ISSN: 2414-1895 DOI: 10.6919/ICJE.202205_8(5).0049

Study of Frequency Domain Lift-off Intersections of Ferromagnetic and Non-ferromagnetic Materials

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Abstract

In this paper, the signal characteristics of pulsed eddy currents in ferromagnetic and non-ferromagnetic materials are analyzed, the intermediate signal intercepts of pulsed eddy currents are taken, and the method of measuring peel height is derived through experimental verification. Through the analysis of the pulsed eddy current detection signal, it is found that there is a correlation between the intercept of the intermediate signal and the peeling height in the double logarithmic coordinate system. Combining with the revealed characteristics and change law of the peeling intersection, the research on the acquisition and adjustment method of the peeling intersection of the pulsed eddy current signal is carried out in depth by using theoretical modeling, numerical simulation analysis and experiments.

Keywords

Pulsed Eddy Current Signal; Ferromagnetic; Non-ferromagnetic; Lifting Off Cross Point.

1. Introduction

In pulsed eddy current detection, the time-domain lifting crossover points of ferromagnetic materials can be obtained using the second difference method of pulsed eddy current signals. Comparing the time domain LOI acquisition methods for ferromagnetic and non-ferromagnetic materials, the time domain LOI acquisition methods for pulsed eddy current detection signals of ferromagnetic and non-ferromagnetic materials are not uniform. On the one hand, the feature extraction criteria of time-domain LOI become contradictory signals. In addition, the detection range of time-domain LOI is relatively limited in practical detection conditions. On the other hand, recent studies on LOI focus on the pulsed eddy current time domain signal of non-ferromagnetic materials, but there are few studies on the pulsed eddy current frequency domain signal and frequency domain LOI of ferromagnetic and non-ferromagnetic materials. Therefore, the study of pulsed eddy current frequency domain signal and frequency domain LOI is an effective means to solve this problem in order to unify and extend the acquisition method of LOI and improve the measurement range of LOI. In this paper, the pulsed eddy current differential signals of ferromagnets and non-ferromagnets are analyzed, and the effects of detection boosting on the amplitude spectrum, phase spectrum, real spectrum and imaginary part spectrum of the pulsed eddy current differential signals are investigated. The frequency domain LOI in the spectrum of the pulsed eddy current differential signal is obtained, and the effect of the pulsed excitation signal on the frequency domain LOI and the possibility of the frequency domain LOI thickness measurement are further analyzed.

2. Acquisition of Frequency Domain Lift-off Crossover Points

In the simulation analysis, the conductivity of the non-ferromagnetic material is 37ms/m, the relative permeability is 1, and the thickness is 1mm. the conductivity of the ferromagnetic material is 2ms/m,

ISSN: 2414-1895 DOI: 10.6919/ICJE.202205_8(5).0049

the relative permeability is 60, and the thickness is 1mm. the inner diameter of the probe coil is 4mm, the outer diameter is 6mm, and the height is 6mm. the pulsed eddy current differential signals of the ferromagnetic and non-ferromagnetic materials are simulated. The pulsed eddy current differential signals at different probe lifting distances are shown in Figure 1. It can be observed that the pulse eddy current differential signals of ferromagnetic and non-ferromagnetic materials have opposite amplitude changes, where the pulse eddy current differential signals of ferromagnetic materials do not have the phenomenon of over-zero, while the pulse eddy current differential signals of non-ferromagnetic materials have the phenomenon of over-zero. [1]Compared with the pulse eddy current differential signal of non-ferromagnetic materials, the pulse eddy current differential signal of ferromagnetic materials has a larger change in amplitude, but the stable value of the pulse eddy current differential signal of both materials tends to zero. When the probe lifting distance is changed, the LOI phenomenon appears in the pulse eddy current differential signal of non-ferromagnetic materials, and the LOI phenomenon does not appear in the pulse eddy current differential signal of ferromagnetic materials. Under the two different material conditions, the change of pulse eddy current differential signal with the lifting distance of the probe is the same.

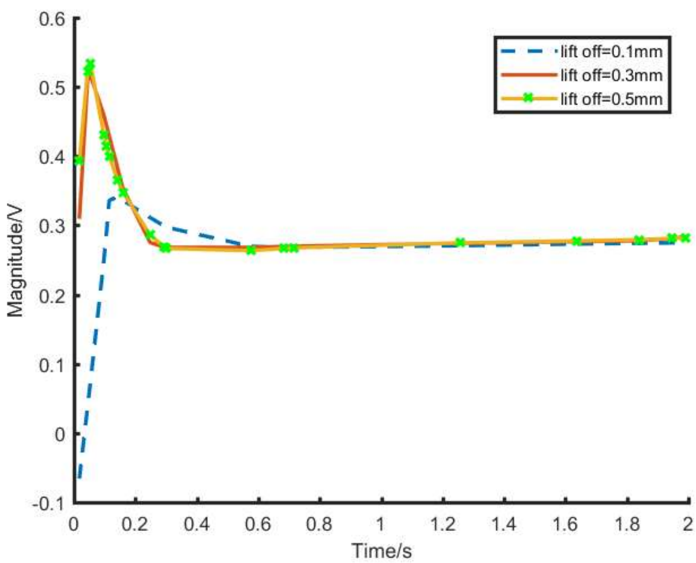

Figure 1. Pulsed eddy current differential signal of ferromagnetic and non-ferromagnetic materials

