International Journal on Magnetic Particle Imaging
Vol 8, No 1, Suppl 1, Article ID 2203054, 4 Pages

Infinite Science Publishing

Proceedings Article

Response characteristics of magnetic particle spectroscopy under different excitation waveforms

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Abstract

Magnetic particle spectroscopy (MPS) is a method to characterize the characteristics of magnetic nanoparticles (MNP), which is of great significance for the research of magnetic particle imaging (MPI) and magnetic hyperthermia. In the MPS system, the waveform characteristics of the excitation magnetic field will directly impact the received particle signal. Sinusoidal excitation waveforms are the default choice in most MPI applications. This study focuses on the excitation effect of trapezoidal and triangular waveforms. The results show that under the excitation frequencies of 10 kHz and 15 kHz, the particle response of the trapezoidal wave is obviously higher than the other two waveforms, and the effect of the triangular wave is the worst. Research on excitation waveforms is fundamental to optimize MPI in the future.

I. Introduction

Magnetic particle imaging (MPI) is a new tomography method [1]. It has attracted extensive attention in the field of biomedical imaging because of its advantages of high contrast, high sensitivity [2] and deeper imaging depth [3]. Magnetic particle spectroscopy (MPS) is a zero-dimensional measurement method closely related to MPI. It can detect the response characteristics of superpara-magnetic iron oxide nanoparticles (SPIONs) under magnetic field excitation. Therefore, studying MPS is of great significance for the application of MPI.

The working principle of MPS is as follows: Apply a magnetic field with large enough amplitude to SPIO to periodically drive particles into and out of the magnetisation saturation region at a particular frequency [4]. The magnetisation curve of SPIONs is usually analysed by a Langevin function, which is described as follows

$$M_L(\mu_0 H) = M_S \cdot \left(\coth\left(\frac{m_0\mu_0 H}{k_B T}\right) - \frac{k_B T}{m_0\mu_0 H}\right) \quad (1)$$

In the formula: M_s is the saturation magnetisation of SPIONs; m_0 is the magnetic moment of SPIONs; μ_0 is the permeability under vacuum; H is the applied magnetic field; k_B is the Boltzmann constant; T is the absolute temperature. It can be seen that the characteristics of the applied magnetic field will directly impact the response of particles. With sinusoidal waves, resonant circuitry can be used (filters, matching) and easy generation, which is of great value for hardware desings of MPI scanners

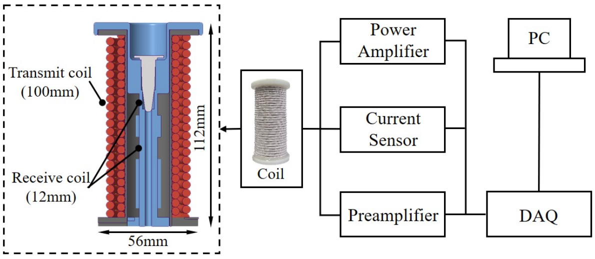

Figure 1: MPS system schematic diagram and coil structure diagram.

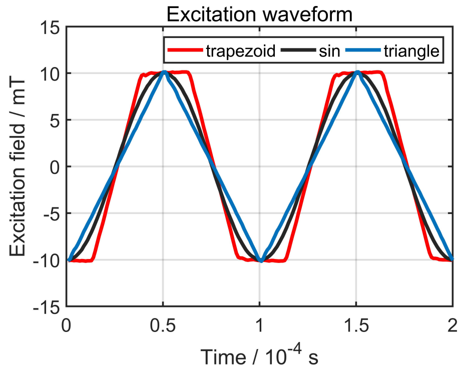

Figure 2: Three types of excitation waveforms used in this research

with large bore diameters. However, due to these advantages, most existing studies use the sinusoidal wave as the excitation wave by default. Therefore, other excitation waveforms need to be studied to characerize the effect for MPI systems.

An arbitrary waveform relaxometer has been proposed and proved by relevant scholars that it can effectively measure the magnetisation characteristics of SPIONs [5-6]. Based on designing and constructing the MPS system, this study selected sinusoidal, trapezoidal and triangular waveforms as excitation waveforms and explored the effect of these on particles at 10 kHz and 15 kHz excitation frequencies. Then we compare and analyse the received signal results generated by the three excitation waveforms. Eventually, the study analyses the effects of excitation waveforms on MPS and MPI systems, and put forward some potential problems, hoping to have positive significance for further research.

