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A Signal Processing Method for Steel Plate Thickness Measurement Using EMATs

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Abstract. The time-of-flight (TOF) of the electromagnetic acoustic transducer (EMAT) echo signal can be used to measure the steel plate thickness. There are two ways to obtain the TOF, which are measure the peak to peak time in the time domain and calculate the echo frequency in the frequency domain. In this paper, a simplified signal model is proposed based on the analysis of received signals. Further, the relationship between the echo signal and excitation signal is considered. The echo signal is separated when the asynchronous demodulation method is applied to the received signal, and the thickness of steel plate can be calculated according to the peak spectral frequency in the low frequency band. The simplified model and signal processing method are verified by the experiment, and the results show that the model is reasonable and the accuracy of the signal processing method is high.

Keywords. EMAT, thickness measurement, asynchronous demodulation.

1. Introduction

EMATs can generate different forms of waves by adjusting magnetic circuit and coil structure and don't need coupling agent, so they have been wildly used in the flaw detection, thickness measurement and fatigue detection [1]. For different application, the EMAT signals have different characteristics. Various signal processing methods have been proposed to meet the testing requirement [2].

When EMATs are applied to metal plate thickness measurement, and the time-interval of echo signal is measured to calculate the thickness of steel plate. Typically, the transit time between two consecutive echoes in an ultrasonic waveform are used to be the time-interval value directly [3]. Therefore, the amplitude of the signal and signal-to-noise ratio (SNR) are important indicators of measurement accuracy. In previous studies, many methods had been proposed to improve SNR and improve the measurement accuracy. The timing average and linear filtering method are widely used to reduce the white and grain noise [4], [5]. Stationary wavelet and variational mode decomposition linked wavelet method have been studied in recent years and combined with other method for denoising [6],[7]. These works greatly improve the signal quality in the time domain.

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Frequency component analysis was proposed to gauge the thickness of aluminum sheet by Dixon [8]. Different from those traditional methods, echo frequency is calculated by applying the Fast Fourier transform (FFT) to the signal and then obtain the thickness of aluminum sheet. Therefore, SNR has a small influence on the frequency component analysis. In this paper, the relationship between echo frequency and excitation frequency in the steel plate received signal is studied. Based on the relationship, echo frequency and thickness information are obtained from the received signal by applying asynchronous demodulation to the signal.

2. Signal analysis and processing method

The working process of EMATs includes the coupling between the electric field, magnetic field and sound field. Therefore, the complete mathematical expression of wave is difficult to obtain. Based on the analysis of the received signal, a simplified waveform function is employed to express the relationship between the main component in the signal and then a signal processing method is proposed to obtain the echo frequency based on the waveform function.

2.1. Waveform analysis

The typical received signal of EMATs is analyzed to find an appropriate method and extract the echo frequency in the frequency domain. Figure 1 shows the whole received process of the EMAT. If the paralysis time in the beginning of the signal is ignored, the positive half envelope of the whole signal shows an exponential decay. Then, a segment of the EMAT signal is enlarged in the Figure 2, and it can be seen that the received signal mainly contains two different cycles which are excitation signal cycle and echo signal cycle. The relationship between two signals is that the echo signal is modulated by the excitation signal.

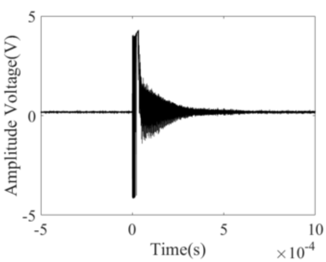

Figure 1. Whole received signal of EMAT.

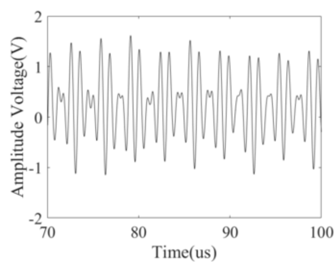

Figure 2. A segment of EMAT signal.

2.2. Signal processing

From the analysis above, the EMAT signal mainly contains the paralysis time, an exponential decay, a sinusoidal excitation signal, and a periodic echo signal. If the paralysis time, harmonic frequency component and noise ignored, a fitting function only contains exponential decay, echo cycle and excitation cycle can be obtained:

$$S(t) = A_0 e^{-\tau t} \sin(2\pi f_0 t) \cdot \left|\sin(\pi f_1 t + \varphi)\right| \tag{1}$$

Where, A_0 and τ are system dependent coefficients, f_0 is the frequency of the excitation signal and f_1 is the frequency of echo signal, τ is the phase difference between the excitation signal and echo signal. The value of A_0 and τ can be obtained by using two point on the positive envelope of the received signal.

As shown in the Figure 4, the signal amplitude and SNR decrease at the end of the received signal. So, this part of the signal needs to be removed from the analyzed signal. Then a segment of echo signals with a sampling time of T_s can be obtained for analysis.