Based on the pulsed eddy current differential signals of ferromagnetic and non-ferromagnetic materials, the amplitude spectrum, phase spectrum, real part spectrum and imaginary part spectrum signals of the pulsed eddy current differential signals are further analyzed, and the influence of the probe lifting distance on the spectral signals is investigated. First, the amplitude spectral signals of the pulsed eddy current differential signals of ferromagnetic and non-ferromagnetic materials were extracted separately. The amplitude signals under different probe lifting conditions are shown in Figs. 2. It can be observed that, in general, the amplitude of the pulsed eddy current differential signal varies mainly in the frequency band from 0 to 50 kHz, while the amplitude tends to zero and remains constant in the subsequent higher frequency band. From the amplification of the amplitude spectrum from 0 to 50 kHz, it can be seen that the amplitude of the pulsed eddy current differential signal of ferromagnetic and non-ferromagnetic materials gradually decreases as the probe lifting distance increases, and the amplitude variation of the pulsed eddy current differential signal of ferromagnetic and non-ferromagnetic materials is mainly concentrated in the frequency band from 0 to 50 kHz, and the amplitude signal in the higher frequency band remains basically unchanged and is not affected by the lifting height of the probe.

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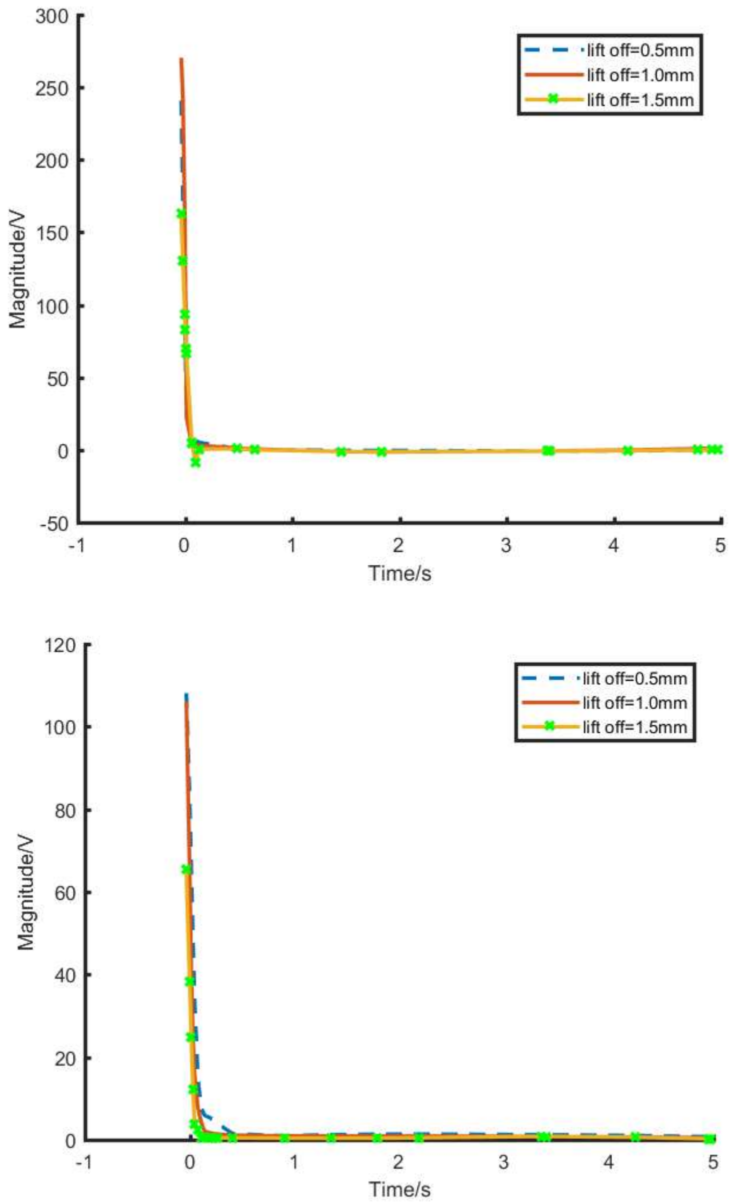

Figure 2. Amplitude spectrum of pulsed eddy current differential signal

Similarly, the phase spectrum signals of the pulsed eddy current differential signals of ferromagnetic and non-ferromagnetic materials were extracted. The phase spectra at different probe lift-off heights are shown in Figures 3. It can be observed that the phase spectra of the pulsed eddy current differential signals of ferromagnetic and non-ferromagnetic materials remain almost constant in the initial frequency band and the subsequent high frequency band, independent of the change in the probe lifting height. [2]In the frequency range of 150 kHz to 350 KHz, the phase spectrum of the pulsed eddy current differential signal of ferromagnetic and non-ferromagnetic materials decreases with increasing frequency and decreases with increasing lift-off force. Compared with ferromagnetic materials, the phase spectrum of the pulsed eddy current differential signal of non-ferromagnetic materials varies more significantly, and the high frequency and initial low frequency are almost unaffected by the probe lift-off effect.

