

Proceedings Article

X-ray-induced magnetic particle acoustic signal acquisition enhanced by magnetic field modulation

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Abstract

A magnetic field-modulated X-ray Induced Magnetic Particle Acoustic Imaging (xMPAI) technique is proposed, combining an external static magnetic field with ultrashort pulsed X-ray excitation for targeted signal enhancement from magnetic nanoparticles (MNPs). Under a controlled external magnetic field, MNPs exhibit enhanced thermoacoustic response due to magnetic polarization. Phantom experiments demonstrate a significant signal enhancement, with a 50% increase in frequency-domain amplitude and improved signal-to-noise ratio (SNR). By introducing magnetic field modulation, this method improves the detection sensitivity of MNPs, providing a potential strategy for high-contrast molecular sensing and imaging.

I. Introduction

X-ray Induced Magnetic Particle Acoustic Imaging (xMPAI) integrates the deep penetration of X-rays with the quantitative potential of magnetic nanoparticles (MNPs). While MNPs are excellent contrast agents, sensitive molecular detection relying solely on pulsed X-ray excitation remains limited. External magnetic fields can modulate the magnetization state of MNPs, potentially improving their energy absorption and conversion efficiency under pulsed excitation [1].

In this work, we introduce an external static magnetic field during ultrashort X-ray pulse excitation to polarize MNPs and amplify their thermoacoustic emission. This approach enhances signal intensity and enables spatial control over signal generation, offering a novel pathway for magnetically guided biomedical sensing [2,3].

II. Materials and methods

The acrylic phantom ($20 \times 20 \times 16 \text{cm}^3$) had a top opening. A neodymium permanent magnet ($200 \times 50 \times 15 \text{cm}^3$) was placed outside, generating a surface field of 1.2 T. The

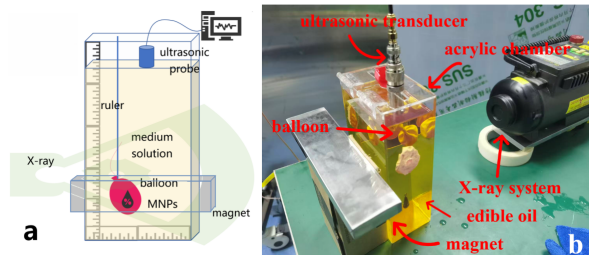


Figure 1: a) Schematic of xMPAI setup with external magnet. b) Photograph of setup.

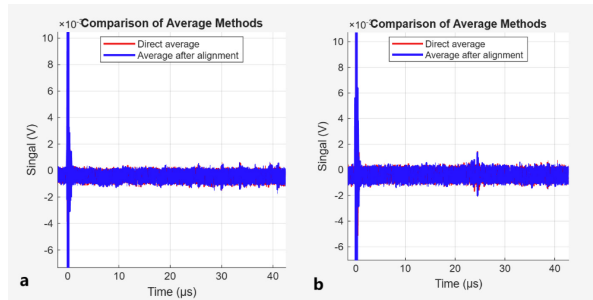


Figure 2: Time-domain responses of 50% MNPs: a) without field, b) with field. Signal duration: 40 μs . Amplitude scale: $\times 10^{-3}$ V.

field at the MNP location inside the oil-filled phantom was estimated to be 0.8–1.0 T, with a gradient < 50 mT/cm along the depth direction. Field distribution was characterized using a gaussmeter. An X-ray source (XR200, 150 kVp, 50 ns pulse) was placed in front. An ultrasonic transducer (I2-2.25P13-H, 2.25 MHz) was placed atop the phantom through the opening. MNP samples at 100% and 50% concentration were enclosed in rubber balloons immersed in oil (Figure 1).

Signals were acquired via an oscilloscope. Each measurement was repeated five times under with- and without-field conditions, and averaged to assess magnetic field effects. Standard deviation was $< 5\%$ of peak amplitude across repeats, indicating good repeatability.

III. Results and discussion

Acoustic signals from MNPs were analyzed with and without magnetic field modulation. In the time domain (Figure 2), the external magnetic field enhanced MNP signals, improving SNR. The signal duration was 40 μs . The direct and averaged signals showed high consistency, with amplitude differences $< 5\%$ of peak values. The dynamic range (peak-to-noise ratio) was 5:1.

In the frequency domain (Figure 3), signals under magnetic field exhibited a significant amplitude increase. The main frequency range was 0–5 MHz. The maximum amplitude increased from 4×10^{-4} V (without field) to $6 \times$

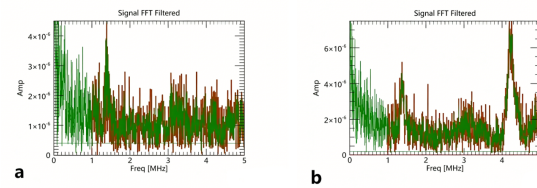


Figure 3: Frequency-domain responses of 50% MNPs: a) without field, b) with field. Frequency range: 0–5 MHz. Amplitude scale: $\times 10^{-4}$ V. Maximum amplitude increased by 50% with field.

10^{-4} V (with field), corresponding to a 50% enhancement. Noise amplitude remained below 2×10^{-4} V in both cases.

The enhancement is attributed to magnetic polarization aligning MNP magnetic moments, promoting more efficient energy conversion from X-ray pulses to thermoacoustic emission. The applied field reduces MNP response non-uniformity, leading to stronger and more coherent acoustic output.

The tested concentrations (50% and 100%) showed consistent enhancement trends. Future work will include a broader concentration range to investigate scaling behavior.

The top-placed transducer geometry in this proof-of-concept study allowed clear signal acquisition from the shallow phantom. For in vivo applications, tissue attenuation, depth penetration, and optimal transducer positioning will need further investigation. Safety considerations regarding high-intensity X-ray pulses and strong static magnetic fields will also be addressed in future translational studies.

IV. Conclusion

We demonstrated that an external magnetic field can significantly enhance X-ray-induced acoustic signals from MNPs, with a quantifiable 50% amplitude increase and improved SNR. The proposed method improves signal amplitude and provides a means for spatial control via magnetic modulation. Future work will optimize field geometry, explore dynamic fields, and integrate xMPAI with magnetic particle imaging (MPI) toward a multimodal platform.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant No. 82227802, 62471370, and 62471320, and in part by the Key Project of Liaoning Provincial Department of Science and Technology under Grant No. 2022JH1/10500004.

Author's statement

Conflict of interest: Authors state no conflict of interest.

Informed consent: Not applicable. Ethical approval: Not applicable.

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