Experimental and simulation studies on the behavior of signal harmonics in magnetic particle imaging

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INTRODUCTION

Recently, a new imaging method called magnetic particle imaging (MPI) has been introduced [1] that allows for imaging the spatial distribution of magnetic nanoparticles (MNPs) such as superparamagnetic iron oxide (SPIO) with high sensitivity, high spatial resolution, and high imaging speed. Thus, MPI is considered to be a promising imaging modality in the field of molecular imaging. MPI uses the nonlinear response of MNPs to detect their presence in an oscillating magnetic field [drive magnetic field (DMF)]. Spatial encoding is realized by saturating the MNPs almost everywhere except in the vicinity of a special point called the field-free point (FFP) using a static magnetic field [selection magnetic field (SMF)] [1]. Due to the nonlinear response of MNPs to an applied DMF, the signal induced from MNPs in a receiving coil contains the excitation frequency as well as the harmonics of this frequency. These harmonics can be determined by Fourier transformation of the induced signal, and are used for image formation in MPI [1]. Thus, the quality of MPI directly depends on the characteristics of these harmonics. It is known that the magnetization response of MNPs depends on not only the magnetic properties but also the particle size and its distribution of MNPs [2]. For better understanding and optimization of MPI, it appears to be important to investigate the behavior of signal harmonics under various conditions of the DMF and SMF and their dependency on the particle size distribution. To the best of our knowledge, however, these studies have not yet been sufficiently performed. To accomplish these studies, computer simulation will be useful and effective, because it enables us to create a large number of study conditions that cannot practically be realized in experimental studies. The purpose of this study was to investigate the behavior of the signal harmonics in MPI under various conditions of DMF and SMF by use of experimental and simulation studies. We also investigated the dependency of the signal harmonics on the particle size of MNPs by the simulation studies based on the particle sizes actually measured.

MATERIALS AND METHODS

In experimental studies, we made an apparatus for MPI, in which both DMF and SMF were generated using a Maxwell coil pair. The MPI signals from MNPs were detected using a solenoid coil. Background subtraction was performed by subtracting the blank signal acquired without placing a sample inside the solenoid coil from the signal acquired with placing it inside the coil. The odd- and even-numbered harmonics were calculated by Fourier transformation of the MPI signals. In this study, we used magnetite (Fe_3O_4) as MNPs. The particle size of MNPs was measured by the transmission electron microscopy (TEM), dynamic light scattering (DLS), and x-ray diffraction (XRD) methods.

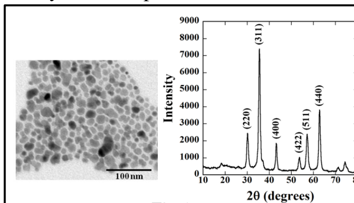

Fig. 1

In simulation studies, the magnetization and particle size distribution of MNPs were assumed to obey the Langevin theory of paramagnetism and a log-normal distribution, respectively. As in the experimental studies, the odd- and even-numbered harmonics were calculated by Fourier transformation under various conditions of DMF and SMF and for three different particle sizes.

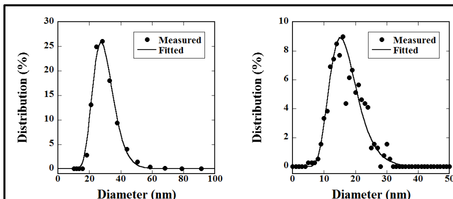

Fig. 2

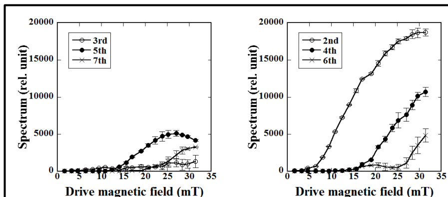

Fig. 3

RESULTS AND DISCUSSION

Figure 1 shows the TEM image (left) and the XRD intensity pattern (right). Figure 2 shows the particle size distribution measured by DLS (left) and that measured from the TEM image (right). We obtained the particle size as 10.2±1.1 nm (mean±SD), 29.8±7.1 nm, and 17.1±4.9 nm from Fig. 1 (right) (XRD), Fig. 2 (left) (DLS), and Fig. 2 (right) (TEM), respectively.