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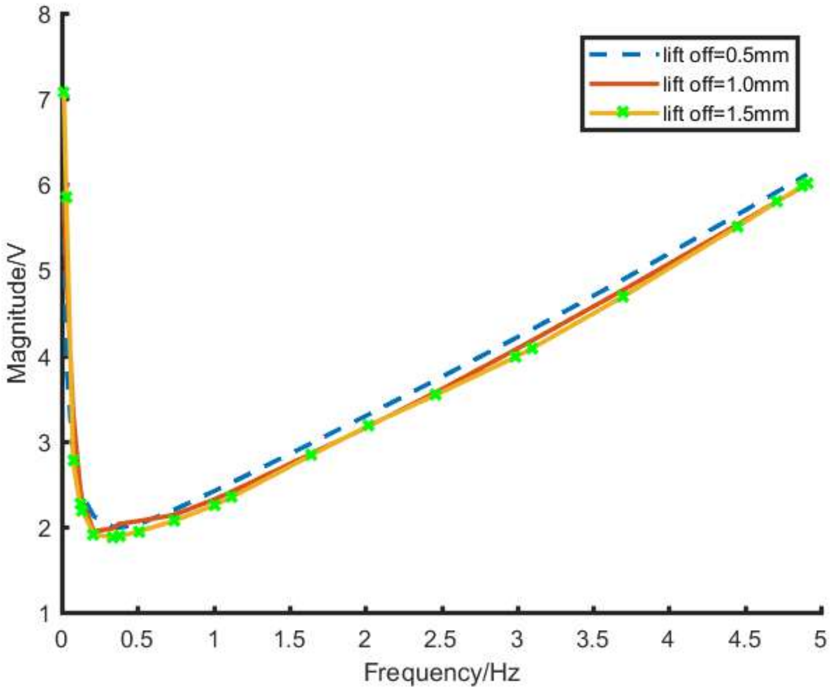

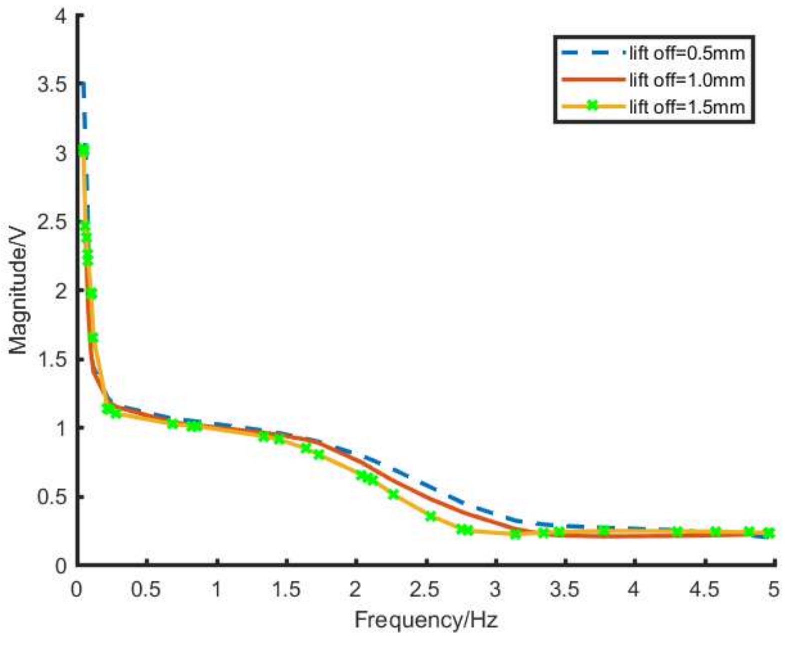

Figure 3. Phase spectrum of pulsed eddy current differential signal

Then, the real part of the spectral signals of the pulsed eddy current differential signals of ferromagnetic and non-ferromagnetic materials are extracted. The real part of the spectral signals at different probe lift-off heights are shown in Figs. 4. It can be observed that the variation of the real part spectrum of the pulsed eddy current differential signals of ferromagnetic and non-ferromagnetic materials is mainly concentrated in the frequency band from 0 to 50 KHz, and the amplitude spectrum signal in the later high frequency band tends to zero and remains unchanged. Compared with the amplitude spectrum signal, the real part of the spectrum signal has LOI phenomenon and over-zero phenomenon. Due to the change of the probe lifting height, the real part of the spectrum signal is mainly concentrated in the frequency band of 0-50 KHz.

