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Research Article

Feasibility of Residual Stress Nondestructive Estimation Using the Nonlinear Property of Critical Refraction Longitudinal Wave

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Residual stress has significant influence on the performance of mechanical components, and the nondestructive estimation of residual stress is always a difficult problem. This study applies the relative nonlinear coefficient of critical refraction longitudinal (L_{CR}) wave to nondestructively characterize the stress state of materials; the feasibility of residual stress estimation using the nonlinear property of L_{CR} wave is verified. The nonlinear ultrasonic measurements based on L_{CR} wave are conducted on components with known stress state to calculate the relative nonlinear coefficient. Experimental results indicate that the relative nonlinear coefficient monotonically increases with prestress and the increment of relative nonlinear coefficient is about 80%, while the wave velocity only decreases about 0.2%. The sensitivity of the relative nonlinear coefficient for stress is much higher than wave velocity. Furthermore, the dependence between the relative nonlinear coefficient and deformation state of components is found. The stress detection resolution based on the nonlinear property of L_{CR} wave is 10 MPa, which has higher resolution than wave velocity. These results demonstrate that the nonlinear property of L_{CR} wave is more suitable for stress characterization than wave velocity, and this quantitative information could be used for residual stress estimation.

1. Introduction

Residual stress is an inherent stress which keeps the stress balance in the inner material when the mechanical components are unaffected by external strength. The service properties of mechanical components, such as fatigue life and strength, could be considerably influenced by residual stress, and this would result in considerable expenditure in repair and maintenance of components. Therefore, the effective estimation of residual stress is very important for mechanical components.

Residual stress measurement methods could be categorized into destructive and nondestructive methods [1]. The slice and contour methods are destructive, and the blind-hole and deep-hole methods are destructive too. The destructive methods belong to the category of stress release and would cause the damage of components, which is fatal and must be avoided [2], while nondestructive methods are more widely applied in recent years, such as X-ray diffraction technique [3, 4], thermoelastic stress analysis (TSA), and ultrasonic method [5]. TSA is a noncontacting and sensitive experimental stress analysis technique [6, 7], which provides full-field stress data over the surface of a cyclically loaded specimen or component [8]. Robinson [7] gave significant attention to the effect of plastic deformation on the thermoelastic constant and the influence of the mean stress on the thermoelastic response in stainless steel and aluminium. In [9], it was shown that mean stresses significantly influenced the TSA results for titanium-based alloys and nickel-based alloys. And, in [10], the mean stress sensitivity was established for both titanium and nickel alloys. Zhukovskii and Gokhman [11] proposed the method of determining the residual stresses in metallic sheets, which consisted in finding the strain field induced by central point heating and calculating the field of residual stresses using a functional relation between a linear thermal expansion coefficient and residual stresses. The stress diagram of the whole component or a certain part can be obtained, which only requires few surface preparations and does not need further data processing. However, this technique merely provides information on the surface stress field in structures. The ultrasonic method has the characteristics of high resolution, high penetration, and no harm to human body; therefore it is one of the most promising nondestructive measuring methods.

The traditional ultrasonic technique for residual stress measurement applies the acoustoelasticity theory [12], which is based on the finite deformation of continuum mechanics to study the relationship between the stress state and wave velocity of ultrasonic. Based on the acoustoelasticity theory, the sensitivity of different types of ultrasonic to stress is explored. In Cartesian coordinate system, seven kinds of equations of propagation velocity and stress in solids are established; taking the derivative of wave velocity to stress, the stress-sensitive coefficients of seven kinds of ultrasonic can be obtained [13]. When the longitudinal wave propagates along the stress direction, the stress-sensitive coefficient is 8.085, which is much higher than six other sensitive coefficients, 1.025, 0.503, 0.505, 2.495, 0.153, and 0.153, respectively. Based on above analysis, the longitudinal wave propagating along the stress direction is the most sensitive to stress; that is to say, the longitudinal wave is the most sensitive to tangential stress. When the longitudinal wave propagates along the tangential stress, it is named as L_{CR} wave. Because the L_{CR} wave has the highest sensitivity to tangential stress, the L_{CR} wave based on the acoustoelasticity theory is applied to measure the residual stress [14, 15]. However, Bray [16] found that when the stress variation was below 26 MPa, the variation of transmit time or wave velocity of ultrasonic was not obvious. On the other hand, the variation of wave velocity caused by stress is very small; for example, the change of wave velocity is only about 0.1% in aluminium and 0.01% in steel induced by 100 MPa stress variation. Therefore, the accurate measurement of residual stress based on the acoustoelasticity theory is often a difficult task.

Because of the earlier performance, degradation and dislocation structures would not cause obvious change in macroscopic properties of ultrasonic wave, such as attenuation and wave velocity. Nevertheless, the accumulation of dislocations would cause the distortion of ultrasonic; higher harmonics are generated when a monochromatic ultrasonic propagates through the medium. The nonlinear ultrasonic technique has shown the ability to evaluate the fatigue damage [17] and plastic deformation [18] of metal material which has a close relationship with the microstructure evolution of material. The dislocation string model [19] and the dislocation dipole model [20] establish the relationship between the ultrasonic nonlinear coefficient and stress. Those studies provide the theoretical foundation of applying the nonlinear properties of ultrasonic to characterize and evaluate the stress of material.

Applying the nonlinear property of ultrasonic to characterize the stress state gets more and more attention. Bartoli et al. [21] applied the nonlinear guided wave for stress monitoring in prestressing tendons for posttensioned concrete structures. Liu et al. [22] used the nonlinear Rayleigh wave to detect the residual stress in shot-peened aluminum plates; the nonlinear ultrasonic parameter was sensitive to residual stress. Kim et al. [23] proposed the use of the nonlinear resonant ultrasonic spectroscopy (NRUS) for the stress state monitoring of concrete.

