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Development of contaminant detection system based on ultra-low field SQUID-NMR/MRI

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Abstract. We have developed an ultra-low field (ULF) NMR/MRI system using an HTS-rf-SQUID and evaluated performance of the system as a contaminant detection system for foods and drinks. In this work, we measured 1D MRIs from water samples with or without various contaminants, such as aluminum and glass balls using the system. In the 1D MRIs, changes of the MRI spectra were detected, corresponding to positions of the contaminants. We measured 2D MRIs from food samples with and without a hole. In the 2D MRIs, the hole position in the sample was well visualized. These results show that the feasibility of the system to detect and localize contaminants in foods and drinks.

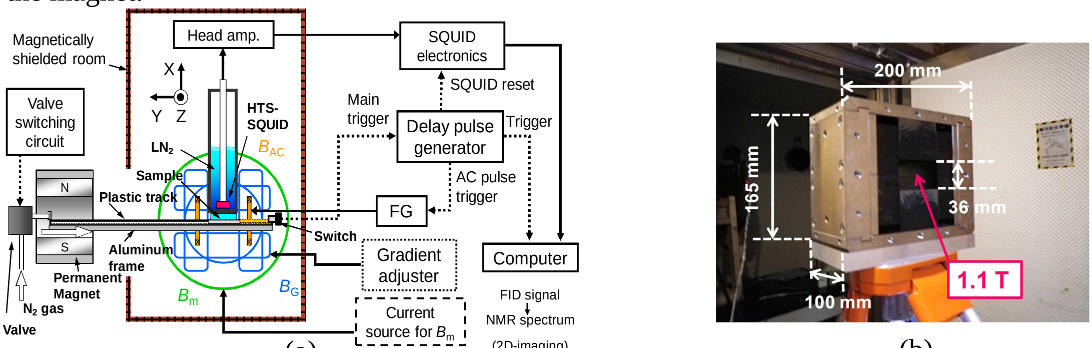
1. Introduction

Nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) in ultra-low field (ULF) using SQUID have attracted attention not only in the medical fields [1-2] but also in the other applications. For example, explosive liquid detection in airport [3-4] and disease diagnosis of cancer tissues have been proposed and researched [5]. On the other hand, we have developed an ULF NMR/MRI system using HTS-rf-SQUID for a new application, which aims to detect contaminants in foods and drinks [6]. By using NMR/MRI for the application, various kinds of contaminants may be detected, taking advantages of the matured techniques, such as T_1 and T_2 contrasts. Use of the HTS-SQUID offers lower running cost, easiness to handle, and inexpensive system. In this paper, we showed feasibility of the contaminants detection by our system by measuring one-dimensional (1D) MRIs on water samples with small contaminants. The 1D MRI can determine whether contaminant exists or not, but it is difficult to localize contaminant position. Therefore, we developed two-dimensional (2D) MRI system and evaluated the performance of the system by measuring 2D MRIs of vegetable samples.

2. ULF SQUID-NMR/MRI system

2.1. System configuration

The ULF SQUID-NMR/MRI system developed in this study is shown in Figure 1. The system consists of an HTS-rf-SQUID, cryostat, SQUID electronics unit, Helmholtz-type measurement coil, AC pulse coil, three field gradient coils, permanent magnet of 1.1 T, sample transfer mechanism, delay pulse generator, current source, function generator, and computer for data acquisition. All of the coils used in the system are room-temperature (RT) coils. The HTS-SQUID is positioned at the bottom of the cryostat, in which liquid nitrogen is filled. The RT coils and the cryostat are located in a magnetically shielded room (MSR) with opened door. The permanent magnet is located outside the MSR and about 2 m away from the SQUID. The sample transfer mechanism utilizes aluminum frames and a plastic track, on which a sample is transferred. A water sample, which is pre-polarized in the permanent magnet, is transferred to under the SQUID, and then exposed in a measurement field B_m from the measurement coil in the *z* direction. Subsequently, by applying a 90° pulse and 180 ° pulse field B_{AC} in the *y* direction from the AC pulse coil, a FID signal or an echo signal from the sample is measured by the SQUID. The signals are converted to 2D MRIs and recorded by the computer. The permanent magnet used for the pre-polarization magnetic field B_p is shown in Figure 1 (b). In order to reduce influence of a leakage field from the magnet on the measurement field, yoke magnets are arranged around the magnet.



(a) (b)

Figure 1. (a) Schematic diagram of system. (b) Permanent Magnet.