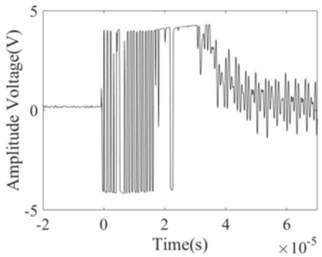

Figure 3. Paralysis time of the EMAT system.

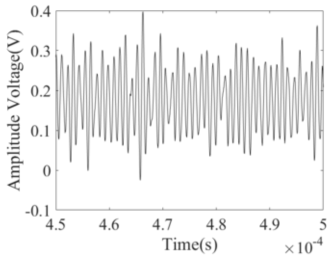

Figure 4. The late signal of the EMAT system.

According to the above analysis and the fitting function, the echo signal frequency can be obtained if the received signal is demodulated. Compared with synchronous demodulation, asynchronous demodulation is easy to implement and can avoids the influence of the excitation frequency shift. The first step of the asynchronous demodulation is half-wave rectification, which can be expressed by Eq. (3).

$$S_1(t) = [S(t) + |S(t)|]/2 \tag{2}$$

The echo signal is demodulated from the received signal when the signal $S_1(t)$ filtered by the low-pass filter and the echo frequency can be obtained after the FFT is applied to the filtered echo signal. According to the relationship between frequency domain resolution and sampling time, the frequency domain resolution of the signal frequency spectrum is the inverse of the sampling time. The low-pass filtering process is omitted and the echo frequency is obtained by reading the peak spectral frequency in the low frequency spectrum after the FFT is applied to $S_1(t)$ directly.

3. Experiment results and discussions

3.1. Experiment setup and procedure

An EMAT experiment platform shown in Fig. 5 is built to study the fitting degree of the fitting function with the actual signal and to verify the correctness of the signal processing method. In the platform, the signal generator and power amplifier circuit generate an oscillating signal about 1MHz and lasts for about 3 cycles. The received signal generated in the probe flow into the preamplifier circuit for processing, and the oscilloscope is used to collect the received signal. The amplification of the signal conditioning circuit is 100db and the oscilloscope used in the experiment is Teledyne

3024 which has a sampling rate of 200MHz. To reduce the impact of noise, the received signal were averaged 128 time by the oscilloscope. All the steel plates used in the experiment are made of 16MnR, in which the propagation velocity of vertical shear wave is 3200 m/s. The thicknesses of the steel plates are 5.20 mm, 7.70 mm and 10.75 mm, and the lift-off between the steel plate and EMAT is 2 mm.

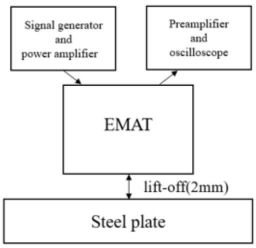

Figure 5. Experiment system diagram.

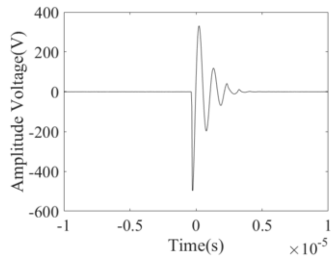

Figure 6. Exciting signal of the system.

To obtain the fitting degree of the fitting function and actual signal, an important step is to calculate the coefficients of the fitting function. The parameter A_0 and τ can be calculated through the positive half envelope, and fitting function can be obtained if the excitation frequency and the thickness of steel plate already known. In the experiment, using the signal of 7.70 mm steel plate as an example, and the fitting function can be expressed as the Eq. (4):

$$S(t) = 2.2467 \cdot e^{-5504.4286t} \cdot \sin(2\pi \cdot 10^6 \cdot t) \cdot \left|\sin(\pi \cdot 103896 \cdot t + \varphi)\right| \tag{3}$$

To verify the relationship between the excitation frequency and the echo frequency, the FFT is applied to the 7.70 mm steel plate directly. The frequency spectrum of the fitting function and actual testing signal are shown in Figures 7 and 8, respectively. It can be seen from the spectrum that the fitting function fits the actual signal have a similar frequency component. And as predicted, the echo frequency in the actual signal is modulated by the excitation frequency.

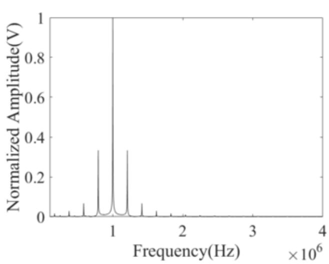

Figure 7. The spectrum of 7.70 mm steel plate fitting function.

