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Low-Cost Magnetic Resonance Sensors for Process Monitoring in the Food Industry

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Abstract: Low-cost magnetic resonance (MR) sensors have in recent years been used to investigate a number of systems by measuring the relaxation times T_1 and T_2^{eff}. These measured parameters vary in line with changes in many systems giving the investigator a useful non-invasive probe. While the use of MR for in-line or on-line process monitoring in the food industry is not a novel concept, much of the work conducted previously has involved acquiring spatially resolved data which requires a magnetic resonance imaging system. These are both expensive to purchase and maintain, occupy large amounts of space and present problems with safety. In this work we show the value that a very inexpensive magnet and coil geometry (<€200) can bring to process monitoring. A MR sensor utilising an eight-element Halbach cylinder with internal diameter of 10mm has been constructed giving a highly uniform magnetic field yielding a strong signal-to-noise ratio. It is shown to be useful for assessing the relaxation times of a range of relevant samples.

Keywords: magnetic resonance; Halbach; low-field sensor; T_1; spin-lattice relaxation

1. Introduction

A use of magnetic resonance (MR) in a number of areas away traditional laboratory or medical environment has occurred in recent years due to the development of relatively low-cost permanent magnet systems. These 'low-cost' systems are cheap in comparison to the large superconducting magnets used for human imaging, and in fact there is a large spectrum of prices of permanent magnets systems depending on the required functionality. At a cost of thousands to tens of thousands of Euros

complex Halbach arrays comprising of tens of magnet can allow for sufficiently uniform magnetic field for imaging to be conducted [1]. Imaging provides the greatest range of analytical tools that magnetic resonance can offer, including spatially resolved internal structural details and information about diffusion within the sample. On the order of one or two hundred Euros a magnet and coil geometry comprised of a single bar-magnet [2, 3], or another simple magnet arrangement [4] can be produced. While these systems are incapable of imaging, and cannot detect an FID preventing NMR spectroscopy, they can collect useful relaxation data which can provide some indication of the samples properties.

The monitoring of processes in the food industry is an obvious area where MR might prove to be a useful tool given the obvious advantages of having a non-destructive probe for a product intended for sale. Much of the existing literature on exploring foods with MR has focused on the information that imaging can provide [5], or the analysis of spectra [6, 7], however studies have been conducted where relaxation times are used to investigate the properties of foodstuffs, such as some oils [8].

In this work a low-cost magnet and coil (<€200) based on an eight-magnet Halbach cylinder is presented. The Halbach cylinder has become an increasingly popular design for permanent magnet sensors given the very uniform magnetic field produced [1]. Successful operation of the probe is shown and a brief study on is presented where the T_1 relaxation against glycerine concentration has been investigated. While glycerine is used in food preparation, for example some processed fruits, this sample was chosen as the T_1 relaxation as a function of concentration is well understood [9] so provided a useful validation of the probes operation.

2. Experimental Section

2.1. MR Sensor Designs

The MR sensor used was an eight element Halbach cylinder [10] where eight 130 x 8 x 5 mm N42 magnets (polarized on the 8 x 130 mm face; first4magnets®, Tuxford, UK) were separated by 20 mm in the pattern shown in Figure 1a, generating a magnetic field of 362 mT at the center of the magnet arrangement corresponding to a proton resonant frequency of 15.4 MHz. This field changed by ±2 mT over the length of the coil in the axis of the magnet arrangement bore (corresponding to a 0.1 MHz change). The magnet arrangement was comprised of a mixture of 8 mm and 4 mm thick acrylic spacers. The spacers at the center of the arrangement had a larger aperture to accommodate the RF coil, fixing it securely in the center of the arrangement.

For transmitting/receiving RF signals a 30 mm long, 15 turn solenoid using enameled copper wire (o.d. = 0.8 mm, Rowan Cable Products Ltd., Potters Bar, UK), was formed over a section of acrylic pipe (o.d. = 10 mm), and fixed in place at the center of the magnet arrangement (Figure 1(b)). The RF coil was part of a tuning-matching resonant circuit which included two 1 – 30 pF variable capacitors (Johanson Manufacturing Corporation, Boonton Township, USA). The RF coil and the capacitors were joined by a 0.8 m inductive tuning element. The RF pulse calibration determined an optimal 90° pulse as being 12.7 μs using the 100 W amplifier on a Kea 2 spectrometer (Magritek, Wellington, New Zealand), and 6 μs using the modified RM Costruzioni Elettroniche KL203 amplifier run with the Apollo spectrometer (Tecmag Inc., Houston, USA).