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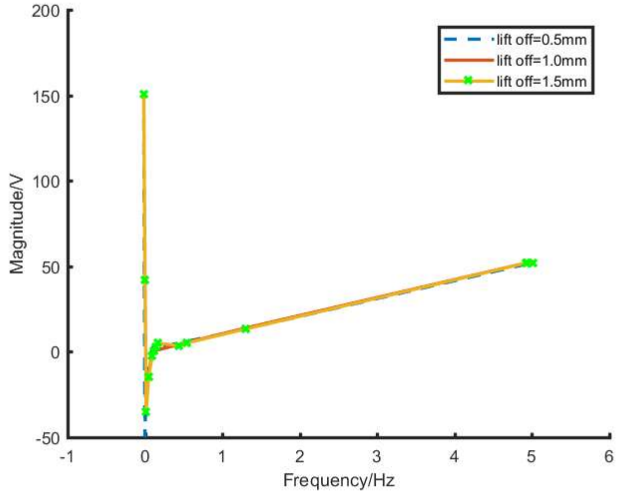

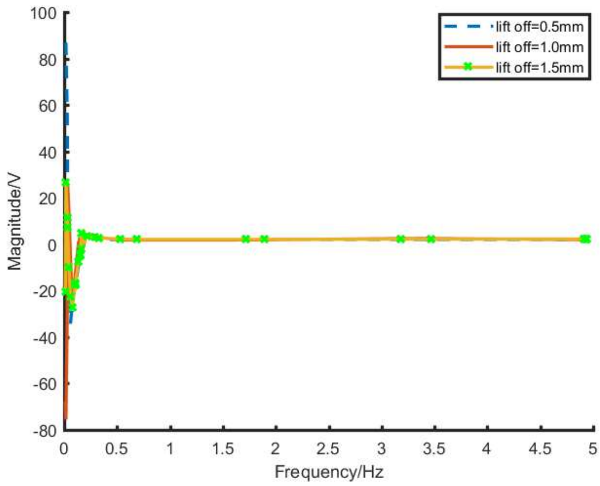

Figure 4. Real part spectrum of pulsed eddy current differential signal

3. Feasibility Analysis of Frequency Domain Lift-off Cross-point Thickness Measurement

LOI exists in the real and imaginary part of the spectrum of the pulsed eddy current differential signals of ferromagnetic and non-ferromagnetic materials. In order to further analyze the validity of the frequency domain real and imaginary LOI of ferromagnetic and non-ferromagnetic materials, the feasibility of obtaining the frequency domain real and imaginary LOI thickness measurements under the conditions of ferromagnetic and non-ferromagnetic materials is analyzed.[3].

In the simulation analysis, the measured parameters of the ferromagnetic and non-ferromagnetic materials are the same as in the above analysis, and the probe size and pulse excitation parameters are the same, but the measured part thicknesses are different. The thicknesses of the measured ferromagnetic and non-ferromagnetic materials were between 0.1 mm and 1 mm. First, the true LOI in the frequency domain is extracted for the ferromagnetic and non-ferromagnetic material conditions, respectively. as the measured part thickness increases, the LOI of the true part in the frequency domain obtained for the ferromagnetic and non-ferromagnetic material conditions varies along the direction of the smaller amplitude and frequency parameters. The variation pattern of the LOI of the real part in the frequency domain with thickness obtained in both material conditions is the same. In contrast, the amplitude and frequency parameters of the frequency domain real LOI variation curves obtained under non-ferromagnetic material conditions are larger, while the amplitude variation of the frequency domain real LOI variation curves obtained under ferromagnetic material conditions is relatively small. When the thickness of the specimen is large, the variation of LOI of the real part

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obtained under the condition of ferromagnetic material is relatively small with the increase of thickness.

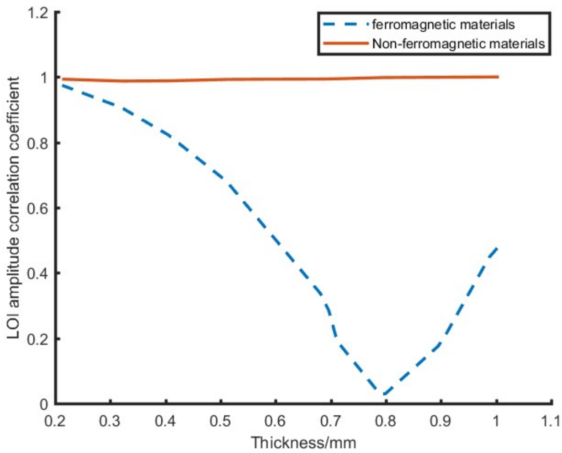
The frequency domain true part LOI obtained under ferromagnetic and non-ferromagnetic material conditions can be used for thickness measurement of the part under test, and the LOI amplitude and frequency parameters can be used directly to evaluate the thickness of the part under test. In contrast, the thickness measurement accuracy of the real LOI amplitude and frequency parameters for non-ferromagnetic materials is high, while the thickness measurement accuracy of the real LOI amplitude and frequency parameters for ferromagnetic materials is relatively low, and the thickness measurement accuracy of the real LOI frequency parameters for ferromagnetic materials is higher than the thickness measurement accuracy of the LOI amplitude parameters.