II. Material and methods

II.I. Design and construction of MPS system

We designed and set up an MPS system to explore the characteristics of response signals generated by magnetic particles under various excitation waveforms. It can satisfy the requirements of changing excitation waveform and excitation frequency arbitrarily during the experiment. Figure 1 shows the overall system.

The excitation magnetic field is generated by the double-layer wound solenoid coil. Moreover, to ensure the magnetic field uniformity in the detection area as much as possible, the coil length is chosen to be 100 mm, and the internal diameter is 26 mm. The excitation coil is 124 turns and is made of Litz wire with a diameter of 3 mm. The receive coil consists out of two parts, each 12 mm in diameter, and symmetrically distributed at a distance of 12 mm, which are made of 100 turns of copper wire with a diameter of 0.2 mm. The winding direction of the two parts is opposite. The upper part is used to detect the magnetization response signal of the sample, and the lower part is to eliminate irrelevant signals other than particles.

II.II. Experimental method

In this study, Perimag (Micromod Partikelt-echnologie GmbH, Germany) stock solution was used as experimental sample. The iron particle concentration of the solution is 5 mg / ml. Each experiment used 0.2 ml of liquid put into the plastic sample tube for the test.

The study applied three different waveforms to the excitation coil: A triangular wave, a trapezoidal wave, and the widely used sinusoidal wave. In the time of each cycle, the rising and falling times of the triangular wave accounted for 1/2 and the rising, horizontal and falling intervals of trapezoidal wave accounted for 1/3 respectively. The slewrate at the zero-crossing is 4546 mT/s and 8393mT/s.

The excitation amplitude was set as 10 mT among all experiments. Figure 2 illustrates the actual measurement of three excitation waveforms. Simultaneously, distinct waveforms were measured separately under two frequencies of 10 kHz and 15 kHz to comprehensively compare the effects of distinct excitation. Each experiment was conducted five times after subtracting background signals, and the average value was taken as the final data.

III. Results and discussion

Figure 3 shows the particles' time-domain signals received under conditions of two excitation frequencies and three kinds of excitation waveforms. Under the same excitation frequency and excitation magnetic field intensity, the particle signal peaks produced by different excitation waveforms are obviously different. The highest signal peak belongs to the trapezoidal wave, and the lowest one belongs to the triangular wave. The height of the sinusoidal wave is between the above two waveforms. This phenomenon is applicable at excitation frequencies

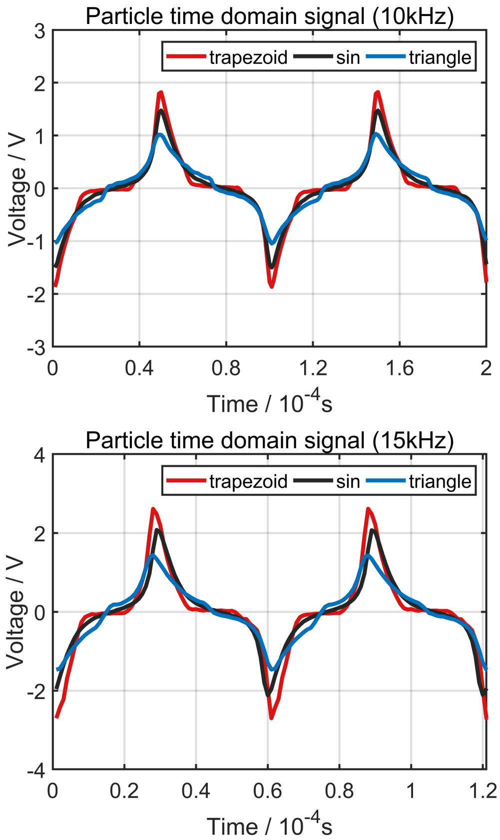

Figure 3: Time domain signals with different excitation waveforms. (a) The excitation frequency is 10 kHz. (b) The excitation frequency is 15 kHz.

