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Ultrasonic Nonlinearity Parameter Analysis Technique for Remaining Life Prediction

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14. ABSTRACT
A technique for using conventional pulse-echo configuration ultrasonic scanning to generate full wave time and frequency domain data has been developed. This method has demonstrated that fast Fourier transform frequency and amplitude data can be collected over the full area of a component. In comparison with similar techniques that have been developed, this method allows for ultrasonic nonlinearity parameter determination over the entire part from a single full wave scan. By collecting the data in this manner, future applications can be developed for generating second harmonic wave, nonlinearity parameter, and fatigue life image maps to aid in the prediction of remaining useful life in structural parts.

15. SUBJECT TERMS
ultrasonic, nonlinearity parameter, second harmonic wave, acoustic imaging, fatigue testing

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1. Introduction

Elastic and plastic nonlinearities in materials (i.e., dislocation accumulations that cause strain localization and fatigue) result in ultrasonic wave distortion, which leads to the generation of second and higher order harmonics in the frequency spectrum.[1] The second harmonic signal has been shown to be sensitive to microstructural changes in the material and the amplitude values linked to fatigue damage.[1–6] While analyzing the second harmonic signal independently has been proven to be insufficient for predicting remaining useful life, an ultrasonic nonlinearity parameter has been developed and correlated to material fatigue life.[2,7,8] This parameter requires measurement of the fundamental and second harmonic frequency amplitudes. While similar methods for collecting this data have explored different types of ultrasonic waves (i.e., Lamb waves)[2] and different transducer configurations (i.e., pitch-catch, through transmission)[2,7] for point analysis of a specific location, a technique has been developed for using standard longitudinal transducers in pulse-echo configuration to acquire full wave harmonic frequency amplitude data. Instead of being limited to single point analysis, which restricts the region under inspection, this method can generate data for the full area of the part. This can potentially allow for high-resolution imaging of changes in the fatigue state for a full-size component and help to determine its remaining useful life. In addition, this method can be used to generate amplitude and time-of-flight (TOF) C-scan images of the entire part, enabling both traditional and novel ultrasound evaluation to be conducted simultaneously.

2. Method

This technique was developed using an ultrasonic scanning system with a 5-MHz longitudinal transducer in pulse-echo configuration. It was demonstrated on a titanium bar designed for fatigue testing, which was submerged in an immersion tank with water as the coupling medium. The transducer was placed over the center of the sample, and the top surface signal reflection of the part was located (Fig. 1). The angle and position of the transducer were adjusted to optimize the signal amplitude. An ultrasound software program was used for signal and scanning parameter setup, transducer manipulation, and data collection. First, an amplitude scan (A-scan) window for the time domain settings was set up, with analog-to-digital signal delay and width (in microseconds) adjusted to secure a window for signal analysis during scanning. The pulser-receiver gain (in decibels) was adjusted to maximize the top surface signal amplitude while avoiding saturation. Four gates were set up using gate start, gate width, and synchronization threshold settings to collect amplitude and TOF data for the top surface signal, bottom surface reflection signal, bulk region between the top and bottom signals, and the first echo (Fig. 1). C-scan imaging parameters were set, including x- and y-direction scan length, resolution, and