Under the condition of non-ferromagnetic materials, the amplitude and frequency parameters of the imaginary LOI in the frequency domain decrease as the thickness of the specimen increases. Under the condition of ferromagnetic material, the imaginary LOI in the frequency domain first increases and then decreases, and the frequency parameter gradually decreases. In contrast, the amplitude parameters of the imaginary LOI obtained in non-ferromagnetic materials vary more. Under the condition of ferromagnetic material, the amplitude parameter of imaginary LOI is non-monotonic.[4] The frequency parameter of the imaginary LOI obtained in both ferromagnetic and non-ferromagnetic materials decreases as the thickness of the specimen increases.

4. Effect of Pulsed Excitation Signal on Frequency Domain Lifting Off Crossover Point

In order to further elucidate the effect and law of pulse excitation signal variation on frequency domain LOI, this subsection will analyze the effect law of pulse excitation signal frequency and rise time variation on frequency domain LOI, and point out the application of frequency domain LOI in the detection of ferromagnetic and non-ferromagnetic materials and the selection of pulse excitation signal parameters.[5].

In the simulation analysis, the measured parameters of ferromagnetic and non-ferromagnetic materials are the same as in the previous chapters, and the sample thickness is kept at 1 mm. the frequency of the pulse excitation signal is varied from 100 Hz to 400 Hz with a time constant of 40 and an amplitude of 10 V. First, the real LOI of ferromagnetic and non-ferromagnetic materials are extracted separately. the variation of LOI under different pulse excitation signal frequencies is shown in Figure 5. It can be observed that the true LOI obtained under ferromagnetic and non-ferromagnetic material conditions varies with the frequency of the pulse excitation signal, but not monotonically. In the same range of variation of pulse excitation signal frequency, the true LOI amplitude obtained under ferromagnetic material condition varies more, while the true LOI amplitude obtained under non-ferromagnetic material condition varies less.



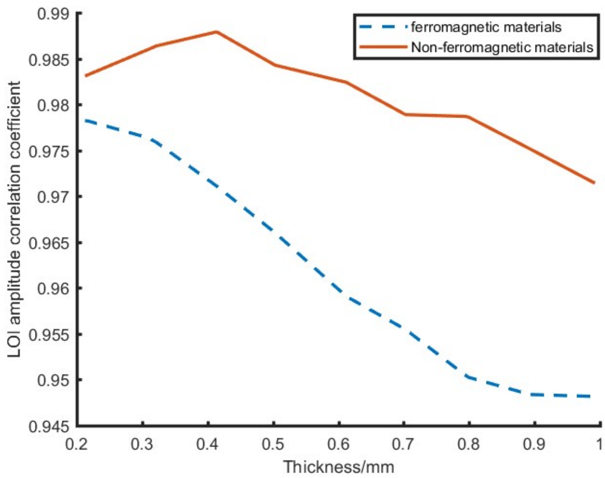


Figure 5. Correlation coefficient of the thickness measurement curve of the LOI parameter in the imaginary part of the frequency domain

To further analyze the influence of the rise time of the pulse excitation signal on the imaginary LOI, the amplitude and frequency parameters of the imaginary LOI obtained under the conditions of ferromagnetic and non-ferromagnetic materials were extracted separately, and the function curves were fitted using the time constants of the pulse excitation signal.[6] As the time constant of the pulse excitation signal increases, the frequency parameters of the imaginary LOI in the frequency domain of ferromagnetic and non-ferromagnetic materials gradually decrease, and the changes of the LOI frequency parameters are basically the same. On the other hand, as the time constant of pulse excitation signal increases, the amplitude parameter of imaginary LOI of ferromagnetic material decreases, while the amplitude parameter of imaginary LOI of non-ferromagnetic material changes relatively little. The change of pulse excitation signal rise time cannot effectively change the real and imaginary LOI distributions obtained under the condition of non-ferromagnetic materials, but can effectively change the real and imaginary LOI distributions obtained under the condition of ferromagnetic materials. Within a certain range, the variation of the rise time of the pulse excitation signal can directionally change the distribution of the real part LOI obtained under the condition of non-ferromagnetic materials, and can also directionally adjust the frequency parameters of the real part LOI and imaginary part LOI obtained under the condition of non-ferromagnetic materials.