Most of those studies use the guided or Rayleigh waves to detect the stress of specimens, while the nonlinear property of L_{CR} wave for stress measurement has been little researched. Therefore, in this paper, a preliminary study is performed to investigate the dependency between the stress state and the nonlinear property of L_{CR} wave. Firstly, the ultrasonic measure system based on the L_{CR} wave is established to conduct the nonlinear ultrasonic experiments for prestress specimens and the relative nonlinear coefficient is calculated. Then the relationship between the relative nonlinear coefficient and prestress is established and analyzed. At last, the sensitivity and resolution of nonlinear ultrasonic methods for stress measurement are detected. Based on above results, the dependency between the prestress state and the relative nonlinear coefficient is investigated; the possibility of residual stress estimation based on the nonlinear property of L_{CR} wave is verified.

2. Theoretical Background

2.1. Ultrasonic Nonlinear Coefficient. When a pure sinusoidal wave propagates through the nonlinear solid medium, higher harmonics are generated due to the nonlinearity of medium. The ultrasonic nonlinear coefficient is generally defined to characterize and evaluate the nonlinearity of medium, and the expression is

$$\beta = \frac{8A_2}{k^2 x A_1^2}, \tag{1}$$

where k and x are the wave number and propagation distance of ultrasonic, A_1 and A_2 represent amplitudes of fundamental wave and second harmonic wave, respectively, in the frequency spectrum of receiving signals in nonlinear ultrasonic experiments.

If the ultrasonic has fixed driving frequency, wave number, and propagation distance, the ultrasonic nonlinear coefficient is proportional to A_2/A_1^2. Therefore, for the convenience of computing in this study, the relative nonlinear coefficient is defined as

$$\beta' = \frac{A_2}{A_1^2}. \tag{2}$$

If the stress state of metal material varies, the elastic constants would be changed and the variation of ultrasonic nonlinear coefficient would occur. Therefore, the ultrasonic nonlinear coefficient could be applied to characterize the stress state of metal material in theory.

2.2. The Testing Principle of L_{CR} Wave. When a longitudinal wave propagates from the medium with lower wave velocity

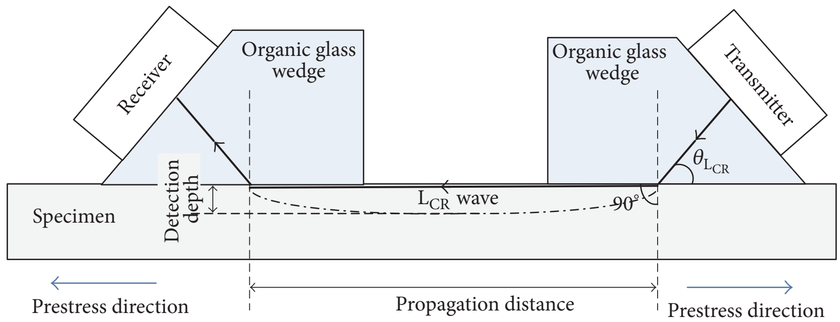


Figure 1: The mechanism of L_{CR} wave.

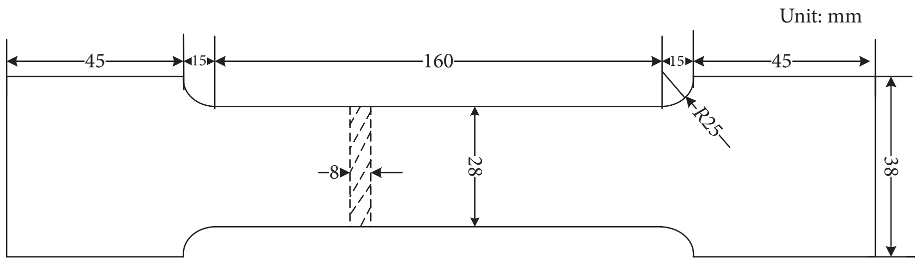


Figure 2: Dimension and shape of grade 45 steel specimen.

to the other medium with faster wave velocity, according to Snell's law, there is an incident angle making the refraction angle of longitudinal wave equal to 90°. In this case, the incident angle is called for the first critical angle and the longitudinal wave with 90° refraction angle is named for the L_{CR} wave. Taking the organic glass wedges, transducers, and grade 45 steel specimens as an example, as shown in Figure 1, the calculation formula of the first critical angle is $\theta_{L_{CR}} = \sin^{-1}(V_1/V_2)$, where V_1 and V_2 represent the longitudinal wave velocity in organic glass and grade 45 steel. Due to the fact that $V_1 = 2720$ m/s and $V_2 = 5925$ m/s, the first critical angle is $\theta_{L_{CR}} = \sin^{-1}(2720/5925) = 27.3°$.

Due to the fact that the stress would not only influence the wave velocity [12] but also transform the nonlinear property of ultrasonic, the L_{CR} wave propagates in the specimen in some depth which is related to the frequency of L_{CR} wave; the relative nonlinear coefficient and the wave velocity are calculated to study the relationship between the nonlinear/linear characteristics of ultrasonic and stress. Therefore, in this research, the wave velocity and the relative nonlinear coefficient of specimens with different prestress levels are calculated to verify the possibility of residual stress estimation based on the nonlinear property of L_{CR} wave.

3. Specimens and Experimental Setup

3.1. Specimens Preparation. The material used in this research is standard grade 45 steel with yield limit of 355 MPa which is high-quality carbon structure steel with a nominal chemical composition of C, 0.42~0.50%; Si, 0.17~0.37%; Mn, 0.50~0.80%; Cr, ⩽0.25%; Ni, ⩽0.30%; and Cu, ⩽0.25%. Dog-bone specimens are machined from a rolled steel plate; the dimension of specimens is displayed in Figure 2. The thickness of the specimen is 8 mm and the span is 160 mm. There are five specimens in this study. Due to the fact that the residual stress may be presented in the rolled steel plate processed specimens, before the prestress loading experiments, the original stress state of specimens is detected, where the nonlinear ultrasonic experiments are conducted on them and the relative nonlinear coefficients are calculated based on receiving signals. The measured relative nonlinear coefficients are 0.000467 V^{-1}, 0.000469 V^{-1}, 0.000485 V^{-1}, 0.000479 V^{-1}, and 0.000473 V^{-1} for five specimens. The maximum deviation of those values is (0.000485 − 0.000467)/0.000467 = 3.85%, which is within the range of the allowable error in this manuscript, 5%. Because the measured relative nonlinear coefficient can reflect the stress state of specimens, the detected results indicate that the original stress state of five machined specimens is consistent. Three specimens, p1, p2, and p3, were used to conduct the nonlinear experiments to study the relationship between the relative nonlinear coefficient and stress; furthermore, three specimens were also used to conduct the traditional ultrasonic experiments to study the relationship between wave velocity and stress. The other two specimens, p4 and p5, are applied to study the stress detection resolution of two different ultrasonic techniques.

