

# A Resonant Type AC Magnetometer for Evaluation of Magnetic Nanoparticles



Nazatul Sharreena Suhaimi, Mohd Mawardi Saari, Hamzah Ahmad, Mohd Rusllim Mohamed and Nurul Akmal Che Lah

**Abstract** Characterization of magnetic nanoparticles is crucial in order to optimize them for different applications requiring specific characteristics. In this article, we report a characterization system using AC susceptibility method. An AC magnetometer system which is composed of the induction coil and resonant capacitors is developed to evaluate the performance of the magnetic nanoparticles. The induction coil consists of excitation and detection coil. The excitation coil is designed with solenoid coils and fabricated with a Litz wire which is composed of 60 strands of copper wire with 0.1 mm diameter to reduce the increase of AC resistance at high frequency. The detection coil is designed to be a first-order differential coil which is used to reduce the environmental noise and cancel the excitation magnetic field. The detection coil is fabricated with a copper wire and it is placed at the center of the excitation coil. The excitation coil is connected to the resonant capacitors to cancel the reactant component and to permit the high magnetic field in the high-frequency region. The resonant capacitors are fabricated with multiple values of capacitors. When the developed system is in the resonant mode, the current flow is constant up to the frequency of 32.5 kHz. The developed system can evaluate the magnetic nanoparticles at different frequency responses. Using the developed system, it is shown that the Neel particles exist inside the solution of magnetic nanoparticles used in this study.

**Keywords** AC magnetometer • Magnetic nanoparticles • Coil

---

N. S. Suhaimi · M. M. Saari (✉) · H. Ahmad · M. R. Mohamed  
Faculty of Electrical & Electronic Engineering, Universiti Malaysia Pahang,  
Pekan Campus, 26600 Pekan, Pahang, Malaysia  
e-mail: mmawardi@ump.edu.my

N. A. Che Lah  
Innovative Manufacturing, Mechatronics and Sports Lab (iMAMS),  
Faculty of Manufacturing Engineering, Universiti Malaysia Pahang,  
Pekan Campus, 26600 Pekan, Pahang, Malaysia

© Springer Nature Singapore Pte Ltd. 2018  
M. H. A. Hassan (ed.), *Intelligent Manufacturing & Mechatronics*,  
Lecture Notes in Mechanical Engineering,  
[https://doi.org/10.1007/978-981-10-8788-2\\_9](https://doi.org/10.1007/978-981-10-8788-2_9)

## 1 Introduction

Magnetic nanoparticles are mostly applied in the biomedical areas such as *in vivo* imaging [1], magnetic hyperthermia [2], and magnetic immunoassay. There are different applications of magnetic nanoparticles requiring different characteristics of the magnetic nanoparticles. Therefore, the characterization of the magnetic nanoparticles is important. The characterization of the magnetic nanoparticles can be done by AC susceptibility [3], magnetic relaxation [4], and remanence measurement. In this paper, the AC susceptibility is used to characterize the magnetic properties of the magnetic nanoparticles. The AC susceptibility measurement can provide the information of size distribution, harmonics and magnetic anisotropy with a fast response to the measurement. Moreover, the use of a phase sensitive detector can permit a higher sensitivity. In this method, the excitation coil will apply an AC field to a sample and the detection coil will detect the AC response that produced by the sample [5]. During this process, magnetic relaxations such as Neel and Brownian relaxations can be observed. Neel relaxation occurs when the rotation of magnetic moment occurs within the nanocrystals while Brownian relaxation occurs when the particles are physically rotated and the magnetic moment is blocked at a certain direction [6].

For that purpose, an AC magnetometer system is developed to evaluate the performance of the magnetic nanoparticles. There are a few systems, that have been developed such Imego AC susceptometry using an ordinary induction coil technique [7]. This system is possible to measure the dynamic magnetic properties from 1 Hz until 10 MHz at a low excitation field of  $H = 24$  A/m. There is also another system was reported that measure hysteresis loop in a high frequency region using an air-cooled Litz wire coil [8]. Since the magnetic nanoparticles are applied in different frequencies and excitation fields, an AC magnetometer that is able to characterize them in a wide region of frequency and excitation field is highly desired. This AC magnetometer can also serve as a standardization technique for magnetic nanoparticles.

