2D-MPI System using second harmonic with HTS-SQUID

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Abstract. Magnetic Particle Imaging (MPI) is an imaging technique, with high sensitivity and high speed imaging, utilizing non-linear magnetization response for detection of superparamagnetic iron oxide nanoparticles (MNP). MPI measures the magnetization change in the MNP under the AC magnetic field. Since the signal of the magnetization change is much smaller than the signal generated by the AC magnetic field, the signal response at the fundamental frequency cannot be used. Accordingly, it is the third harmonic of the response that is generally measured. However this method has disadvantages that the power of the AC magnetic field is large and as a result the system increased in size. In this study, we investigated the 2D imaging using a second harmonic, which can be theoretically obtained with a greater signal than in the case of the third harmonic. Moreover, an HTS-SQUID (Superconducting Quantum Interference Device) magnetometer was employed in the study to enhance the peak signal to noise ratio (PSNR). A 2D-MPI system, which enables an imaging by scanning a DC magnetic field under a gradient magnetic field, was constructed. As a result, PSNR was increased by 1.5 times using SQUID with a Flux Transformer.

1. Introduction

MPI (Magnetic Particle Imaging) is an imaging technique, utilizing non-linear magnetization response for detection of magnetic nanoparticles [1]. Since it has high time resolution, the position and quantity of magnetic nanoparticles injected into the body are possible to grasp in real time. In the signal measurement of MPI, the most commonly employed method is detection of the third harmonic of the magnetic response, but it has disadvantages that power of the AC magnetic field is large and as a result the system increased in size. Therefore, we investigated a method to detect the second harmonic of the magnetization response, externally applying an AC magnetic field with the application of a DC magnetic field [2-6]. In this study, we improved the peak signal-to-noise ratio (PSNR) by applying an HTS-SQUID to a 2D imaging system, which detects the second harmonic of the magnetization response from magnetic nanoparticles.
2. Principle of MPI using second harmonic
In order to perform MPI using the second harmonic, it is necessary to apply a gradient magnetic field, a DC magnetic field, and an AC modulation magnetic field to the imaging region. Figure 1 shows the principle of MPI using the second harmonic. First, we describe 1D-imaging of the Z direction. By generating a gradient magnetic field in the imaging region, as shown in Figure 1 (a), a point FKP (Field Knee Point), indicated as a small square mark in the figure, at which the magnetic nanoparticle is saturated, is generated as positive and negative points (solid line as shown in Figure 1 (b)). The dotted arrows shown in Figure 1 (a) indicate magnetic field lines generated by a pair of NdFeB permanent magnets. By applying a DC magnetic field under this gradient magnetic field, the FKP is moved (dotted line as shown in Figure 1 (b)). Applying an AC magnetic field while scanning, the second harmonic signal, which is twice the frequency of the applied AC magnetic field frequency, becomes its maximum value when a magnetic field corresponding to FFP is applied to the position of the sample. Since + FKP and - FKP differ in phase by 180°, peaks with different polarity are detected. When the DC magnetic field is increased, even after applying an AC magnetic field, the second harmonic cannot be detected because the magnetic nanoparticles are magnetically saturated. For example, when the sample is placed in the center of the imaging region, a signal as shown in the left of Figure 1 (c) is obtained. However, as it is difficult to identify the position, the signal is differentiated as shown in the right of Figure 1 (c), so that a peak appears at the position of the sample. In the MPI using the second harmonic, this differentiated value is used for imaging. The DC field in the Z direction is scanned to obtain a 1D image. After scanning along the Z direction, the DC field in the X direction is changed with a step. By repeating the procedure, a 2D image is obtained.

![Figure 1. Principle of the MPI using second harmonic. (a) Schematic drawing of 2D-MPI system, (b) Gradient magnetic field in the imaging region, (c) Signal processing.](image-url)

2.1. Experimental system
In a 2D-MPI system, an AC magnetic field coil and a DC magnetic field coil were installed to apply DC and AC magnetic fields in the X and Z directions. The experimental system is shown in Figure 2. By controlling the output of the current source with a PC, the DC magnetic field was adjusted so that the scanning step became 0.5 mm. A signal of MPI was measured under the conditions of an AC magnetic field $H_{ac,z} = 1.59 \text{ mT} / \mu_0$ at 5.4 kHz, $H_{ac,x} = 2.32 \text{ mT} / \mu_0$ at 5.4 kHz, a DC magnetic field $H_{dc,z} = \pm 32 \text{ mT} / \mu_0$ and $H_{dc,x} = \pm 12.6 \text{ mT} / \mu_0$. The gradient magnetic fields, which were generated by a permanent magnet, were $G_z = 3.2 \text{ mT/mm}$ and $G_x = 1.3 \text{ mT/mm}$ in the Z and X directions, respectively. The imaging region was set in the range of ± 10 mm from the center in both the Z and X directions. As a sample,
Resovist 20 μl, in which magnetic nanoparticles with iron oxide (γ-Fe₂O₃) as a core were dispersed in water, was used. It was then put in a sample holder with a dimension of φ3 x 5 mm and placed in the center of the imaging region. Applying the DC and the AC magnetic field, the magnetization response from Resovist was detected by the differential detection coil. Then the signal from the magnetically coupled HTS-SQUID was connected to the lock-in-amplifier and the second harmonic component was measured. To reduce the noise, the signals were averaged by five times. The SQUID and the input coil were cooled with liquid nitrogen and they were placed in a three-layer permalloy magnetic shield. The measured signal was differentiated and imaged.

