Post Filtering Technique for High-Resolution Magnetic Image of an HTS Scanning SQUID Microscope

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Abstract. We have developed a post filtering technique by the numerical analysis program in MATLAB to improve the high-resolution magnetic image of an HTS scanning SQUID microscope. The SQUID has a high-permeability flux guide protruded to a sample in air at room temperature. Software filtering has an advantage that an object to analyze can be freely selected in comparison with hardware filters. The magnetic image of such a high-resolution as we can discriminate the magnetic microstructure of a few micron-size magnetic particles was obtained by means of our post filtering processing. It took only 38 seconds in case of our PC with a 2GHz processor.

1. Introduction
The scanning SQUID microscope is a powerful tool to detect fine images of very weak magnetic fields [1-4]. The most important parameter of the SSM is its spatial resolution magnetically. To improve the spatial resolution, Pitzius et. al. developed the SSM having a high permeability probe as a flux guide from the SQUID head to a sample [5]. Our group developed a HTS scanning SQUID microscope with a high permeability flux guide, and they have obtained a one-micron spatial resolution image by use of an extremely sharp tip [6,7]. The further improvement of higher signal-to-noise ratio in the SSM system was required to achieve its higher spatial resolution. In this work, we have developed a new post filtering technique by a numerical analysis program in MATLAB. Software filtering has an advantage that an object to analyze can be freely selected in comparison with hardware. The SSM magnetic image of magnetized toner particles was studied by using the new post filtering technique.

2. Procedure
The HTS scanning SQUID microscope (SSM) we employed is the same system reported by Hayashi and Itozaki [6,7]. The SSM is useful for investigation of magnetic samples at room temperature in air, having a permalloy needle of a tip radius less than 1 micron as a high permeability flux guide. The flux guide protrudes from the washer SQUID magnetometer on a cooled sapphire rod through a glue-hermetically vacuum-sealed glass window into a sample at room temperature in air so as to suck up its magnetic flux. The end of the flux guide was 0.1 mm distant in vacuum from the SQUID. The needle end of the flux guide was less than 5 micron separate from the sample.
Scanning data from the SSM were converted to a two-dimensional magnetic field image by using MATLAB. The $x$-$y$ stage was controlled by a stepper motor and used to move the sample in a raster scan under the SQUID, where $x$ was the scan line direction. The sampling pitch for the scanning was 2 micron in both $x$ and $y$ directions. The speed of each line scan was 0.13 mm/s. To eliminate noises out of the SSM electronics powered at the commercial frequency, the 50 Hz notch, 0.25 Hz high-pass and 1 kHz low-pass filters in hardware were applied to the SQUID output.

3. Results and Discussion
In order to improve the magnetic resolution of the SSM, we have developed a new post filtering technique by the numerical analysis program in MATLAB. The filtering for the elimination of noise from the flux locked loop circuit in the SSM system is made by hardware, in which it is difficult to set the most suitable filter in advance for every sample to measure. The software filtering has an advantage that an object to analyze can be freely selected.

As shown in Figure 1, our main program is composed of the data acquisition from the SQUID, the sampling procedure for fast Fourier transform (FFT), the FFT-filtering of various software filters, the edge emphasis processing, and the image conversion into JPEG. It is also possible directly to convert the SQUID data into a JPEG image for comparison with the processed image.

Figure 2 (a) shows the optical image of a 5 strip-lines sample printed with magnetic ink toners, which is magnetized in the direction of the lines. The magnetic signal spectrum data are obtained by raster-scanning on the sample with a flux guide needle in the SSM system. Figure2 (b) shows the converted magnetic image from the magnetic signal data. The magnetic signal gets a maximum at the center and decreases from the neighbors to the ends because the magnetic flux from both the neighboring and the end lines is superposed on that of a central line. Therefore, high frequency and low frequency noises are necessary to cut from the magnetic signal spectrum by using the FFT filtering. The filtering of the magnetic signals obtained from the SSM system is made by converting the time-domain into the frequency-domain using the FFT, on which the low-pass filter for passing through a lower frequency than $f_{LC}$, the high-pass filter for passing through a higher than $f_{HC}$, and the band-pass filter between $f_{LC}$ and $f_{HC}$ are employed. The FFT filtering is made with an ideal filter. In this analysis, we used the FFT due to the multiplication of functions of time components, which could operate faster and simpler than the convolution due to frequency components. The sampling procedure
of time-serial data points is important to the FFT. The signal spectrum is formed with space-serial data points, $N$, which can convert to time-serial data points with the constant scan speed of 0.13 mm/s. It is desirable that the operating time of the FFT is short. We examined the following three methods to do the FFT processing with the space-serial points equivalent to the time-serial data. According to the sampling theorem, the operation of the FFT is very efficient if data points $N$ are $2^p$ (the $p$-th power-of-2, where $p$ is an integer). Otherwise, the mixed radix FFT algorithm is applicable to the data points.