In this article, to fulfill the aforementioned system, we have developed an AC magnetometer system using an induction coil technique for the characterization of the magnetic nanoparticles [9]. The induction coil is composed of an excitation and detection coils. The excitation coil is designed as a Helmholtz coil which has two solenoid coils aligned to be co-axial in a series configuration, separated with a 4 mm gap. The radius of the excitation coil is 15 mm. The detection coil is designed as a first-order differential coil. In order to achieve high homogeneity and sufficient amplitude of the excitation magnetic field, the excitation coil with resonant capacitors is developed [10]. The resonant capacitor is developed with the multiple values of the capacitors in order to achieve a resonant frequency up to 82.32 kHz. The capacitors are constructed in the series and/or parallel configuration. For this study, film capacitors such as polypropylene capacitors are used where they are capable to withstand high current and voltage.

## 2 Methodology

### 2.1 System Configuration

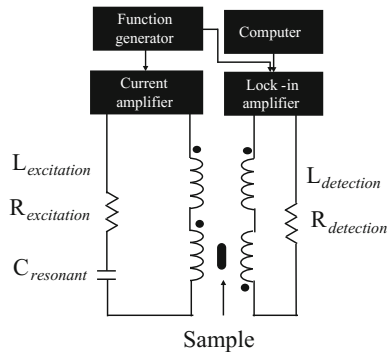
Figure 1 shows the system configuration of AC magnetometer with the resonant capacitor. The detection coil is inserted into the center of the excitation coil. The excitation coil is connected to a current amplifier (TS 250, Accel Instruments). The current amplifier will provide a high current to the excitation coil. The high current from the current amplifier is based on the reference signal that is supplied by the function generator of the lock-in amplifier (LI 5640, NF Corporation). The lock-in amplifier is used as a Phase Sensitive Detection (PSD) to detect the signal. When the high current flows through the excitation coil, the sample is magnetized. The magnetization of the sample can cause the sample to produce a magnetic field. The magnetic field of the sample is detected by the detection coil. The detection coil will send the signal to the lock-in amplifier and lock-in amplifier will send the signal to a computer.

### 2.2 The Design of Excitation Coil

The excitation coil is designed based on the Helmholtz coil configuration with two solenoid coils. The design of the excitation coil is referred to the Biot-Savart's law based on a multi-layer surface current model and can be expressed as;

$$\mathbf{B}(\mathbf{r}') = \frac{\mu_0}{4\pi} \sum_{n=1}^N \sum_{i=1}^S \frac{\mathbf{J}_n S_{i,n} \times (\mathbf{r}' - \mathbf{r}_n)}{|\mathbf{r}' - \mathbf{r}_n|^3}, \tag{1}$$

**Fig. 1** The schematic diagram of the developed AC magnetometer system with resonant capacitors



where  $\mu_0$  is referred to the vacuum magnetic permeability,  $\mathbf{J}_n$  is the surface current density vector at  $n$  layer,  $s_{i,n}$  is the surface unit area,  $\mathbf{r}_n$  is the position of the surface current and  $\mathbf{r}'$  is the position of the point observation. From the Eq. (1), it shows that the strength of the magnetic field can be high if the distance between the current element to the observation point is reduced and this is equal to the radius minimization of the excitation coil. The radius of the excitation coil should not be designed too big or small because it will give an effect to the reduction of the magnetic field uniformity area. However, the radius of the excitation coil must fit the diameter of the detection coil.

The excitation coil was fabricated of two solenoid coils which are connected in series and both solenoid coils are separated by a 4 mm gap. The excitation coil is fabricated from a Litz wire which is composed of 60 strands of the copper wire. The number of turn for each side of the coil is 150 turns. The length and radius of the coil are 26 mm and 15 mm. The resistance and inductance of the excitation coil were measured to be 1.3516  $\Omega$  and 1.5176 mH at 1 V and 1 kHz by a LCR meter (GW INSTEK LCR-816).

Then, the excitation coil will be connected to the resonant capacitor in a series connection and it will form an RLC circuit. The resonant capacitor is designed with the multiple values of capacitors. In the resonance mode, the capacitance can be calculated as;

$$C = \frac{1}{(2\pi f)^2 \times L}, \quad (2)$$

where  $f$  is the frequency and  $L$  is the inductance of excitation coil. From the RLC circuit, the resonant frequency can be calculated by manually selecting the values of capacitors. The range of the resonant frequency was set from 581 Hz to 82.32 kHz.