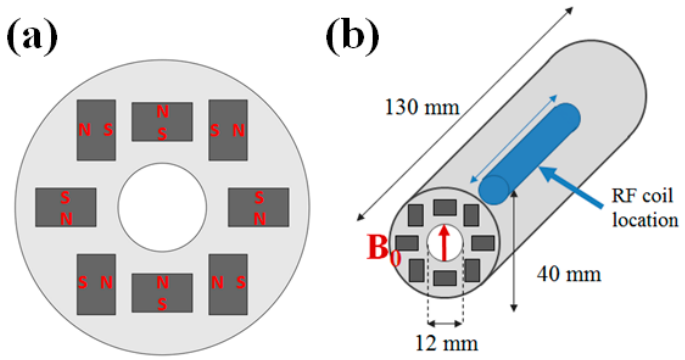

Figure 1. Schematic representation of the MR sensor. (**a**) Front-on view of the Halbach cylinder showing the magnet orientations. (**b**) Axonometric view of the MR sensor with relevant measurements. The RF was located at the center of the magnet arrangement.

2.2. Experimental Protocol

All magnetic resonance measurements were taken using a CPMG sequence. T_2^{eff} was acquired by taking 256 echoes, with an echo time (τ_E) of 300 μs and a repetition time of 6000 ms. 16 experimental repeats were averaged. T_2^{eff} was then extracted by mono-exponentially fitting the echo integrals to the time using Igor Pro (Wavematrics, OR, USA).

T_1 measurements were taken using a using a saturation recovery method, with the inter-experimental repetition time between CPMG sequences varied between 25 ms and 6000 ms in non-uniform increments. The CPMG sequences were run with four echoes (τ_E = 175 μs), which were summed to improve the signal intensity. For each T_1 measurement where the Kea 2 spectrometer was used 16 experimental repeats were taken and averaged, and 128 experimental repeats were recorded using the Apollo spectrometer. Signal intensity was plotted against repetition time and mono-exponentially fit using Igor Pro to extract T_1 values for the Kea data, and Matlab (MathWorks®, Natick, USA) for the Apollo data. Errors given for both T_1 and T_2^{eff} values were taken from the error on the mono-exponential fitting unless otherwise stated. For all experiments the probe was situated in a copper clad box to reduce noise sources.

2.3. Sample Preparation

The solutions used in this study were made up from glycerine (Fisher Scientific, Loughborough, UK) and water (distilled) in six concentrations (0 %, 20 %, 40 %, 60 %, 80 %, 100 %). New glycerin was used to prepare samples to limit the absorption of water from the air. Once prepared four samples were extracted from the vial with 1 ml syringes (BD Plastipak™, Franklin Lakes, USA).

3. Results and Discussion

A sample of sunflower oil was used to calibrate the optimal 90° pulse for the probe. After this the sample was replaced with a distilled water sample and the successful operation of the probe was determined by recording a T_2^{eff} measurement using a CPMG sequence, where T_2^{eff} = 12.8 ± 0.8 ms.

The first four echoes in this train have been shown in Figure 2a, with the entire sequence of echo integrals shown in Figure 2b.