In case of method 1, twice the data points, $2N$, are sampled not larger than $2^p$ so as to satisfy the sampling theorem. The sampled are $2^{14}$ points = 16384 points > $2N$ (2×7500 points), where $N$ is related to the Nyquist frequency. In case of method 2, some points of signal zero are added to both the sides of serial data points $N$ so as to equal $2^p$, where $p$ is an integer. The sampled are $2^{13}$ points = 8192 points = $N$ (7500 points) + 0 (692 points). In case of method 3, data points $N$, which can be factorized by prime numbers, can be exceptionally sampled due to the mixed radix algorithm. The sampled are $N$ (7500 points) = $2^2$×$3$×$5^4$, in which the operation speed of the FFT is 29% faster than in case of $2^{13}$. Figure 3 shows the magnetic signal spectra of magnetic signals due to the method 1, 2 and 3. The FFT filtering of these serial magnetic data is made by software program described in MATLAB. The inverse FFT can restore the magnetic signal spectra from the sampling signal spectra due to the method 1, 2 and 3. The FFT filtering due to these methods is made by software program described in MATLAB. The inverse FFT can restore the magnetic signal spectra from the sampling signal spectra due to the method 1, 2 and 3. The band-pass filter frame was adapted for noise elimination from the low cut-off frequency $f_{cL} = 5 \times 10^{-4}$ $\mu$m$^{-1}$ to the high cut-off frequency $f_{cH} = 10^{-2}$ $\mu$m$^{-1}$. The method 1 and 3 showed almost the same restored magnetic spectra, while the method 2 had a fairly faster processing time and obtained such a faithful image to the sample as shown in Figure 4. So we used the method 2 for the FFT filtering.

![Figure 3. Magnetic signal spectra due to (a) the method 1, (b) 2 and (c) 3.](image)

![Figure 4. Restored magnetic image due to the method 2.](image)

In order to compare the unprocessed magnetic image with the processed one by our post filtering technique, now we employed a sample that 12·0 letters were laser-printed in magnetic toner ink. The contrast between black and white in the processed magnetic image was fairly improved by modifying the gray scale between the maximum 1.1 nT and the minimum 0.6 nT. However, this magnetic image was not yet clear in comparison with the optical image. So we tried the edge emphasis processing, which was made by superposition of the magnetic signal on its space-derivative. The image of the modified gray scale was improved better than the processed image by the edge emphasis. Figure 5 shows that the full data processing time of the numerical analysis program took 38 s, for which our PC processed the data length of 2,000,000 points.

We have succeeded in the high-resolution magnetic image of widespread small magnetic sources by means of our post filtering technique. Figure 6 shows (a) the optical image and (b) the unprocessed, (c) the processed magnetic images by our post filtering technique. The microstructure of the sample
magnetized in parallel to the sample sheet is observed clear. The particles in the magnetic image is seen to expand 1.5 times larger than about 3 micron-size toners in the optical image because the magnetic flux is spread out from the magnetic particles. As shown in comparison with the unprocessed and the processed magnetic images, the processed magnetic image is so clear that the direction of magnetization can be well discriminated in each magnetic particle. Individual toner particles and their different sizes can be distinguished definitely.

4. Conclusion
We have obtained the high-resolution magnetic images of a few micron magnetic toner particles by means of our post filtering technique. The processed image is so clear that the magnetic microstructure in each particle can be discriminated.

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