5. Experimental Verification of the Frequency Domain Lifting Off the Crossover Point

5.1 Experimental Conditions

The tested parts are stainless steel 430 steel strip and aluminum strip, the thickness varies from 0.1mm to 2.0mm, the size is 150mm×150mm. the experimental probe is the same as before. Data acquisition card sampling frequency is 1MHz, rising edge trigger, the number of samples is 2000 points. The function generator is used to generate pulse excitation signal with frequency varying from 150Hz to 250Hz, rising time varying from 70us to 130us, and amplitude of 10V.

5.2 Experimental Results

First, in order to confirm the existence of real and imaginary LOI in the pulsed eddy current differential signals of ferromagnetic and non-ferromagnetic materials, the thickness of the test piece was set to 1 mm. the test piece of steel strip was tested and the pulsed eddy current differential signals of the steel strip were collected. [7] Then, the frequency domain real and imaginary part signals of the pulsed eddy current difference signal of the steel strip were extracted under the conditions of different detection distances, and the results are shown in Figure 6. With the change of the detection distance, it is found that the LOI phenomenon exists in the real and imaginary parts of the pulse eddy

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current difference signal of the steel strip, and the real and imaginary signals affected by the change of the detection distance are mainly concentrated in the low frequency band. This is the same rule of variation as the simulation results.

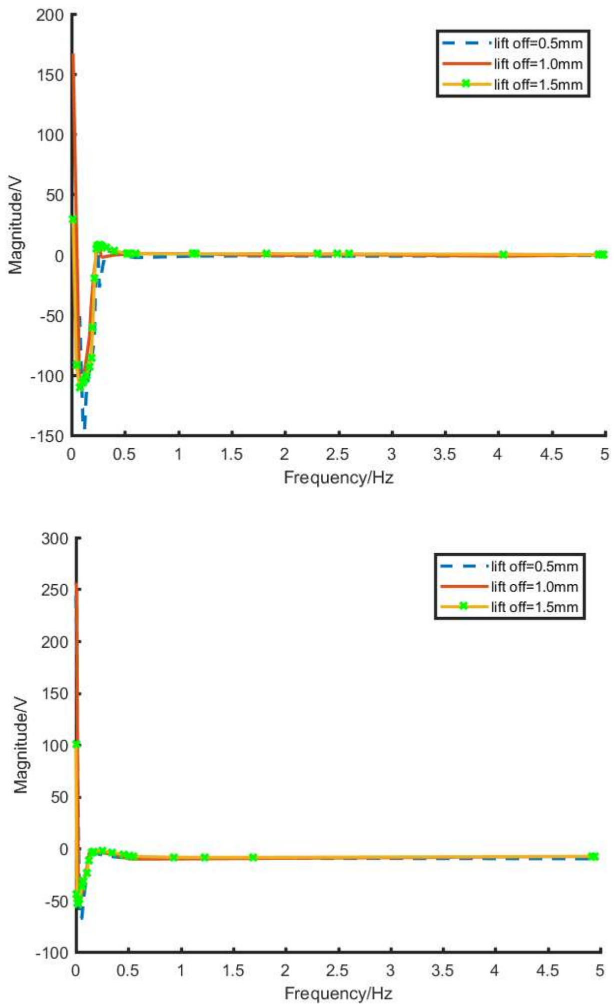
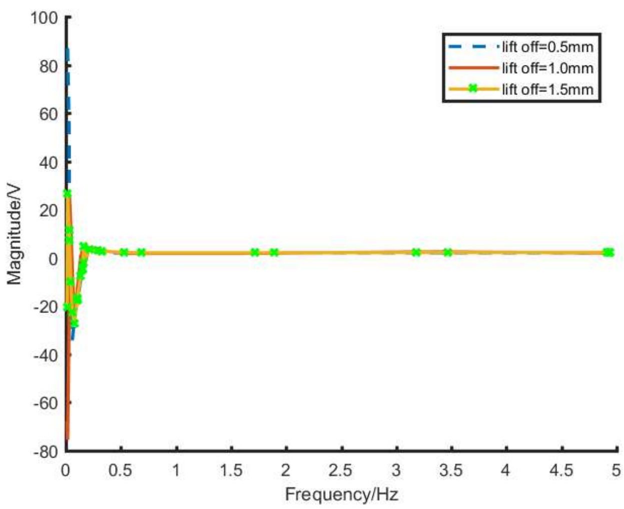


Figure 6. Real and imaginary part spectra of the pulsed eddy current differential signal of a steel strip