scan speed to ensure that the area of the entire part would be included. The full wave scanning option was selected to save the full waveform at each collected point. Next, a frequency domain window was set up with fast Fourier transform (FFT) settings (Fig 2). The y-axis start and end conditions were set up to contain the fundamental and additional harmonic frequency amplitudes without saturating them. Spectrum gates were set up, adjusting spectrum gate positions (in megahertz) and detection thresholds (%) for the fundamental (F1) and second wave (F2) frequency harmonic peaks. These gates were used to monitor frequency and amplitude data. Since the lower gain settings used to avoid saturation of the top surface signal resulted in low-amplitude harmonic peaks (and failure to detect higher order harmonic peaks), the gain was increased to generate fundamental, second wave, and third wave harmonic peaks that could be further assessed (Figs. 1 and 2).
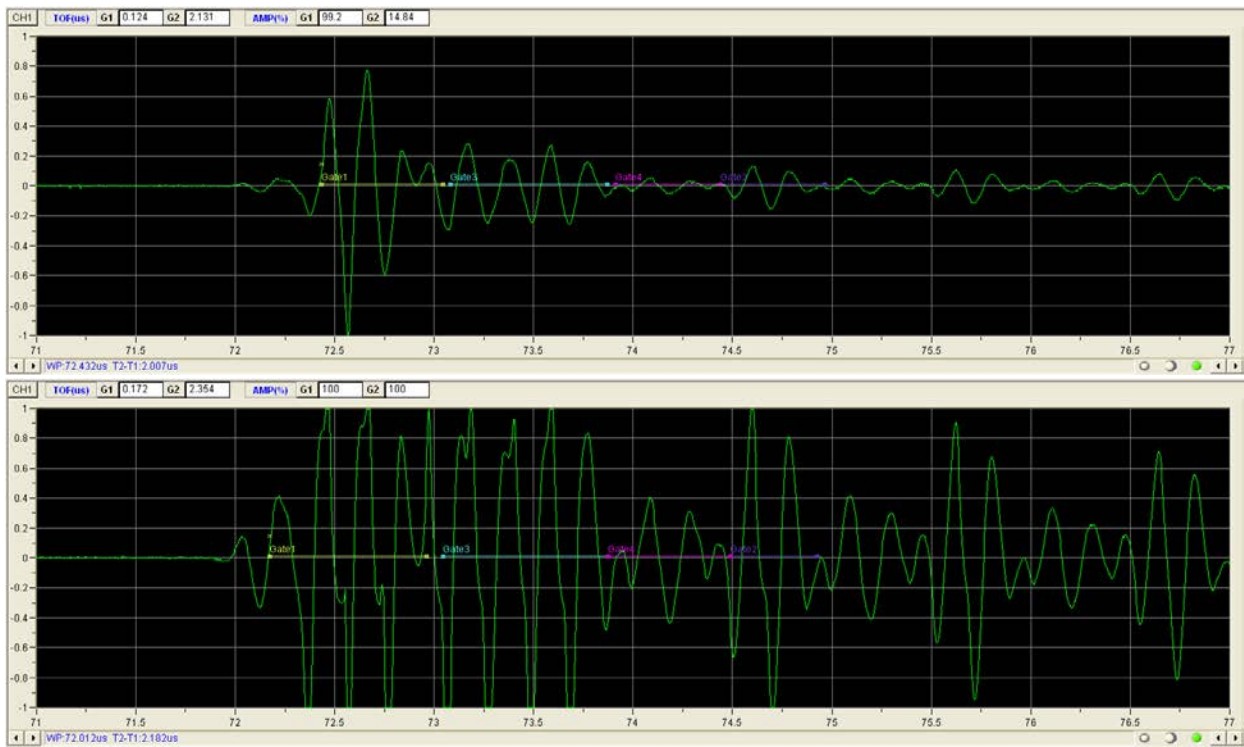