In order to ensure the specimens with different stress state, the prestress loading method is applied. The specimens are fixed on the electronic universal testing machine, WDW3100, and different prestress states could be obtained. The specimens are used to conduct the tensile test with a loading rate of 0.5 mm/min. Because of the fact that the yield limit of grade 45 steel is 355 MPa, in some actual engineering application, the measured residual stress would be bigger than the yield stress for the service components and parts. In order to really simulate the residual stress states of components in actual engineering application, the prestress for the tested specimen changes from 0 MPa to 400 MPa, where the stress, 400 MPa, is a little more than the yield limit of grade 45 steel, 355 MPa. The loading test is interrupted every 20 MPa without specimens unloaded, where the full load time is 150 s; the nonlinear ultrasonic experiments are performed at the full load time to record the receiving signals, while the traditional ultrasonic experiments are conducted every 40 MPa to measure the wave velocity, because the variation of wave velocity is negligible when the stress variation is less than 26 MPa [16].

3.2. Ultrasonic Measurement. A schematic diagram of nonlinear ultrasonic experiment based on L_{CR} wave is shown in Figure 3. Two commercial piezoelectric longitudinal wave transducers with center frequencies of 2.25 MHz and 5 MHz are used as the transmitter and receiver to excite and receive the ultrasonic wave, and the receiver with center frequency of 5 MHz has higher sensitivity to the second harmonic. In order to generate and receive the L_{CR} wave in specimens, the transducers are clamped to organic glass wedges with the first critical angle, which are coupled to the surface of specimens. The compound lubricant is used to enhance the coupling among transducers, wedges, and specimens.

A tone burst is generated by the RITEC RAM-5000 system with a high-power gated amplifier, where the length of tone burst is 30 cycles and 70% of the maximum output level of the amplifier is selected to make a reliable nonlinear ultrasonic experiment. The amplified high-voltage signal passes through a 50 ohm load and low-pass filter to suppress the transient behavior due to the mismatch in electrical impedance between the amplifier and transducers. The receiving signals are recorded by an oscilloscope (Tektronix MDO3022), where the sampling rate is 100 MHz, and averaged 256 times to increase the signal to noise ratio and then transferred to a computer for further signal processing.

In the nonlinear ultrasonic experiment, the L_{CR} wave propagates in the specimens within a certain depth. The detection depth has a close relationship with the frequency of incident ultrasonic. Based on related experimental studies, the relationship between detection depth and incident frequency is $D = v \times f^{-0.96}$, where D is the detection depth (mm), f is the incident frequency (MHz), and v is the wave velocity in metal component (km/s) [13]. According to above equation, when the incident frequency is big, the detection depth of L_{CR} wave is small. If the incident frequency is 1 MHz, the corresponding detection depth is 6 mm; while the incident frequency is 2.2 MHz, the corresponding detection depth is 2.5 mm.

When choosing the incident frequency of ultrasonic, it not only considers the influence on detection depth but also takes into account the waveform of receiving signal of receiver in nonlinear ultrasonic experiment. Because the center frequency of incident transducer is 2.25 MHz, when the incident frequency changes from 1 MHz to 5 MHz, the waveform and amplitude of receiving signal recorded by oscilloscope are compared. It is found that when the incident frequency is 2.2 MHz, the waveform of receiving signal is relatively better and the amplitude is the biggest. Therefore, based on the above analysis, the incident frequency of ultrasonic is selected at 2.2 MHz, and the detection depth of residual stress for established system is 2.5 mm.

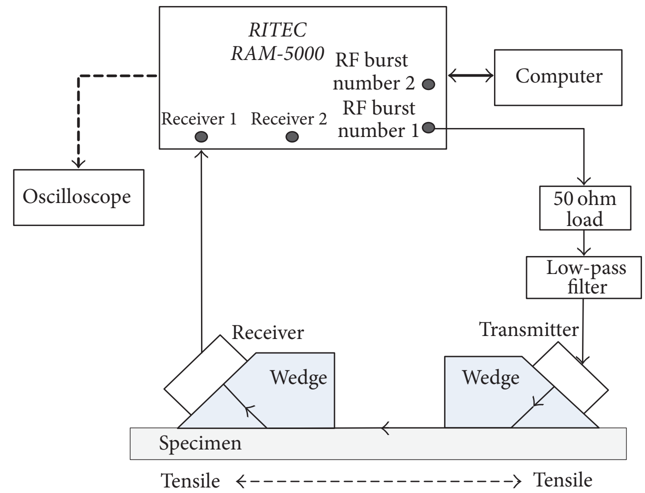
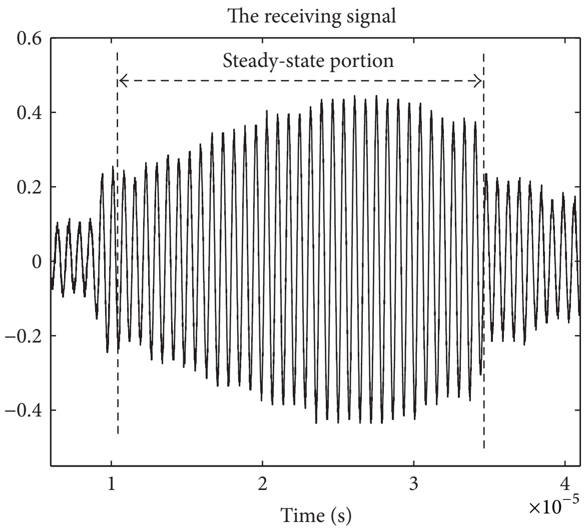


Figure 3: Experimental setup for the ultrasonic measurement based on L_{CR} wave.