### 2.3 The Design of Detection Coil

The detection coil is designed as a first-order differential coil. The first-order differential coil is chosen because it can minimize the environmental magnetic noise and external magnetic field. The detection coil is composed of a copper wire with the diameter of 0.25 mm. The length and the radius of the detection coil are 19 mm and 7 mm. The number of turn for each side of the coil is 1000 turns and the detection coil was wound in the opposite direction for both sides of the coil [9]. The resistance and inductance of the detection coil were measured to be 41.456  $\Omega$  and 16.755 mH.

## 2.4 The Preparation of the Iron Oxide Nanoparticles as a Sample

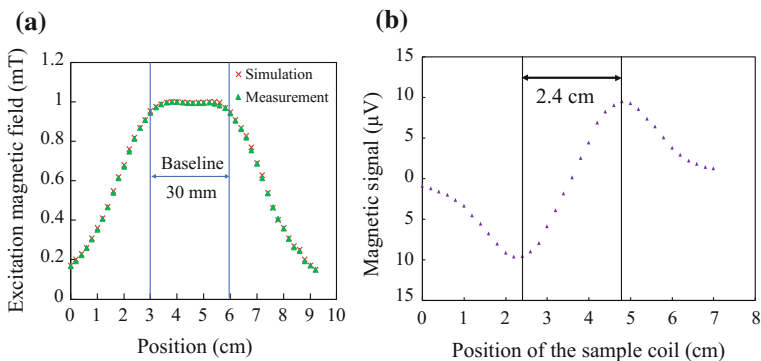
The iron oxide nanoparticles (Nanomag-D102, Micromod Partikeltechnologie GmbH) with a median diameter 100 nm was used in the experiment. The iron oxide nanoparticles of D102 were prepared in two different environments such as liquid and dry states to evaluate their frequency response. The solution was filled inside a tube whose diameter is 7 mm and it will be placed at the center of one detection coil. For this experiment, the sample of D102 was prepared in 200  $\mu\text{l}$ .

## 3 Result and Discussion

### 3.1 The Characteristic of the Excitation Coil

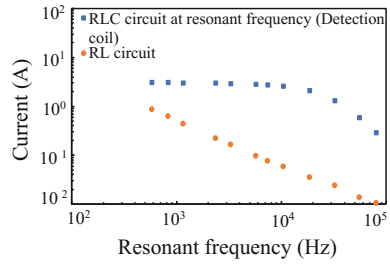
The distribution of magnetic field was determined by using a teslameter. The rod of the teslameter was moved through the excitation coil from 0 mm to 92 mm with the interval of 2 mm. Figure 2a shows the distribution line of the excitation magnetic field at the excitation coil with respect to the different positions of the teslameter. The magnetic field was uniform from the region of 30 mm to 60 mm which was from the center of one coil to the center of another coil and the magnetic field produced at the center was 5.22 mT/A. The result of measurement was compared to the result of the simulation. The simulation result showed the same value with the measurement result. The inhomogeneity in this region has been calculated to be 7%.

The small sample coil with 30 turns was fabricated to detect the magnetic signal at the detection coil. The small sample coil was moved along the detection coil from 0 mm to 72 mm with 2 mm interval. Figure 2b shows the magnetic signal of the



**Fig. 2** **a** The distribution line of excitation magnetic field at the excitation coil with respect to the position of rod teslameter. **b** The magnetic signal of the detection coil with respect to the position of the small sample coil

**Fig. 3** The intensity of current flow through the excitation coil with respect to the frequency



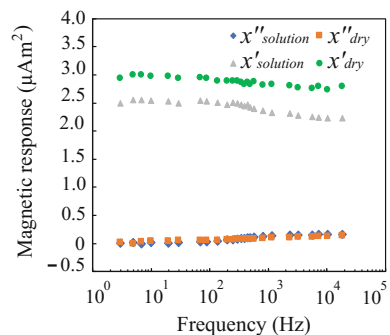
detection coil by moving the small sample coil along the detection coil. The highest magnetic signal was produced from the center of each coil. The distance between the first peak to the second peak was 24 mm which was the distance between the centers of each coil. The negative and positive magnetic signal produced by the detection coil was referred to the turn direction of each coil.