Fig. 1 A-Scan time domain signals from the sample at lower (top) and higher (bottom) gain
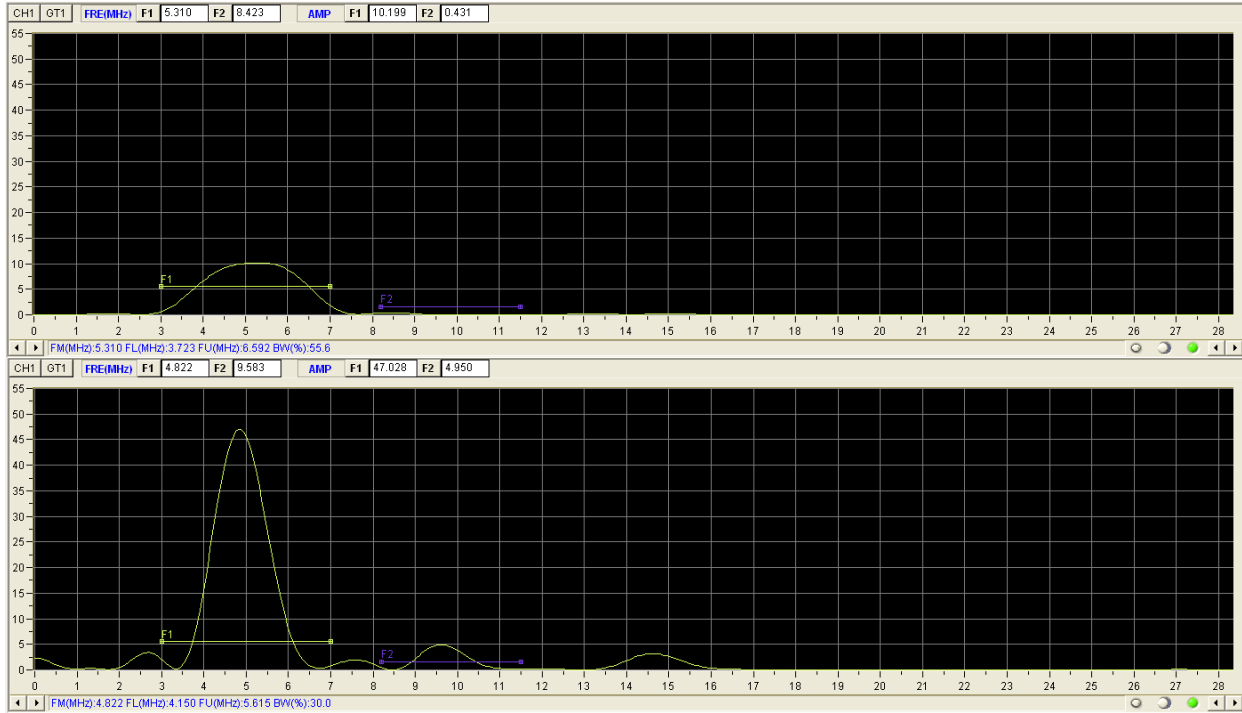
Fig. 2   A-Scan frequency domain signals from the sample at lower (top) and higher (bottom) gain

3.   Results

After setting up all of the aforementioned time and frequency domain parameters, the full wave scan was run, and the results for the titanium bar sample included amplitude and TOF C-scan images for all 4 gates (Fig. 3), A-scan FFT data for the selected points on the map, A-scan TOF and amplitude data for the selected points on the map, B-scan cross-sectional imaging of the signals through the sample, and tables of quantitative positional, amplitude, and TOF data for the selected points on the map (Fig. 4). The C-scan image maps showed variation in material integrity over the part, with higher amplitude signals near the center where fatigue tests were to be performed. While the top surface signal amplitude data were saturated due to the necessary increase in gain for detecting second and third wave harmonic peaks, images of the signals from the other gates effectively showed significant differences from the center to the edge of the sample (Fig. 3). While collecting this standard ultrasonic testing data, frequency domain data of the fundamental and second harmonic frequency and amplitude were also collected at each point over the sample (Fig. 4). This data was used to calculate the ultrasonic nonlinearity parameter at each point, according to the equation