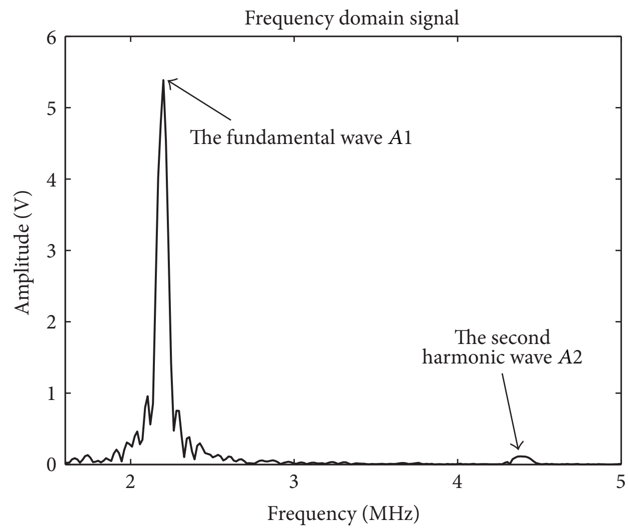
A typical receiving signal in nonlinear ultrasonic experiment is shown in Figure 4(a), which includes a transient part at the first few cycles, a steady state in the middle part, and a turn-off ringing at the last few cycles. The rectangular window is used to acquire the steady-state part for Fast Fourier Transform and eliminate the contribution of transient part for nonlinearity. Figure 4(b) shows the frequency spectrum of receiving signals; the amplitudes of the fundamental frequency and the second harmonic are determined. The amplitude A_1 is about fifty times larger than A_2 which is still above the noise level from nearby frequencies. According to (2), the relative nonlinear coefficient could be calculated based on A_1 and A_2.

In the nonlinear ultrasonic experiments, the propagation distance of L_{CR} wave has a great influence on the measured relative nonlinear coefficient, where the most suitable propagation distance should be chosen for the experiment. Because the span of prepared specimen is 160 mm, according to the size of organic glass wedge and transducer, the propagation distance shown in Figure 1 changes from 20 mm to 120 mm for the proposed measurement system. When other experimental parameters are identical, the specimen with prestress of 200 MPa is used to conduct the nonlinear ultrasonic experiment with propagation distance of ultrasonic changing from 20 mm to 120 mm. The relationship between the propagation distance and measured relative nonlinear coefficient is shown in Figure 5, where the error bars represent the random error of three repeated measures for every propagation distance.

It can be seen from Figure 5 that the relative nonlinear coefficient tends to firstly increase and then decrease and has a maximum value when the propagation distance is 80 mm. When the propagation distance changes from 20 mm to 80 mm, the relative nonlinear coefficient monotonically increases with propagation distance. Because more obvious



(a) The time domain of receiving signals in nonlinear ultrasonic experiment



(b) The frequency spectrum of receiving signals in nonlinear ultrasonic experiment

Figure 4

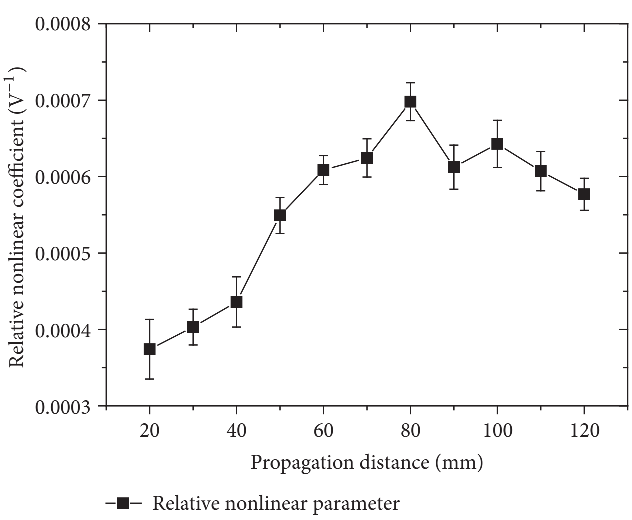


Figure 5: The relationship between the propagation distance and the relative nonlinear coefficient.

nonlinear interaction between ultrasonic and material would occur with increase of propagation distance, the nonlinearity presents the cumulative effect; thus the relative nonlinear coefficient monotonically increases with the propagation distance. While the propagation distance changes from 80 mm to 120 mm, the relative nonlinear coefficient decreases with the propagation distance; this is mostly due to the fact that the attenuation of ultrasonic caused by material absorption and the geometric spreading of wave would become obvious with increasing of propagation distance. Based on above analysis, when the propagation distance is 80 mm, the measured relative nonlinear coefficient could fully display the nonlinearity of specimen. Therefore, the propagation distance of 80 mm is applied in the nonlinear ultrasonic measurements.

The ultrasonic system shown in Figure 3 is also used to conduct the traditional ultrasonic experiment where the driving frequency is 2.2 MHz and the propagation distance of L_{CR} wave is 30 mm, and the experimental parameters are consistent with the national standard GB/T 32073, 2015. And the only difference with the nonlinear ultrasonic measure is that the receiver with the center frequency of 2.25 MHz is applied. The transit time of L_{CR} wave is measured when the prestress of specimens p1, p2, and p3 is 40 MPa, 80 MPa, 120 MPa, 160 MPa, 200 MPa, 240 MPa, 280 MPa, 320 MPa, 360 MPa, and 400 MPa; then, according to $v = d/t$, the wave velocity could be calculated, where v indicates the wave velocity, d is the propagation distance of ultrasonic, and t is the propagation time.

Furthermore, in order to compare the detected minimum stress of nonlinear and traditional ultrasonic methods, the stress detection resolution is studied. On the basis of 80 MPa prestress of specimens p4 and p5, when the prestress is 120 MPa, 110 MPa, 100 MPa, 90 MPa, and 85 MPa, respectively, where the stress curve is shown in Figure 6, the nonlinear and traditional ultrasonic measurements are conducted, and the variations of the relative nonlinear coefficient and wave velocity are computed to analyze the resolution of two methods.

