence VII, 122740P (7 December 2022); doi: 10.1117/12.2635309

Event: SPIE Security + Defence, 2022, Berlin, Germany

Electromagnetic imaging with atomic magnetometers: applications in security and surveillance

Ferruccio Renzoni

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

ABSTRACT

We give an overview of our research programme on the use of atomic magnetometers to detect and image concealed conductive objects via electromagnetic induction. The extreme sensitivity of atomic magnetometers at low frequency, several orders of magnitude higher than a coil-based system of similar size, allows for their operation in such a frequency range, thus permitting deep penetration through different barriers. This overcomes the limitations usually associated with electromagnetic detection. Applications in security and surveillance are discussed.

Keywords: Atomic magnetometers, electromagnetic induction imaging

1. INTRODUCTION

This paper reviews our progress in electromagnetic induction imaging with atomic magnetometers to detect and image concealed conductive objects, with direct application in security and surveillance. Atomic magnetometers are ideal sensors for electromagnetic induction detection as they retain extreme sensitivity at low frequency, thus overcoming the limitations of coil-based systems. Operation at low frequency is thus possible, and allows for deep penetration through different barriers. The combination of the penetration capabilities and the lack of ionising radiation makes electromagnetic induction imaging very attractive for large scale security screening and for surveillance applications, despite the inherent low resolution of the technique.

The paper is organised as follows. We first introduce the basic principles of electromagnetic induction imaging and of atomic magnetometers. We then describe proof-of-concept demonstrations of imaging through barriers of different nature with direct applications in security and surveillance. We finally discuss the current state of the technology, in particular describing our new compact setup for imaging with atomic magnetometers. Electromagnetic induction imaging was demonstrated with an unshielded, portable radio frequency atomic magnetometer scanning over the target object. This configuration satisfies standard requirements in typical applications in security screening and surveillance applications.

2. BACKGROUND

This section provides a background of the key concepts and technologies that underpin electromagnetic induction imaging with atomic magnetometers. We first introduce the basic concepts of electromagnetic induction imaging (EMI) (or magnetic induction tomography (MIT)).[1] Then, we introduce the principles of atomic magnetometers[2] (AMs) – focussing in particular on radio-frequency AMs which are widely used for EMI applications.

Further author information: (Send correspondence to F.R.)
F.R.: E-mail: f.renzoni@ucl.ac.uk, Telephone: +44 (0)207 679 7019

Emerging Imaging and Sensing Technologies for Security and Defence VII, edited by Gerald S. Buller, Richard C. Hollins, Robert A. Lamb, Martin Laurenzis, Proc. of SPIE Vol. 12274, 122740P
© 2022 SPIE · 0277-786X · doi: 10.1117/12.2635309

2.1 Electromagnetic Induction Imaging

EMI is a non-contact technique which allows one to probe a sample's electromagnetic properties. It can provide maps of the electromagnetic properties of a target object, i.e. the conductivity σ, the relative permittivity ϵ_r, and the relative permeability μ_r.

The key principles of electromagnetic induction imaging are shown in Fig. 1. An oscillating magnetic field – referred to as the primary field – is applied to induce eddy currents in the target object. Eddy currents generate a response magnetic field component - the secondary field. The sample's electromagnetic properties determine the properties of the secondary field. Therefore, its detection, via a magnetic field sensor, allows a measurement of them. Electromagnetic induction images of samples can be generated by taking spatially resolved measurements of the secondary field.

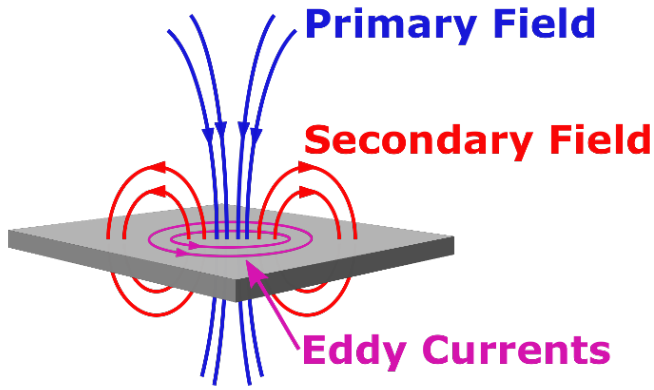

Figure 1. Principles processes in electromagnetic induction imaging: the application of an oscillating magnetic field induces eddy currents in the target objects and leads to the generation of the secondary field which carries information about the sample.

An interesting feature of electromagnetic induction imaging is the possibility of penetrating barriers, by lowering the frequency of the applied oscillating magnetic field. Indeed, a barrier with electromagnetic properties μ_r, ϵ_r and σ_r can be penetrated by the magnetic field by lowering its frequency ω so that the skin depth

$$\delta = \sqrt{\frac{2}{\sigma\omega\mu}}\sqrt{\sqrt{1+\left(\frac{\omega\epsilon}{\sigma}\right)^2}+\frac{\omega\epsilon}{\sigma}} \tag{1}$$

becomes comparable or larger to the thickness of the barrier. This allows detection and imaging of target objects concealed behind the barrier, as it will be further discussed in the following.