$$\beta = \frac{A2}{(A1)^2} ,\tag{1}$$

3

where A1 is the amplitude of the fundamental harmonic peak and A2 is the amplitude of the second harmonic peak.[2,7,8] This parameter is critical for quantifying damage-induced nonlinearity for correlation to the remaining useful life of the part.[2]
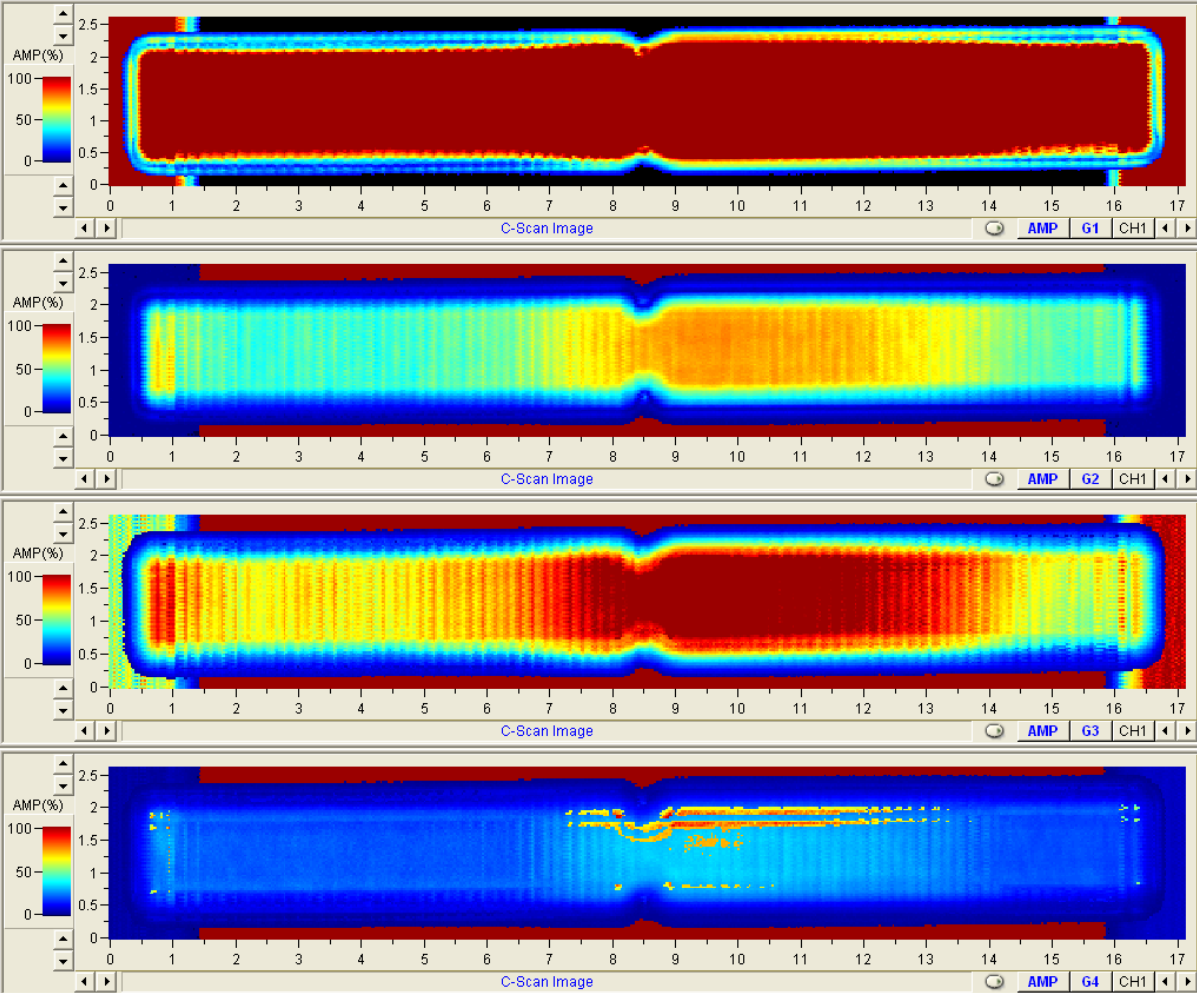

Fig. 3   Amplitude C-scan images from gates 1–4 (from top to bottom, respectively)

Fig. 4 A-scan, B-scan, and point analysis data from gates 1–4 (top to bottom, respectively)

4. Conclusion

A technique for using conventional pulse-echo configuration ultrasonic scanning to generate full wave time and frequency domain data has been developed. This method has demonstrated that FFT frequency and amplitude data can be collected over the full area of a component. In comparison with similar techniques that have been developed, this method allows for ultrasonic nonlinearity parameter determination over the entire part from a single full wave scan. By collecting the data in this manner, future iterations could include the ability to generate full wave second harmonic image maps and nonlinearity parameter image maps. By collecting the data periodically over a specified number of fatigue cycles, maps could be generated to look at the

evolution of material fatigue life over the entire area of a component. This data could then be correlated to the prediction of remaining useful life in structural parts and lead to appropriate repair and replacement decision making.

5. References

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