4. Results and Discussion

4.1. Verification of the Reliability of Nonlinear Ultrasonic Measurement. In the nonlinear ultrasonic measurement, the reliability of measurement should be firstly verified, because the experimental equipment, the coupling medium, and transducers would bring in the nonlinearity. If the wave number and propagation distance are fixed in (1), the reliability of nonlinear ultrasonic measurement could be verified based on A_2 proportional to A_1^2. When the driving voltage increases

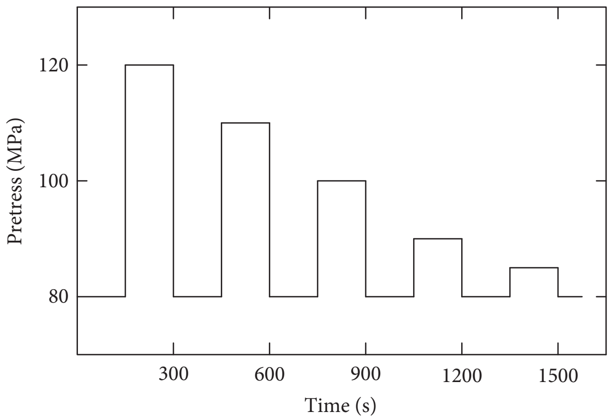


Figure 6: The prestress curve for stress detection resolution study.

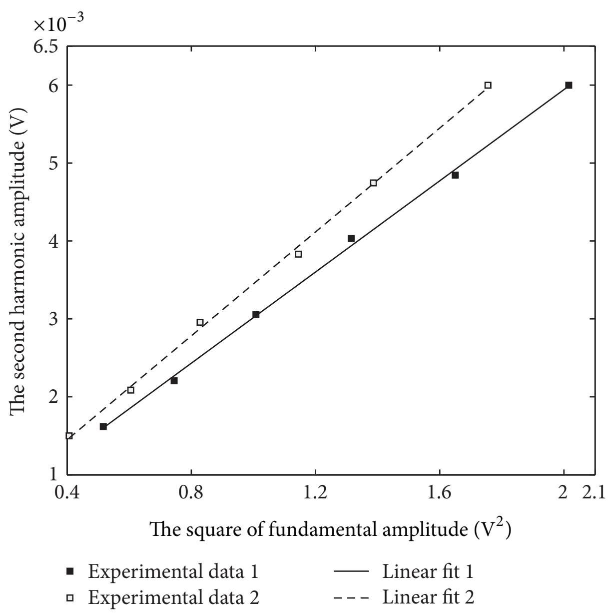


Figure 7: Second harmonic amplitude versus the square of fundamental amplitude for the input voltage increasing from 300 V to 400 V.

from 300 V to 400 V, increasing by 20 V per time, the value of square of fundamental wave and the second harmonic are calculated for two original specimens p1 and p2. Figure 7 displays the calculation results.

As shown in Figure 7, a linear relationship is easily found for different driving voltage level, the optimal linear fitting equations for specimens p1 and p2 are $A_2 = 0.000489A_1^2 + 9.9073 \times 10^{-5}$ and $A_2 = 0.000503A_1^2 + 7.2851 \times 10^{-5}$, respectively, and the linear correlation coefficients are $R^2 = 0.9984$ and $R^2 = 0.9979$, which indicates that A_2 is highly correlated with A_1^2. According to (2), the relative nonlinear coefficient of two specimens is 0.000489 V^{-1} and 0.000503 V^{-1} which remains constant for different driving voltage within a certain range. Therefore, the reliability of nonlinear ultrasonic measure based on $\mathrm{L_{CR}}$ wave could be verified.

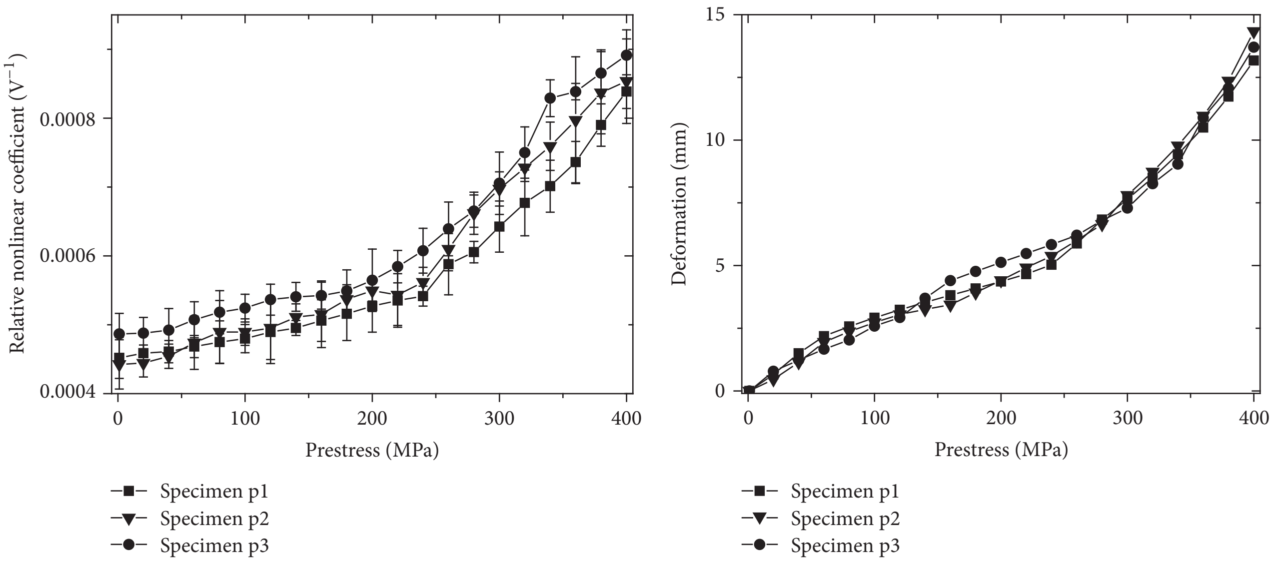
4.2. The Stress Estimation by the Relative Nonlinear Coefficient. Three specimens, p1, p2, and p3, with different prestress status are used to conduct the nonlinear ultrasonic experiments. According to the frequency spectrum of receiving signals, the relative nonlinear coefficient is estimated. The relationships between the relative nonlinear coefficient and prestress for three specimens are shown in Figure 8(a); the error bars are obtained by repeating the nonlinear ultrasonic measure four times at a certain prestress level. Figure 8(b) shows the variation of deformation as a function of stress value which is roughly represented by crosshead displacement of testing machine.