2.2. Flux Transformer
The flux transformer consists of a differential detection coil, a filter, an input coil and a HTS rf-SQUID. The HTS rf-SQUID and driving electronics used in the experiment are made by Jülicher SQUID GmbH in Germany. The circuit diagram is shown in Figure 3. When the SQUID was not used, the detection coil was directly connected to the lock-in-amplifier as shown in Figure 3 (a). When the SQUID was applied, the detection coil was connected to the input coil through a filter as shown in Figure 3 (b). The input coil and the HTS-SQUID were cooled at 77 K and magnetically coupled with a mutual inductance of 16 nH. Regarding the filter set, a band elimination filter (BEF) with a center frequency of 5.3 kHz and low pass filter were designed. Figure 4 shows the frequency characteristic of the flux transformer. Figure 4 (a) shows the spectra of the signal detected by the SQUID when the white noise of 1 Vpp was applied to the filter by the function generator (NF-WF 1974). In this case, the detection coil was removed. Although the center frequency of the BEF was designed as 5.3 kHz, the measured frequency was 5.4 kHz; as can be seen in Figure 4 (a). For this reason, the fundamental frequency of the applied AC magnetic field was set as 5.4 kHz. Since the resonant frequency was 10.8 kHz, the detection frequency of the lock-in-amplifier was set at 10.8 kHz as well. The shift of the frequency by 0.1 kHz may arise from an error of the capacitor. Figure 4 (b) shows the ambient magnetic field noise of the flux transformer without water sample, which was measured by the SQUID. The peak spectrum at the fundamental frequency of 5.4 kHz was 135 fT/Hz1/2 as small as the white noise level, while the

![Figure 2. MPI system.](image-url)
commercial frequency of 60 Hz was as large as 8.06 pT/Hz\(^{1/2}\). Concerning the detection frequency of 10.8 kHz, which is the second harmonic, the peak spectrum increased as 452 fT/Hz\(^{1/2}\) by the LC resonant. This means that the fundamental frequency was sufficiently suppressed and that the filter set worked well. Thus, measurement was carried out using the flux transformer with the filter set.

![Figure 3](image_url)  
**Figure 3.** Circuit diagram. (a) Direct amplification, (b) Using SQUID and flux transformer.

![Figure 4](image_url)  
**Figure 4.** Signal intensity dependent on frequency. (a) Spectra of filter, (b) Spectra of ambient magnetic noise of flux transformer.

### 3. Results and Discussion

Using the 2D-MPI system, measurements were carried out in the both cases, using the SQUID with the flux transformer or not. First, the signal of the detection coil was directly connected to the lock-in-amplifier. The sample Resovist 20µl was placed at the center of the imaging region. Then the sequence was started and the signal was recorded. For comparison, both of the signals with and without the sample were obtained. The phase was automatically adjusted by the lock-in-amplifier so that dispersion of the second harmonic component became a minimum. Figure 5 shows the result of the differentiated value of the measured signal in the Z direction. Figure 5 (a) shows 1D image at X = 0. As shown in the figure, the position of the peak was the same as the sample position. This indicates that the sample position was successfully identified by the system. Figure 5 (b) shows 2D contour images, which 1D image in the Z direction was repeatedly taken by changing the position in the X direction from X = -10 mm to 10 mm by a step of 0.5 mm. In this study, in order to evaluate the quality of the detected signal, the peak signal-to-noise ratio PSNR was defined and introduced. The PSNR was defined as the value, which the peak value of the signal was subtracted by the averaged noise and followed by division by standard deviation of the noise when the sample was placed in the center of the imaging region. From the measurement...
results shown in Figure 5 (b), by calculation using the following values: the peal value of the signal $6.4 \times 10^{-5}$ V/mm, the average value of noise $-2.3 \times 10^{-7}$ V/mm, the standard deviation of noise $1.5 \times 10^{-6}$ V/mm, the PSNR of 42 can be obtained.

Subsequently, measurement was performed using the SQUID and the flux transformer. The output signal of the SQUID was lock-in amplified and differentiated. Figure 6 (a) shows a 1D image obtained at $X = 0$; the position of the peak was the same as the sample position as well as in the case of measurement without the SQUID. Figure 6 (b) shows a 2D contour image made by repeating the 1D scanning along the $Z$ direction at the position of $X = -10$ mm to 10 mm. By calculation using the following values: the peal value of the signal $1.4 \times 10^{-3}$ V/mm, the average value of noise $-3.8 \times 10^{-6}$ V/mm, the standard deviation of noise $2.2 \times 10^{-6}$ V/mm, the PSNR of 64 was obtained.

Comparing the images between the direct lock-in amplification and via the SQUID amplification, the PSNR of the image obtained using the SQUID is 1.5 times larger than that obtained by direct amplification. We note that the contour images shown in Figure 5 (b) and Figure 6 (b) were elongated in the $X$ direction. This is because the gradient magnetic field in the $X$ direction was smaller than that in the $Z$ direction, as a result, the resolution in the $X$ direction may be poor.

**Figure 5.** Measurement results by direct amplification. (a) 1D image with $X = 0$, (b) 2D contour image map.

**Figure 6.** Measurement results is using SQUID. (a) 1D image with $X = 0$, (b) 2D contour image map.
4. Conclusion
In this study, we examined the second harmonic 2D-MPI system applying the flux transformer and HTS-SQUID to enhance the peak signal-to-noise ratio. The second harmonic component with a frequency of 10.8 kHz was amplified via the LC resonator with a resonant frequency of 10.8 kHz connected with the band elimination filter with a center frequency of 5.4 kHz.

From the measured results, the position of the peak was the same as the sample position. This indicates that the sample position was successfully identified by the system. Utilizing the SQUID and the flux transformer, the PSNR measured in the Z direction could be improved by 1.5 times; the advantage of using the SQUID amplification could be demonstrated. In the future, by applying a proper system function and a correction coefficient, the quality of the image will be improved.

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