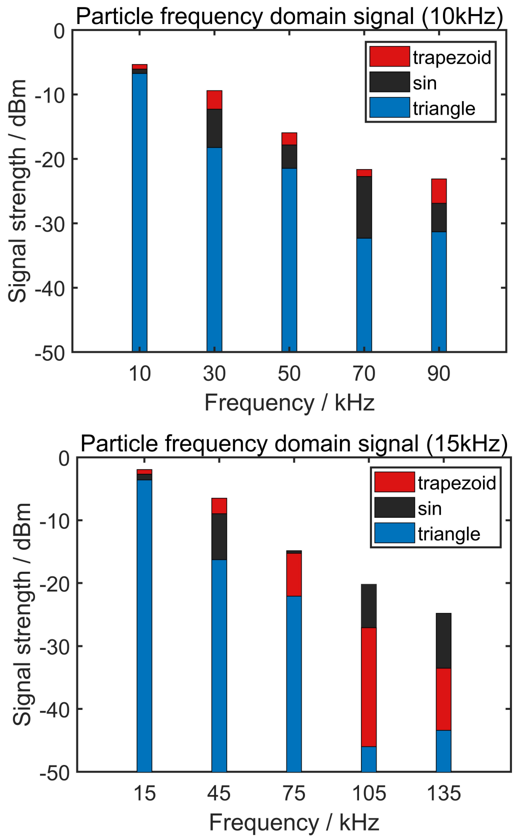

Figure 4: Frequency domain signals with different excitation waveforms. (a) The excitation frequency is 10 kHz. (b) The excitation frequency is 15 kHz.

of 10 kHz and 15 kHz. Additionally, the signal received at 15 kHz is stronger than 10 kHz as a whole.

The frequency of the excitation magnetic field and a series of magnetic responses of the harmonic component can be separated from frequency-domain signals, and they have a direct relation with the characteristic of detected particles [7-8]. To further analyse the characteristics of the received signal, we used a Fourier Transform to convert the receive signal into the frequency domain and plotted the amplitude of the first, third, fifth, seventh and ninth harmonic signals in odd harmonics, in Figure 4. When the excitation frequency is 10 kHz, the amplitude of the harmonic signal generated by a trapezoidal wave excitation is higher than that generated by the other two excitation waveforms, followed by the sine wave and the triangular wave is the worst. When the excitation frequency is 15 kHz, the amplitude of the first and third harmonics of the signal generated by trapezoidal wave excitation is higher, followed by the sine wave. However, the amplitude of the fifth, seventh and ninth harmonics is higher for sine wave excitation and lower for trapezoidal waves. For triangular waves, the effect is still the worst of the three.

Overall, compared with the traditional sinusoidal wave, the trapezoidal excitation wave has apparent advantages, obtaining higher signal strength, while the triangular wave performs poorly. The potential reason is that the trapezoidal wave maintains a higher magnetic field intensity for a longer duration, during which the particles may orientate and relax [9]. However, the triangular wave can only produce two instantaneous peak magnetic field intensity in each cycle. More importantly, the trapezoidal wave magnetic field has the largest rising speed and the triangular wave is the smallest. The variation characteristics of the sine wave magnetic field are between the above two excitation waves, leading to moderate performance. Interestingly, the amplitude of the odd harmonics generally decreases with the increasing frequency, but the amplitude of the 7th harmonic of the triangular wave is slightly lower than that of the 9th harmonic. The phenomenon needs further study, and the preliminary analysis indicates that the reason is maybe the interference of high-frequency noise.

10.18416/ijmpi.2022.2203054

IV. Conclusions

We developed an MPS system to generate arbitrary waveforms and explored the particle response characteristics under different excitation waveforms. The result shows that trapezoidal wave excitation has better signal strength at frequencies 10 and 15 kHz than the sinusoidal wave, while triangular wave excitation has a poor effect. Therefore, replacing the widely used sinusoidal excitation waveform with the trapezoidal wave can obtain a stronger signal. However, the broad-band signals generated by non-sinusoidal waveforms will makes it hard to separate feedthrough from receive signal. This problem brings new challenges to hardware systems such as circuits. The study is of certain reference significance to promote the application of the MPS system. At the same time, it can be inferred that different waveform excitation will have similar imaging effects in the MPI system. Therefore, further research with different excitation waveforms needs to be done on other MPI systems to validate the benefit of non-sinusoidal waveforms for imaging and spectroscopy.

It should be noted that, on the one hand, the shapes of the three excitation waveforms are fixed in this study, so it is necessary to change the parameters of each waveform (such as rising and falling slopes) for a more comprehensive comparative study[5]. On the other hand, except for the sinusoidal excitation wave, only the trapezoidal wave and triangular wave are studied in this study. Therefore, whether other excitation waveforms have better signal effects needs to be further studied.

Acknowledgments

This work was supported in part by the National Key Research and Development Program of China under Grant, 2017YFA0700401; Natural Science Foundation of China under Grant: 62027901; CAS Youth Innovation Promotion Association under Grant 2018167, and CAS Key Technology Talent Program.

Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Not applicable. Ethical approval: Not applicable.

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