As can be seen in Figure 8(a), the relative nonlinear coefficients of three specimens have similar variation tendencies with prestress when the prestress changes from 0 MPa to 400 MPa. The relative nonlinear coefficient increases slowly which is approximately proportional to the stress when the prestress level is less than 200 MPa and increases rapidly when the prestress exceeds 300 MPa especially beyond the yield limit. The increment of relative nonlinear coefficient for three specimens is about 181%, 176%, and 189%, respectively. The similar variation trends of acoustic nonlinear parameter versus stress have been reported in 30Cr2Ni4MoV stainless steel [24] and AZ31 magnesium-aluminum alloy [25].

In Figure 8(b), when the prestress is less than 200 MPa, the deformation of specimens is about 5 mm; the deformation is very small in this stage. According to the normal stress-strain curve of the tested specimen shown in Figure 9, because the proportional limit of 45 steel is $\sigma_p = 200$ MPa, when the stress is below 200 MPa, the specimen has linear elastic deformation and the strain is proportional to the stress; but the strain is relatively small at this stage; thus the deformation of specimens is only about 5 mm. When the stress is more than 200 MPa, the deformation of specimen rises gradually in Figure 8(b); especially when the stress is above the yield stress of grade 45 steel specimen, $\sigma_e = 355$ MPa, the deformation has a big increase, where the deformation is about 10 mm in this stage. From the stress-strain curve shown in Figure 9, when the stress is between 200 MPa and 355 MPa, this is the nonlinear elastic deformation stage and the stress of specimen is no longer proportional to the strain. When the stress is bigger than 355 MPa, the specimen enters the yield stage and has plastic deformation, the strain has a great change although the change of stress is relatively small, and the specimen has a large deformation in this stage.

It also can be found from Figure 8 that when the specimen has bigger prestress, the deformation is more obvious and the measured relative nonlinear coefficient is bigger; thus an increase in deformation of specimen would result in a relevant increase of the relative nonlinear coefficient, which is consistent with the microplasticity model proposed by Kim et al. [26] to quantify the acoustic nonlinear parameter (ANP) caused by microplastic deformation. The experimental results indicate that the relative nonlinear coefficient is closely related to the deformation of specimens, and the dependence of the ultrasonic nonlinearity on the deformation could be found, which happens in the process of stress level increasing.

The microstructures of specimens enduring different prestress are considered the main reason to cause the variation of



(a) Relationship between the relative nonlinear coefficient and prestress when stress increases from 0 MPa to 400 MPa

(b) Relationship between the deformation state and prestress when stress increases from 0 MPa to 400 MPa

Figure 8

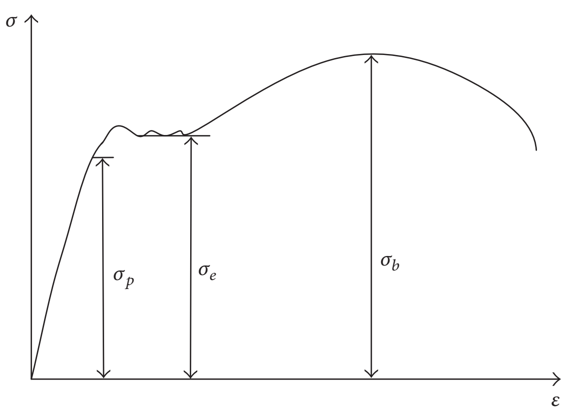


Figure 9: The normal stress-strain curve for grade 45 steel.

the ultrasonic nonlinearity. The optical microscope is applied to observe the microstructure of grade 45 steel specimens enduring stress of 100 MPa, 200 MPa, 300 MPa, and 400 MPa as shown in Figure 10, where the white part is ferrite and the black part is pearlite. When the prestress is 100 MPa, the ferrite and pearlite do not have obvious change; when the prestress is 200 MPa, some ferrite deformation with zonal distribution has already occurred due to low hardness. When the prestress is 300 MPa, white ferrite has zonal distribution and pearlite begins to become out of shape, which explains the reason for quick variation of relative nonlinear coefficient from microscopic aspect. When the prestress is 400 MPa, the zonal distribution of ferrite becomes refinable and the pearlite has obvious deformation. Therefore, with increase of the deformation of ferrite and pearlite, the relative nonlinear coefficient increases quickly.

4.3. The Stress Estimation by Wave Velocity. When the prestress of three specimens is 0 MPa, 40 MPa, 80 MPa, 120 MPa, 160 MPa, 200 MPa, 240 MPa, 280 MPa, 320 MPa, 360 MPa, and 400 MPa, specimens are also used to conduct the traditional ultrasonic experiment to calculate the wave velocity of L_{CR} wave. The measurement results are presented in Figure 11. The calculated wave velocity is the mean value of four repeated measurements for a certain stress level.

As shown in Figure 11, the wave velocity has a measureable decrease with prestress, and the variation tendencies of three specimens are similar. Although three specimens are made from a rolled steel plate, the difference of internal microstructure and the machining process may result in the diversity of wave velocity variation with prestress. When the prestress is 0 MPa, the measured wave velocities of three specimens are 5903.76 m/s, 5907.42 m/s, and 5904.83 m/s, respectively, which are very close to the theoretical wave velocity of longitudinal wave velocity in grade 45 steel, 5900 m/s, while the wave velocity decreases to 5889.32 m/s, 5895.56 m/s, and 5893.68 m/s when the prestress is 400 MPa. The decrement of wave velocity for three specimens is 0.24%, 0.205%, and 0.157%, respectively.