2.2. Pulse sequence

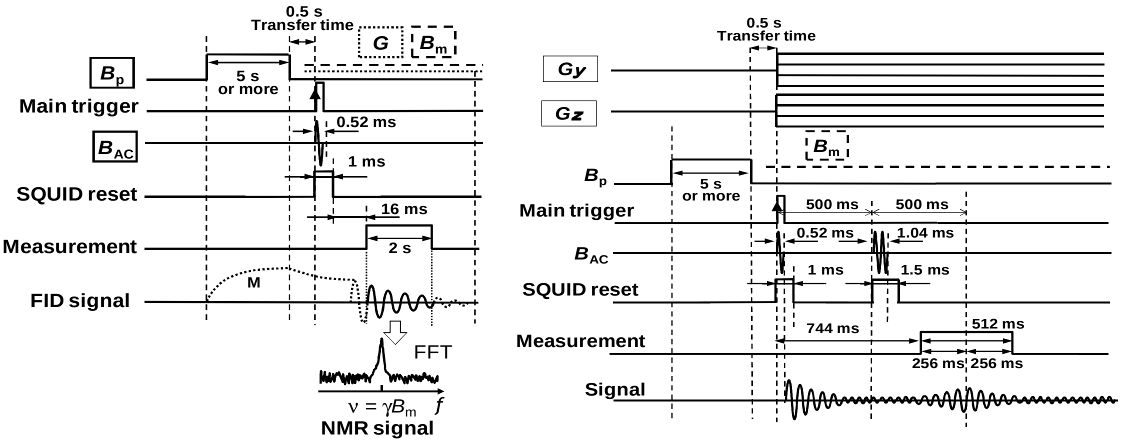
In the system, a 1D MRI measurement pulse sequence shown in Figure 2(a) is used to obtain the ^{1}H-NMR signals from water samples. The pre-polarization field B_p pre-polarizes the sample in the magnet for 5 or more seconds. Then the sample is transferred under the SQUID in about 0.5 s. The measurement field B_m is applied continuously to the area around the SQUID in the MSR. In 1D MRI measurements, a gradient field G_y (dB_z/dy) of 52 nT/cm (corresponding to 2.3 Hz/cm) in the *y* direction is applied to the sample continuously. After the transfer, a 90° pulse field B_{AC} is applied from the AC pulse coil. At approximately 1 ms after applying the B_{AC}, the SQUID is set in the lock mode to measure the FID signal. At 16 ms after locking the SQUID electronics unit, the signal is recorded for 2 s by the computer. After recording the FID signal, the spectrum analyzer converts the FID signal to a NMR spectrum by fast-Fourier-transform (FFT), and records the spectrum.

A 2D MRI measurement pulse sequence shown in Figure 2(b) is used to obtain the ^{1}H-NMR signals from food samples. In 2D MRI measurements, a combinational gradient field *G* (gradient field G_y (dB_z/dy) and G_z (dB_z/dz)) of 280 nT/cm (corresponding to 11.9 Hz/cm) in the *y* and *z* directions is applied to the sample continuously. To obtain spin echo (SE) signals, the 180° pulse field is applied at 0.5 s after the 90° pulse field is applied. The SQUID is set in the unlock mode until the 180° pulse field is applied as well as 1D MRI. Data acquisition time is 0.512 s to measure a symmetric SE signal.

3. Experiments and results

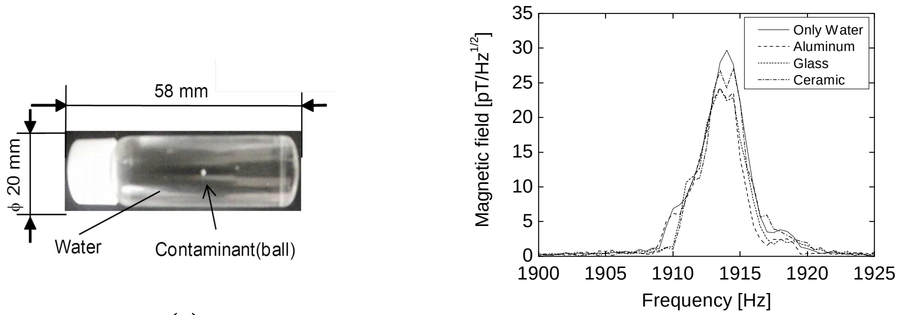
3.1. 1D MRI measurements

We measured 1D MRIs from a tap water sample of 10 ml with contaminants using the above mentioned system and sequence. A glass bottle of 10 ml was used as a container. Balls of various contaminants were prepared as shown in Figure 3(a). Each contaminant was set in the center of the bottom of the bottle. 1D MRI spectra of only water and water with the aluminum, glass, and ceramic, balls of 1.5 mm in diameter are shown in Figure 3(b). Compared to the MRI spectrum from the water only, the spectra from the water with the contaminant balls changed around the central frequency of about 1914 Hz. This is because distribution of protons of the water was changed with the existence of the contaminant balls. For every kind of the contaminants, the changes of the signal spectra were measured at the central frequency, where corresponded to the positions of the contaminants. From these results, it is shown that existence of contaminants can be distinguished by this technique.