Figure 3 shows the experimental results for the relationship between the spectrum and the DMF strength for the odd-numbered (3rd, 5th, and 7th) harmonics (left) and those for the even-numbered (2nd, 4th, and 6th) harmonics (right). In these cases, the SMF strength was taken as 5 mT. Figure 4 shows the experimental results for the relationship between the spectrum and the SMF strength for the odd- (left) and even-numbered harmonics (right). In these cases, the DMF strength was taken as 20 mT.

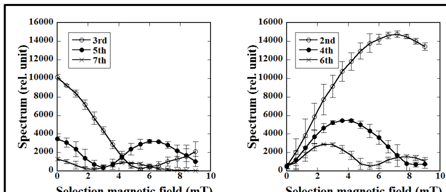

Fig. 4

Figure 5 shows the simulation results for the relationship between the spectrum and the DMF strength for the odd- (left) and even-numbered harmonics (right). In these cases, the SMF strength was assumed to be 5 mT, and the particle size was assumed to be 10.2±1.1 nm (upper), 17.1±4.9 nm (middle), and 29.8±7.1 nm (lower). Figure 6 shows the simulation results for the relationship between the spectrum and the SMF strength for the odd- (left) and even-numbered harmonics (right). In these cases, the DMF strength was assumed to be 20 mT, and the particle size was assumed to 10.2±1.1 nm (upper), 17.1±4.9 nm (middle), and 29.8±7.1 nm (lower).

As shown in Figs. 5 and 6, the behavior of the signal harmonics largely depended on the particle size of MNPs. When using the particle size obtained from the TEM image, the simulation results were most similar to the experimental results. The similarity between the experimental and simulation results for the even-numbered harmonics was better than that for the odd-numbered harmonics. This was considered to be due to the fact that the odd-numbered harmonics were more sensitive to background subtraction than the even-numbered harmonics.

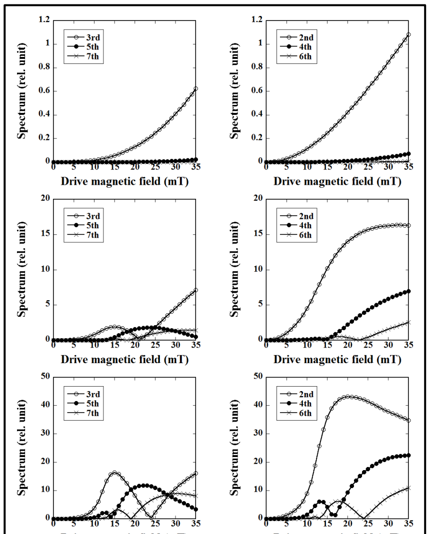

Fig. 5

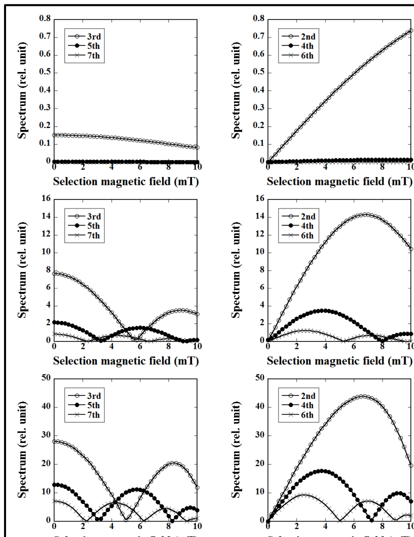

Fig. 6

CONCLUSION

This study will be useful for better understanding, optimization, and development of MPI and for designing MNPs appropriate for MPI.

REFERENCES

[1] Gleich B, et al. Nature 2005; 435:1214-1217.
[2] Biederer S, et. al. J Phys D: Appl Phys 2009; 42:205007 (7 pages).