2.2 Atomic magnetometers

Atomic magnetometers (AMs)[2] constitute an ultra-sensitive approach to the detection of magnetic fields. Importantly, AMs fundamental limit of sensitivity is not frequency-dependent, so AMs can retain extreme sensitivity at low frequency. The ability to tune AMs while retaining high sensitivity is the key to applications in security and surveillance, as it allows for lowering the operational frequency so to achieve the desired penetration depth.

Several different types of atomic magnetometers exist. All the results reviewed here[3–6] were obtained using radio-frequency atomic magnetometers (RF-AMs).[7] They detect oscillating magnetic fields by bringing them into resonance with Zeeman transitions in the ground state. The operating frequency can be tuned with the help of a bias magnetic field over a wide range, from near DC to the MHz band. The core of our RF-AM is a 25 mm cubic quartz cell cell containing rubidium vapour and 20 Torr of Nitrogen as a buffer gas. The laser fields arrengement follow the standard configuration for RF-AMs.[7] A circularly polarised laser beam, propagating along the direction of the applied DC bias field, polarises the atomic vapour. The magnitude of the bias field determines the desired operational frequency of the atomic magnetometer. An oscillating magnetic field perpendicular to the bias field drives the atomic precession. This field, applied at the frequency specified by the bias field so to be resonant with the ground state Zeeman transitions, also serves as the primary field for EMI. The atomic precession is measured by a weak linearly polarised probe beam, propagating perpendicularly to the pump beam. The precession of the atomic spins is transferred to the probe beam as rotations in its plane of polarisation. Such rotation is monitored with the help of a balanced polarimeter and a lock-in amplifier.

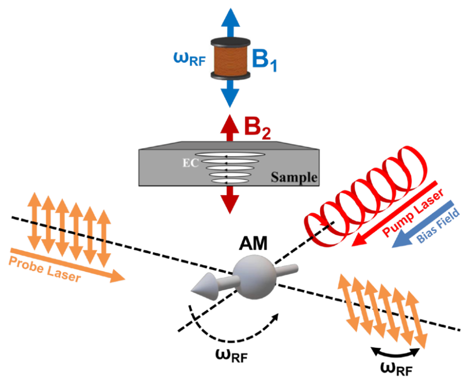

Figure 2. Configuration of the RF-AM and set-up for EMI measurements.

The variation in phase and amplitude of the measured total magnetic field with respect to the primary field carry information on the electromagnetic properties of the target object. Images are created by displacing the target object with respect to the sensor.

3. IMAGING THROUGH BARRIERS

The ability to operate the AMs at low frequency while retaining high sensitivity constitutes an important advantage with respect to coil-based EMI systems. In fact, low-frequency operation leads to large penetration depths, thus enabling a wealth of applications in security and surveillance. In the following, proof-of-concept demonstrations in these two areas are reviewed.

3.1 Detection and imaging through metallic shields

Imaging through metallic shields is a requirement in many security procedures, from cargo and vehicle screening to parcel inspection. Through-barrier EMI for security applications was first demonstrated with a coil-based system,[8] with successive developments[4] with RF-AMs showing the full potential of the technique to penetrate thick metallic barriers. That work demonstrated imaging of a Cu disk of 30 mm diameter and 2 mm thickness through a combination of a 2.5 mm steel shield and 2 mm Al shield, at an operating frequency of 330 Hz so to guarantee penetration through the barriers.

It is interesting to compare EMI with the gold standard for imaging through barriers: X-ray imaging. While EMI is inherently a low-resolution technique, it has the significant advantage over X-ray imaging of not requiring ionizing radiation. This is a crucial advantage for large scale security screening.

3.2 Underwater tracking and localisation

Low-frequency operation of RF-AM based EMI systems also allows for underwater detection applications. Active detection, localization, and real-time tracking of submerged conductive, nonmagnetic targets was demonstrated using an array of RF-AMs operating in EMI-modality[5] .

EMI-AM has some advantage for underwater detection with respect to existing techiniques. With respect to the use of atomic magnetometers in passive mode, active detection does not rely on the spontaneous magnetisation of the target object, and thus makes de-gaussing techniques ineffective. With respect to acoustic waves based techniques, EMI does not suffer from reflections from the sea bed, and thus it is effective also in shallow waters, of interest for harbour security. Finally, EMI-AM is also interesting for safe navigation, as it has great potential to effectively detect submerged metallic objects near a ship hull.