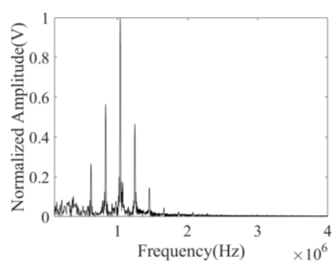

Figure 8. The spectrum of 7.70 mm steel plate testing signal

Obviously, asynchronous demodulation can be applied to obtain echo frequency. The first step of asynchronous demodulation is half-wave rectification, and the spectrums of the fitting function and the actual testing signal after half-wave rectification are obtain in the Figure 9 and Figure 10, respectively.

$$d_s = \frac{V_s}{2f_e} \tag{4}$$

Compared with the original spectrum, the echo frequency is separated from the excitation frequency in the low frequency band. From the peak spectral frequency (f_e) in the low frequency band, the thickness information can be obtained using the Eq. (5):

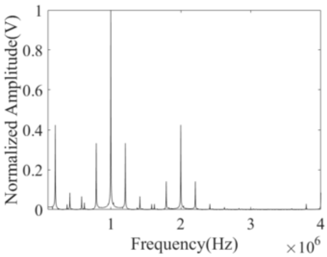

Figure 9. The spectrum of 7.70 mm steel plate fitting function after half-wave rectification

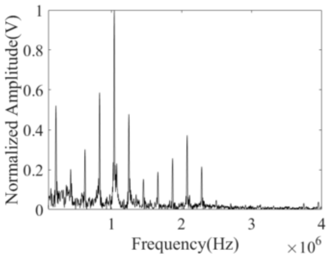

Figure 10. The spectrum of 7.70 mm steel plate actual testing signal after half-wave rectification

3.2. Results and Discussions

By comparing the spectrums of fitting function and actual signal, the correctness of the fitting function and the relationship between the excitation frequency and echo frequency have been verified. And asynchronous demodulation can be used to obtain the echo frequency in the low frequency band. The frequency band can be selected according to the measuring range.

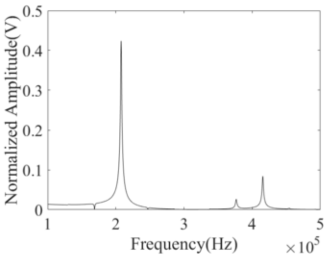

Figure 11. The 100K~500KHz spectrum of 7.70mm steel plate transformed function

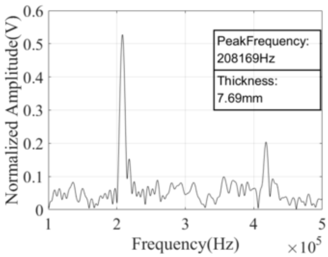

Figure 12. The 100K~500KHz spectrum of 7.70mm steel plate transformed signal

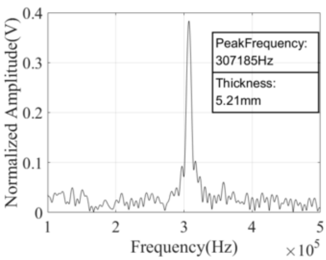

Figure 13. The 100K~500KHz spectrum of 5.20 mm steel plate transformed function

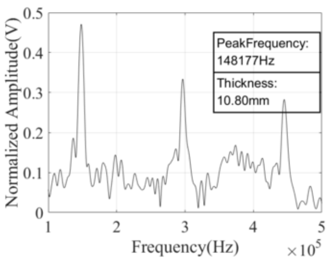

Figure 14. The 100K~500KHz spectrum of 10.75 mm steel plate transformed function

In the experiment, the frequency band is selected at 100KHz to 500KHz and the measuring range is 3.20 mm to 16.00 mm. Following the processing steps, the thickness can be obtained and the results are shown in Figures 12 to 14. Table 1 show the calculated and actual thickness and the measuring error. In general, the noise coupling into the echo signal will not change the main frequency component of the signal. Compared with transit time measurement, frequency measurement is relatively insensitive to the noise. And the signal processing step is simple and easy to implement by only using hardware.

Table 1. Measurement results and measurement error

Actual thickness	Measured thickness	Absolute error	Relative error
7.70	7.69	0.01	0.1%
5.20	5.21	0.01	0.2%
10.75	10.80	0.05	0.5%

However, as can be seen in Figures 12 to 14, the thickness of the plate should not be too thick, the thicker the plate, the larger amplitude of other frequency component, which may cause mismeasurement.

4. Conclusion

A frequency domain signal processing method for steel plate thickness measurement using EMATs is proposed in this paper. In the first place, simplified waveform function is employed to express the relationship between the main component in the signal and then a signal processing method is proposed to obtain the echo frequency. Then experiment is carried out and results indicate that the simplification of the signal is reasonable. The experiment also verified that the relationship between the excitation frequency and echo frequency is that echo frequency is modulated by the excitation frequency. Most important, the signal processing method obtain a high accuracy in the experiment, and the maximum absolute error of the measured thickness in the frequency is 0.05mm, and the maximum relative error is 0.5%.

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