(a) (b)

Figure 2. (a) Typical pulse sequence for 1D MRI data acquisition. (b) Typical pulse sequence for 2D MRI data acquisition.



(a) (b)

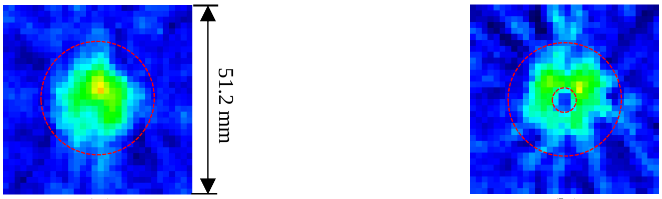
Figure 3. (a) Water sample containing a contaminant. (b) 1D MRI measurement results of water with and without contaminant balls of 1.5 mm in diameter.

3.2. 2D MRI measurements

We measured 2D MRIs in the *y-z* plane from cucumber samples using the above mentioned system and sequence. The filtered back projection reconstruction was utilized to obtain the 2D MRIs. Projection number was 12, because the gradient field directions were rotated for 15° step by step to cover 180°. Cover angle is 180°, which is half of 360° (full angle) because we utilized the spin echo sequence. For all projections, SE signals were recorded without averaging. The space resolution is 1.953 Hz/pixel (corresponding to 0.16 cm/pixel), while the field of view (FOV) is 51.2 ×51.2 mm in area ,which correspond to 62.5 Hz in bandwidth, or 32 ×32 points in pixel. Measured sample is a cucumber of 33 mm in diameter and 8 mm in thickness, which was cut perpendicular to the longitudinal direction. We measured the cucumber samples with and without a hole using the 2D MRI sequence. An air hole in raw foods like cucumbers can be a quality problem. The photograph of the cucumber samples with and without a hole in the center are shown in Figure 4(a) and (b). The results of 2D MRI measurements are shown in Figure 5(a) and (b). The sizes of the 2D MRIs of the cucumbers (about ϕ22 mm) are smaller than the actual sample sizes (about ϕ33 mm) because the samples sizes are larger than the SQUID's size (about 10 mm square). In the images shown in Figure 5(b), the image intensity at the hole position was clearly lower compared to Figure 5(a). From this result, it is shown that the hole position can be localized by this technique. As the next challenge, we plan to utilize flux transformer or increase SQUID channel, to expand the SQUID's detection area.

(a) (b)

Figure 4.(a) cucumbers sample without a hole. (b) cucumbers sample with a hole.



(a) (b)

Figure 5.(a) 2D MRI measurement results of cucumbers without the hole. (b) 2D MRI measurement results of cucumbers with the hole. Dotted lines indicate the actual sample size.

4. Discussions and Conclusions

In this research, we developed the ULF NMR/MRI system using HTS-SQUID and evaluated the performance of the system as the contaminant detection system for foods and drinks. It was shown that the contaminants such as aluminum, glass and ceramics balls in the water sample could be detected by the 1D MRI measurements. By using the cut cucumber with the air hole, it was shown that the hole position in the sample can be localized by 2D MRI measurements. From these results, the possibility of applying the ULF SQUID-NMR/MRI system to the contaminant detection was successfully demonstrated. We have planned to introduce the ULF-NMR/MRI system into production line in the future. Since an object is transported in our system, our system will suit to contaminant detection on the production line, compared to the other systems which measure a static object. On the other hand, we had developed contaminant detection systems for fine magnetic contaminants using HTS-SQUIDs for production line [7]. In comparison with these systems, the ULF-NMR/MRI system has possibility to detect many materials other than magnetic materials. In addition, localization and material identification of contaminants are needed to trace the contamination on the production line. Low cost and convenience must be considered for practical use of the system. Using HTS-SQUID is a significant advantage for these requirements.

Acknowledgements

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