4.4. Comparison of the Sensitivity and Resolution of Two Estimation Methods. Due to the fact that the relative nonlinear coefficient and wave velocity could reflect the stress level of material, the sensitivities of nonlinear and traditional ultrasonic methods for stress estimation are compared. The sensitivity parameter is defined as

$$S(p,n) = \frac{|p(n) - p(0)|}{p(0)}, \tag{3}$$

where $S(p,n)$ shows the sensitivity parameter for relative nonlinear coefficient or wave velocity at every prestress, $p(n)$ represents the calculated relative nonlinear coefficient or wave velocity at every prestress, and $p(0)$ indicates the relative nonlinear coefficient and wave velocity of original

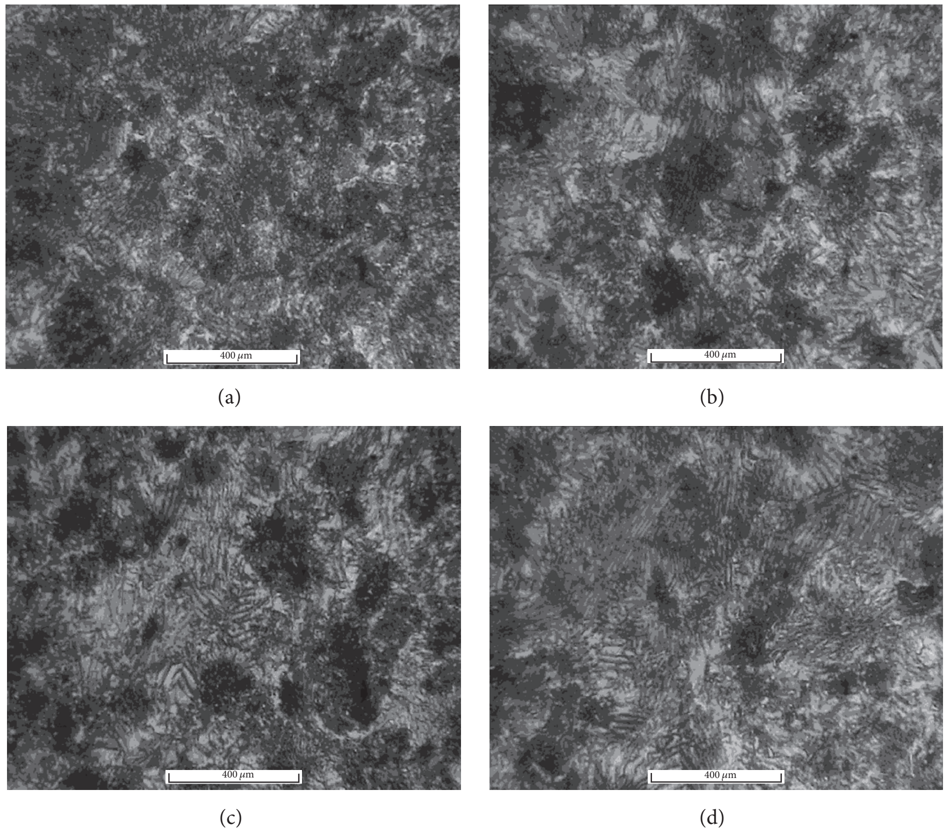


Figure 10: Microstructures of grade 45 steel specimens when the prestress is (a) 100 MPa, (b) 200 MPa, (c) 300 MPa, and (d) 400 MPa.

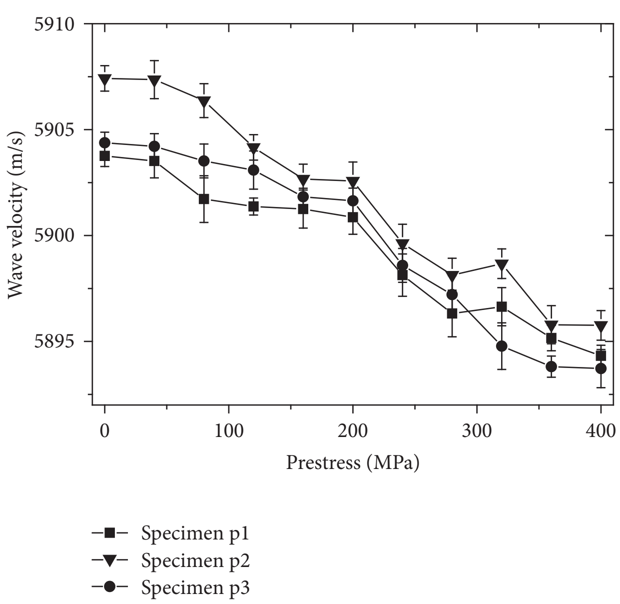


Figure 11: The relationship between the wave velocity and prestress value.

specimens. The sensitivity parameters of relative nonlinear coefficient and wave velocity are listed in Table 1, which are the mean value of three specimens. The sensitivity parameters 1 and 2 denote the sensitivity of relative nonlinear coefficient and wave velocity, while standard deviation 1 represents the discrete degree of measured relative nonlinear coefficient for three specimens at every prestress, and standard deviation 2 represents the discrete degree of calculated wave velocity for three specimens at every prestress.

As shown in Table 1, the sensitivity parameters of the relative nonlinear coefficient are much bigger than wave velocity at the same stress level. Under the 200 MPa prestress level, the sensitivity of wave velocity is very small, below 0.06%, while for the relative nonlinear coefficient the sensitivity parameter is about 19%, where the latter is about 300 times larger than the former. When the prestress is 400 MPa, the sensitivity for the relative nonlinear coefficient is 87.2034%, which is about 420 times higher than wave velocity. Therefore, the sensitivity of nonlinear ultrasonic method is much higher than the traditional ultrasonic technique, and it could be confirmed that the ultrasonic nonlinear coefficient could sensitively represent the prestress state of specimens.