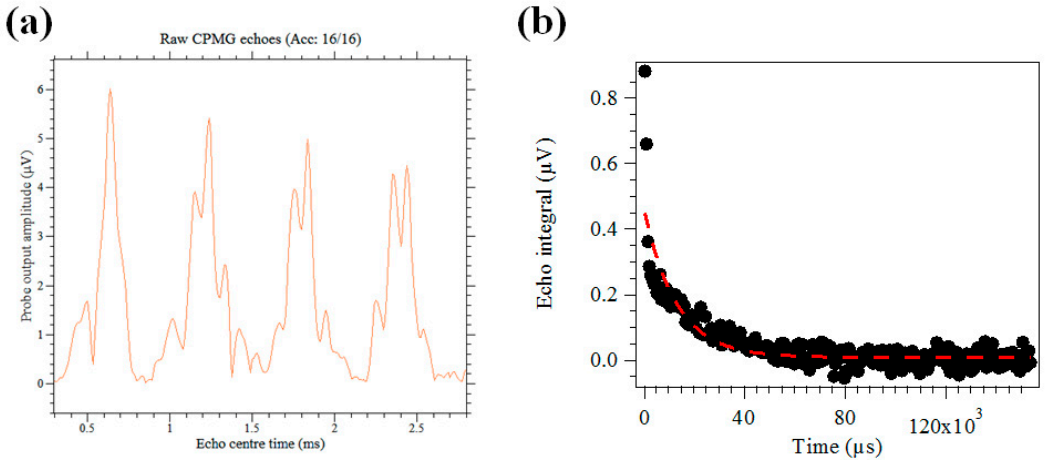

Figure 2. MR data collected from a CPMG sequence on the low-cost Halbach sensor. (**a**) Four echoes taken from a CPMG train. Note the dip on the 2nd, 3rd, and 4th echo indicating the contributions of off-resonance coherence pathways. (**b**) Echo integrals against time for the full train of echoes.

It was interesting to note that despite the good SNR (clear echoes after one scan) the T_2^{eff} value for water was short when compared to other systems. While T_2^{eff} is influenced by a variety of factors a major contribution comes from the magnetic field homogeneity. An inhomogeneous field over the sensitive region within the sensor was possibly due to the size of the RF coil, which was 30 mm long, and a shorter coil may have yield a longer T_2^{eff}. This assertion was further supported by the echo shape shown in Figure 2a. While the first echo had an expected shape for an echo, the second echo had a visible dip at the center which would indicate a negative contribution from off-resonance coherence pathways. This dip became more pronounced on subsequent echoes, as would be expected.

T_1 values were then recorded. This was done using two spectrometers, the Kea 2 and Apollo, to show that the probe was useable on any system and not just under a very specific set of circumstances. The Apollo T_1 values were averaged from the T_1 measurements of four different samples for each concentration, with the errors bars being taken from the standard deviation of these values, in order to show the repeatability from sample to sample. The data from the two spectrometers was plotted along with literature values from Bloembergen *et al*. [9] as shown in Figure 3.

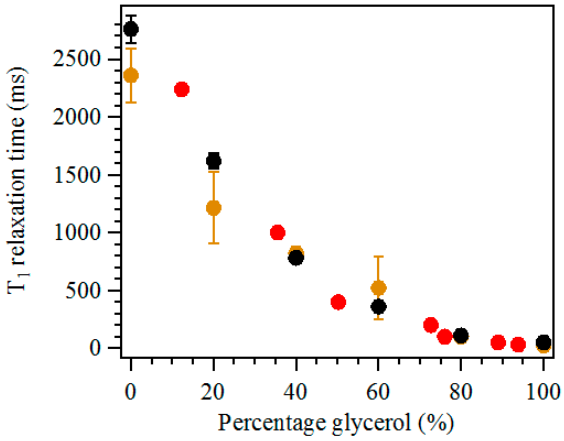

Figure 3. T_1 relaxation times recorded for six glycerin-water solutions. T_1 measurements taken using the Apollo spectrometer (●) represent measurements from four samples (three for the 20 % solution) averaged together. Also shown are a set of measurements taken with the Kea 2 spectrometer (●) and values from the literature (●) [9]. It was clear that the measurements recorded with the low-cost Halbach are in good agreement with literature values.

As shown in Figure 3, the results acquired using the low-cost Halbach are in close agreement with the literature values for both spectrometers. This showed that the probe was suitable for the collection of T_1 measurements, and the characterization of materials where the makeup effects the T_1 time.

4. Conclusions

A cheap (<€200) magnet and coil assembly based on a Halbach cylinder was constructed. T_1 values were collected for six different solutions comprised of various concentrations of glycerine using two spectrometers. The values collected showed good agreement with literature values. Future work will see the probe applied to a practical food process monitoring situation. The initial investigation will explore the T_1 relaxation time of different oil samples to see if a determination can be made. The high SNR and low cost of the probe also raises the potential of using it for other applications.

Author Contributions

This work involved three authors. M.I. Newton and R.H. Morris proposed the experiments, and reviewed and edited the manuscript. T. Hughes-Riley collected and processed the data and wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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