Figure 3 shows the result of the intensity of current flow through the excitation coil at different resonant frequencies. Before the resonant capacitor was connected to the excitation coil, the current flow through the excitation coil was decreased when the frequency was increased. Then, when the resonant capacitor was connected to the excitation coil, the current flow through the excitation was constant at 3 A until 32.5 kHz.

### 3.2 The Frequency Response of the Magnetic Nanoparticles in Dry and Solution State

Figure 4 shows the magnetic response produced by the D102 at different frequencies. In this experiment, two components such as  $\chi'$  (in-phase magnetization) and  $\chi''$  (out-of-phase magnetization) were measured. For  $\chi'$ , the magnetic response of the D102 in the solution state showed a same characteristic of the magnetic response that produced in the dry state, which it was constant over the frequency

**Fig. 4** The magnetic response of the D102 with respect to the frequency



region. This was because the sample of D102 did not being affected by Brownian relaxation. For the  $\chi''$ , the magnetic response of the D102 is started to increase when the frequency is increased. This could be thought that D102 has undergone Neel relaxation.

## 4 Conclusion

In this work, an AC magnetometer system with resonant capacitors is developed. The AC magnetometer system is able to measure the magnetic response of the magnetic nanoparticles in the range of 3 Hz–32.5 kHz with the amplitude magnetic field per unit current at the center of 5.2 mT/A. The resonant capacitor with the multiple values of capacitance was developed to maintain the flow of current through the resonant circuit until the frequency reached 32.5 kHz. The developed AC magnetometer system was capable to evaluate the magnetic response of the magnetic nanoparticles based on the frequency response. The mechanism of Neel relaxation was observed for D102.

**Acknowledgements** This work was supported by Ministry of Higher Education of Malaysia under grant number of RDU 160115 and Research Management Center of Universiti Malaysia Pahang under grant number of RDU 170377.

## References

1. Enpuku, K., et al.: Magnetic nanoparticle imaging using cooled pickup coil and harmonic signal detection. *Jpn. J. Appl. Phys.* **52**, 87001 (2013)
2. Sadiq, A.A., Othman, N.B., Jamil, M.M.A.: Magnetic Particle Imaging System For Cancer Diagnosis : An Overview, vol. 10, no. 19, pp. 8556–8561 (2015)
3. Ludwig, F., Balceris, C., Jonasson, C., Johansson, C.: Analysis of ac susceptibility spectra for the characterization of magnetic nanoparticles, vol. 9464, no. 3 (2017)
4. Ludwig, F., Heim, E., Schilling, M.: Characterization of superparamagnetic nanoparticles by analyzing the magnetization and relaxation dynamics using fluxgate magnetometers. *J. Appl. Phys.* **101**(11), 113909 (2007)
5. Youssif, M.I., Bahgat, A.A., Ali, I.A.: AC Magnetic Susceptibility Technique for the Characterization of High Temperature Superconductors, vol. 23, pp. 231–250 (2000)
6. Bogren, S., et al.: Classification of magnetic nanoparticle systems—synthesis, standardization and analysis methods in the nanomag project. *Int. J. Mol. Sci.* **16**(9), 20308–20325 (2015)
7. Ahrentorp, F., et al.: Sensitive high frequency AC susceptometry in magnetic nanoparticle applications. *AIP Conf. Proc.* **1311**, 213–223 (2010)
8. Connord, V., Mehdaoui, B., Tan, R.P., Carrey, J., Respaud, M.: An air-cooled Litz wire coil for measuring the high frequency hysteresis loops of magnetic samples—a useful setup for magnetic hyperthermia applications. *Rev. Sci. Instrum.* **85**(9) (2014)
9. Tumanski, S.: Induction coil sensors—a review. *Meas. Sci. Technol.* **18**(3), R31–R46 (2007)
10. Yang, T.Q., Enpuku, K.: SQUID magnetometer utilizing normal pickup coil and resonant-type coupling circuit. *Phys. C Supercond.* **392–396**, 1396–1400 (2003)