In the process of cumulative plastic deformation, the microstructure variation of material is mainly the formation of dislocation and the increase of dislocation density. Studies have shown that the dislocation structures evolution and microplastic deformation would not induce obvious change in macroscopic properties of ultrasonic, for example, the attenuation and wave velocity; therefore, the sensitivity of wave velocity for stress variation is relatively small as shown in Table 1. However, the nonlinear ultrasonic technique has

Table 1: Sensitivity parameters of the relative nonlinear coefficient and wave velocity for stress.

Prestress (MPa)	Sensitivity parameter 1 (%)	Standard deviation 1 ($\times 10^{-6}$)	Sensitivity parameter 2 (%)	Standard deviation 2
40	1.9299	5.99	0.0019	0.413
80	7.3764	6.61	0.0279	0.369
120	10.1532	4.979	0.0392	0.42
160	13.2785	7.084	0.0554	0.582
200	18.9297	9.46	0.0649	0.537
240	23.8714	6.54	0.1197	0.328
280	40.058	8.165	0.1349	0.43
320	56.1403	7.993	0.1664	0.516
360	71.7694	6.064	0.2021	0.484
400	87.2034	5.315	0.2075	0.576

Table 2: The experimental result of stress detection resolution for grade 45 steel.

Parameters	Values				
$\Delta\sigma$ (MPa)	40	30	20	10	5
$\Delta\beta_i$ ($\times 10^5$) (V^{-1})	2.6483	1.7991	1.2674	0.5928	0.0653
Error 1 ($\times 10^{-6}$)	4.7425	5.3217	3.9451	5.854	6.3418
$\Delta\beta_i/\Delta\beta_{40}$	1	0.6793	0.4786	0.2238	0.0247
Δv_i (m/s)	1.2476	0.8938	0.0736	0.0541	0.0622
Error 2	0.4328	0.3946	0.5037	0.5565	0.4932
$\Delta v_i/\Delta v_{40}$	1	0.7164	0.059	0.0434	0.0498

the ability to detect the microstructure evolution of metal material experiencing the microplastic deformation, which is based on the fact that the dislocation formation and the dislocation density increasing would cause the distortion of ultrasonic and higher harmonics would be generated. Therefore, the relative nonlinear coefficient has a close relationship with the microstructure of specimens and the sensitivity for stress variation is much higher. In conclusion, the nonlinear ultrasonic technique based on the L_{CR} wave would be more suitable to characterize and measure the stress state of metal specimens than traditional ultrasonic technique.

Next, the stress detection resolution of nonlinear and traditional ultrasonic method is analyzed. On the basis of 80 MPa prestress of specimens, when the prestress is 120 MPa, 110 MPa, 100 MPa, 90 MPa, and 85 MPa, respectively, the nonlinear and traditional ultrasonic measurements are conducted to calculate the relative nonlinear coefficient β and wave velocity v. For every stress state, experiments are repeated four times to decrease the random error. The variations of the relative nonlinear coefficient and wave velocity are computed as $\Delta\beta_i = \beta_{120/110/100/90/85} - \beta_{80}$ and $\Delta v_i = v_{120/110/100/90/85} - v_{80}$, where subscript i expresses the stress increment of 40 MPa, 30 MPa, 20 MPa, 10 MPa, and 5 MPa, respectively. Based on the calculated relative nonlinear coefficient at 40 MPa stress interval $\Delta\beta_{40}$, other calculated relative nonlinear coefficients are normalized as $\Delta\beta_i/\Delta\beta_{40}$; similarly, the wave velocities are normalized as $\Delta v_i/\Delta v_{40}$; the normalized results are shown in Table 2, where $\Delta\beta_i$ and Δv_i are the mean value of relative nonlinear coefficient and wave velocity at every stress interval; error 1 and error 2 indicate the standard deviation of relative nonlinear coefficient wave velocity at every stress interval.

As shown in Table 2, the variances of relative nonlinear coefficient are relatively obvious when the stress intervals are 30 MPa, 20 MPa, and 10 MPa, and they are very small at 5 MPa stress interval, which indicates that it is not possible to distinguish the stress variation at the condition of 5 MPa stress interval; therefore, it can be obtained that the detected minimum stress of nonlinear ultrasonic method is 10 MPa. And the change of wave velocity is evident at 30 MPa stress interval, while for 20 MPa, 10 MPa, and 5 MPa stress interval, the wave velocity variation is not obvious, which indicates that the detected minimum stress of traditional ultrasonic method is 30 MPa. The analysis results denote that the stress detection resolution using the nonlinear property of L_{CR} wave is 10 MPa, while the resolution based on the wave velocity is about 30 MPa. Therefore applying the nonlinearity property of L_{CR} wave could detect the smaller minimum stress and stress variation.

5. Conclusions

In this paper, the nonlinearity property of L_{CR} wave is proposed to nondestructively characterize and evaluate the stress state of metal material, the dependence between the stress level and the relative nonlinear coefficient is investigated, and the feasibility of residual stress estimation based on the nonlinearity property of L_{CR} wave is verified. Therefore the conclusions could be obtained as follows:

(1) With increasing prestress level, the relative nonlinear coefficient increases slowly before 200 MPa and

fortifies rapidly after 300 MPa, and the increment of the relative nonlinear coefficient is about 80%, which is closely related to the cumulative plastic deformation caused by microstructure evolution of materials. The wave velocity decreases only about 0.2%, and that is because the dislocation structures evolution and microplastic deformation would not induce the significant change in wave velocity.

(2) The sensitivity of nonlinear ultrasonic method for stress is much higher than traditional ultrasonic technique. And the stress detection resolution of nonlinear ultrasonic measurement based on the L_{CR} wave is 10 MPa, while the resolution based on wave velocity is about 30 MPa. Therefore the nonlinearity ultrasonic technique based on L_{CR} wave has higher sensitivity and resolution, which is more suitable for residual stress estimation.

Because the feasibility of residual stress estimation based on the nonlinearity property of L_{CR} wave has been verified, further works should focus on how to apply the proposed method to estimate the residual stress of real mechanical components in actual engineering application.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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