ISSN: 2414-1895
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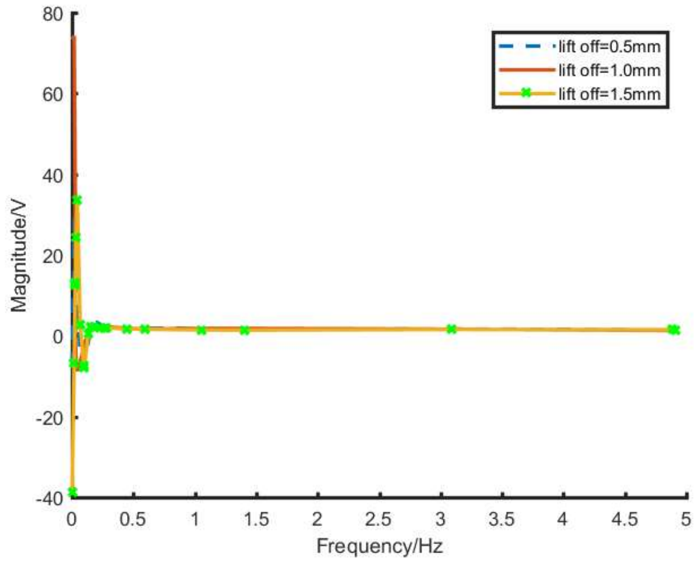

Figure 7. Real and imaginary part spectra of pulsed eddy current differential signal of aluminum strip

On the other hand, the real and imaginary signals in the frequency domain of the pulsed eddy current differential signal of the aluminum strip were extracted separately under the same test conditions, as shown in Figure 7. It can be observed that with the change of the probe lifting distance, the LOI phenomenon also appears in the real and imaginary signals of the pulsed eddy current differential signals of the aluminum strip. The real and imaginary signals affected by the change of the probe lifting height are mainly concentrated in the low frequency band, and the real and imaginary spectral signals in the high frequency band tend to zero and remain unchanged, which is the same as the change pattern of the simulation results. [8] The above results show that LOI exists in both the real and imaginary parts of the frequency domain of the pulsed eddy current differential signal. the simulation results verify the existence of LOI in the frequency domain under the conditions of ferromagnetic and non-ferromagnetic materials, unify the acquisition method of LOI under the conditions of ferromagnetic and non-ferromagnetic materials, and extend the acquisition method of LOI.

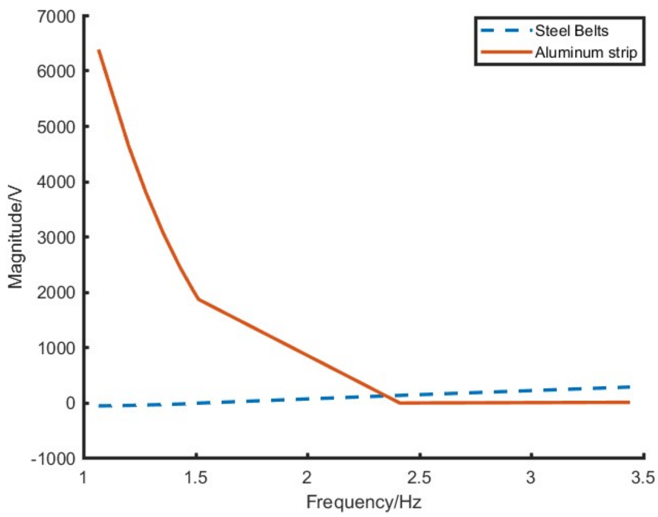

Figure 8. Frequency domain real part LOI variation curve with thickness

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Then, the LOI obtained based on the above frequency domain real part signal is used to measure steel and aluminum strip specimens. When the thickness of the specimens was varied from 0.1 mm to 2 mm, the variation curve of LOI of real parts in the frequency domain was obtained, as shown in Figure 8. It can be observed that as the thickness of the measured steel and aluminum strip increases, the amplitude and frequency parameters of the LOI of the real part in the frequency domain decrease and change, and exhibit a monotonic orientation law change. The variation pattern of LOI of real parts in the frequency domain of the strip and aluminum strip is consistent with the simulation results. In the frequency domain of the steel and aluminum strips, only the amplitude and frequency parameters differ in the LOI variation curves of the real parts.

The LOI obtained from the above frequency domain imaginary part signal was used to measure the steel and aluminum strip samples. When the thickness of the specimen is also varied from 0.1 mm to 2 mm, the obtained frequency domain imaginary part LOI variation curves are shown in Figure 9. It can be observed that the amplitude and frequency parameters of the imaginary LOI of the aluminum strip decrease as the thickness of the measured part increases, while the amplitude parameters of the imaginary LOI obtained in the steel strip condition first increase and then decrease, and the frequency parameters of the imaginary LOI of the steel strip also decrease. The variation pattern of the virtual LOI is the same as the simulation results, but the amplitude and frequency parameters are different. The above results show that the variation patterns of the frequency domain real and imaginary LOI thickness measurement curves for steel and aluminum strips are consistent with the simulation results, i.e., the frequency domain LOI can be used to measure the thickness of the measured ferromagnetic and non-ferromagnetic materials, and the feasibility of the frequency domain real and imaginary LOI thickness measurement is verified.