4. STATE OF THE TECHNOLOGY

All the proof-of-concept demonstrations discussed so far relied on laboratory-based set-ups, with the atomic magnetometer being fixed in the laboratory frame and images formed by displacing the object with respect to the RF-AM. Real-world applications correspond to different settings. In security, a compact sensor head is required to move over the target object of interest - a cargo container, a vehicle or a parcel for example - to detect and localise suspicious items. Surveillance applications require the installation of a set of sensors at wanted locations in space so to be able to localise and track the target object within the region of interest. Work by the University College London (UCL) team over the last few years towards the realisation of a suitable sensor has culminated with the development of an unshielded portable RF-AM, shown in Fig. 3, which was shown to be able to spatially scan over a fixed target object[6] . This satisfies the requirements for real-world applications.

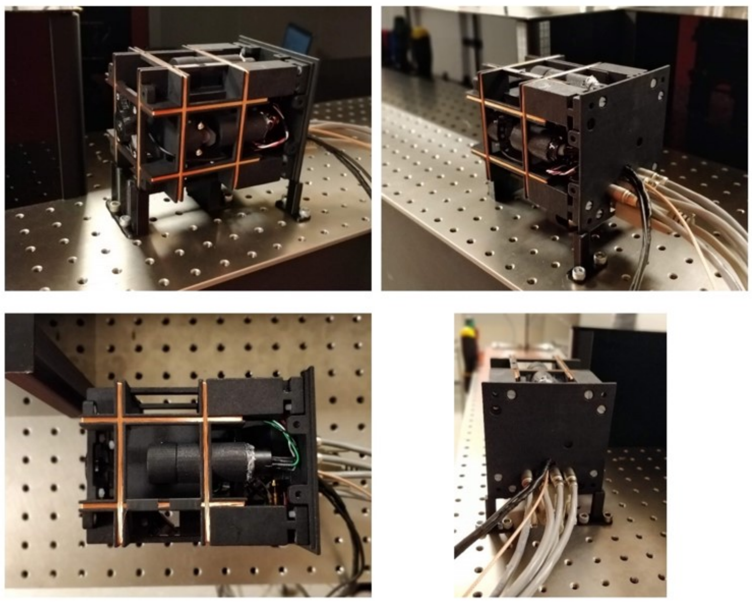

Figure 3. Photo of the UCL compact RF-AM with the cover removed.

A few features of our compact atomic magnetometer are essential for its operation while being displaced at different locations. First, the sensor head includes all the required lasers sources. This avoids the use of optical fibres which make motion problematic. Second, the sensor head includes a set of magnetic field coils for the active compensation of stray magnetic fields. This allows for the compensation of the unwanted background magnetic field after any displacement of the sensor. Finally, a procedure was implemented to reduce the impact of any residual spatial variations in the magnetic environment experienced by the sensor head while scanning over the target object.

5. CONCLUSIONS

Electromagnetic induction imaging has tremendous potential for security and surveillance application. It allows penetration through barriers, without the involvement of ionising radiation. However, its development has been hindered by poor performances of coil sensors at low frequency, as required for through-shield imaging. The work by the UCL team reviewed here demonstrated that the use of RF-AMs overcomes the limitations of coil-based EMI systems, thus realising the full potential at low frequency, in particular allowing imaging through metal shields. Progress in the development of the EMI-AM technique was accompanied by the design and realisation of a portable sensor, suitable for real-world applications.

Future work will include the development of new RF field sources, which will allow improved localisation and steering of the oscillating magnetic field over the target object, with increased potential for resolution and tomographic capabilities. This will be implementated used multiple coils arrangements.[9]

REFERENCES

[1] Griffiths, H., "Magnetic induction tomography," *Measurement science and technology* **12**(8), 1126 (2001).

[2] Budker, D. and Romalis, M., "Optical magnetometry," *Nature Physics* **3**(4), 227–234 (2007).

[3] Deans, C., Marmugi, L., Hussain, S., and Renzoni, F., "Electromagnetic induction imaging with a radio-frequency atomic magnetometer," *Applied Physics Letters* **108**(10), 103503 (2016).

[4] Deans, C., Marmugi, L., and Renzoni, F., "Through-barrier electromagnetic imaging with an atomic magnetometer," *Optics Express* **25**(15), 17911–17917 (2017).

[5] Deans, C., Marmugi, L., and Renzoni, F., "Active underwater detection with an array of atomic magnetometers," *Applied Optics* **57**(10), 2346–2351 (2018).

[6] Deans, C., Cohen, Y., Yao, H., Maddox, B., Vigilante, A., and Renzoni, F., "Electromagnetic induction imaging with a scanning radio frequency atomic magnetometer," *Applied Physics Letters* **119**(1), 014001 (2021).

[7] Savukov, I. M., Seltzer, S., Romalis, M., and Sauer, K., "Tunable atomic magnetometer for detection of radio-frequency magnetic fields," *Physical Review Letters* **95**(6), 063004 (2005).

[8] Darrer J., B., Watson, J. C., Bartlett, P., and Renzoni, F., "Magnetic imaging: a new tool for UK national nuclear security," *Scientific Reports* **5**, 7944 (2015).

[9] Cubero, D., Marmugi, L., and Renzoni, F., "Exploring the limits of magnetic field focusing: Simple planar geometries," *Results in Physics* **19**, 103562 (2020).