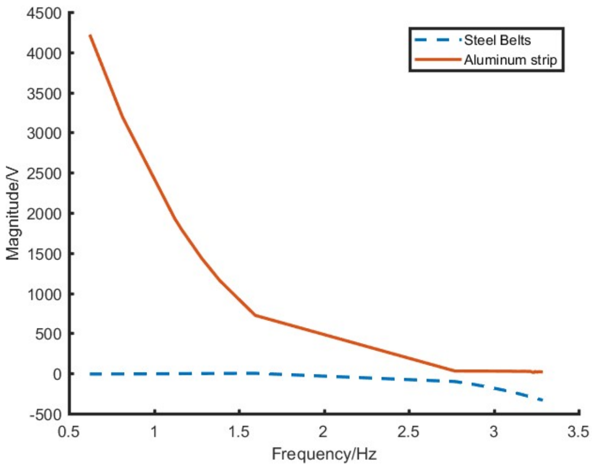

Figure 9. Variation curve of imaginary LOI in frequency domain with thickness

When the rise time of the pulse excitation signal changes from 70 to 130, the real LOI in the frequency domain is extracted under the condition that the thickness of the measured steel and aluminum strips is maintained at 1 mm, as shown in Figure 10. It can be observed that with the increase of the rise time of the pulse excitation signal, the real LOI amplitude parameter in the frequency domain of the aluminum and steel strip shows a gradual increase in the change, while the frequency parameter shows a gradual decrease in the change. The change pattern is the same as the simulation results, and the change direction and amplitude only differ in magnitude. The results show that the change of the rise time of the pulse excitation signal can change the frequency domain true LOI of ferromagnetic and non-ferromagnetic materials to a certain extent, which further verifies the regulation of the pulse excitation signal rise time on the frequency domain true LOI.

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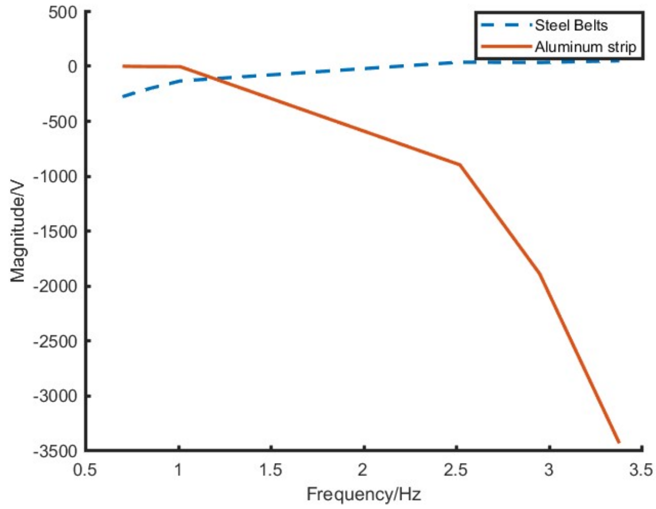

Figure 10. Variation of imaginary LOI in frequency domain with rise time of pulse excitation

The experimental results show that in the spectral analysis of the pulsed eddy current differential signals of steel and aluminum strips, the simulation results of the real and imaginary spectral signals are consistent with the experimental results, and the existence of the real and imaginary LOI in the frequency domain for ferromagnetic and non-ferromagnetic materials is verified. [9] In the validity verification and influence factor analysis of LOI in frequency domain, the variation patterns of real and imaginary LOI with the thickness of the measured parts are consistent with the simulation results, and the feasibility of LOI thickness measurement in frequency domain is verified. The effect of pulse excitation signal on the LOI of real and imaginary parts in the frequency domain is consistent with the simulation results. [10]The change of the pulse excitation signal has a significant modulating effect on the frequency domain real and imaginary LOI.

6. Conclusion

In this paper, the possibility of measuring the real and imaginary thicknesses of ferromagnets and non-ferromagnets was analyzed, and the validity of the real and imaginary LOI in the frequency domain was verified, with the following main conclusions.

(1) The effects of pulse excitation signal frequency and rise time on the LOI of real and imaginary parts of ferromagnetic and non-ferromagnetic materials in the frequency domain are investigated, and the control effect of pulse excitation in the frequency domain is elucidated.

(2) The validity and the possibility of thickness measurement of real and imaginary part LOI in the frequency domain of ferromagnetic and non-ferromagnetic materials are verified. The results show that the real and imaginary part frequency domain LOI of the pulsed eddy current differential signals obtained under ferromagnetic and non-ferromagnetic conditions are valid and can be used to measure the thickness of ferromagnetic and non-ferromagnetic materials.

(3) The distribution of the real and imaginary parts of the frequency domain LOI can be adjusted to some extent when the frequency and rise time of the pulsed excitation signal are changed.

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