Corrosion-fatigue evaluation in Q235A steel using nonlinear Rayleigh surface waves

LI Hai-yang[1], WANG Zhao-ba[1], PAN Qiang-hua[2]

(1. *Science and Technology on Electronic Test & Measurement Laboratory, North University of China, Taiyuan 030051, China*; 2. *China Special Equipment Inspection and Research Institute, Beijing 100029, China*)

Abstract: This paper presents a non-destrcutive evaluation method for the evolution of corrosion fatigue of Q235A steel. Specimen surface degradation due to corrosion fatigue from the combined interaction of corrosion and cyclic loading leads to harmonic generation during Rayleigh wave propagation along the specimen surface, which allows for an early prediction of material fatigue life. The relative nonlinearity parameter β as an evaluation parameter, which is denoted as a ratio of fundamental and second-order harmonic amplitudes, is measured by using an experimental platform based on a pair of wedge transducers to launch and receive Rayleigh wave signal. Subjected to an immersion corrosion method with 10% NaCl solution and a 20 Hz cyclic loading, a corrosion-fatigue specimen was made, and its relative nonlinearity parameter was measured every 10^5 cycles until to 7×10^5 cycles. A measured curve of relative nonlinearity parameter versus fatigue load cycles, which is produced by surface degradation of specimen corrosion fatigue, showed an initial steady trend followed by a rapid increase. Experimental results demonstrate that corrosion fatigue results in the sudden destruction of a Q235A steel specimen and nonlinear Rayleigh surface waves measurement technique can be used to quantitatively characterize fatigue life of Q235A steel.

Key words: corrosion fatigue; nonlinear acoustic; Rayleigh wave; Q235 steel

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0 Introduction

Steel components of deep-water or large offshore structures are exposed to a corrosive environment with high humidity and high salinity for long periods undergoing cyclic loading caused by ocean waves. Metal structure surface peels as a result of the electrochemical interaction of corrosive liquid or water with the metal surface, and then continuous cyclic loading makes discontinuous points on the surface generated, which may extend to cracks and imperfections and finally result in structural failure. The coupled effect of a corrosive medium and a cyclic loading leads to corrosion-fatigue damage generated, which is an important failure form of steel structures and an threaten to the safety and reliable operation of key structural components.

Nonlinear ultrasound is a promising technique to evaluate engineering material degradation and early damage, and it relies on the measurement of higher-order harmonics that are extracted from the elastic nonlinearity from lattice anharmonicity and the material nonlinearity of self-organized substructures. Extensive experimental measurements[1-9] have demonstrated that the nonlinearity parameter calculated from the fundamental and second-order harmonic amplitudes of cyclic loading metals can estimate material fatigue life during fatigue cycles. Cantrell, et al.[10] obtained a function of the fatigue life of an IN100 nickel-based superalloy by the analytical model of microelastic-plastic nonlinearity from dislocations and cracks during each state of the fatigue life. Beside the second-order harmonic, other nonlinearity phenomena also were used to assess fatigue state. Xiang, et al.[11-12] evaluated the thermal degradation using second-order harmonic extracted from an interaction of Lamb wave with a microvoid evolved in the alloy steel during aging. Liu, et al.[13] used a collinear wave mixing to characterize plastic deformation in Al-6061 alloys. Straka, et al.[14] observed experimentally nonlinear elastic wave modulation that is generated on aluminum alloy grade 6082 after a number of fatigue cycles to 50 000 cycles, and then made a conclusion that the relationship between second-order inter-

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Corresponding author: LI Hai-yang (13520151406@163.com)

modulation products increased steadily with an increasing number of fatigue cycles.

Rayleigh surface wave with lots of obvious advantages, such as a one-side pitch-catch access of measurement configuration and a long propagation energy that is concentrated near the free surface, is an improved method to evaluate the metal surface properties. Herrmann, et al.[15] performed a reliable reception of Rayleigh wave's second-harmonic by a laser ultrasonic technique, and then assessed damage in nickel-based high-temperature alloy specimens, at last quantitatively measured material nonlinearity under various loading conditions. Liu, et al.[16] presented the feasibility of a measured residual stress by the method of nonlinear Rayleigh surface wave and observed experimentally a large increase in proportional relation between the nonlinearity parameter and the residual stress.

We experimentally characterized surface damage of Q235A steel specimens under the combined interaction of a corrosive medium and a cyclic loading by a nonlinear acoustic method of Rayleigh surface wave. Two wedge transducers were used to achieve ultrasonic signal emission and reception. The relative nonlinearity parameter, which is defined by fundamental and second-order harmonic amplitudes, was measured as an evaluation parameter for corrosion-fatigue specimens at different stages of fatigue life. Experimental data were fitted to a curve of the number of load cycles, and showed an increasing relationship to predict the remaining life of the corrosion-fatigue specimens.

1 Theoretical analysis

The Rayleigh wave is a superposition of longitudinal wave and shear wave with the same propagation velocity, which can be decomposed into longitudinal and shear displacement components. Because of the symmetry of third-order elastic constants in isotropic solid materials, the shear wave nonlinear coefficient disappears. Therefore, the high-order Rayleigh wave is only related to the longitudinal wave[3-4]. Herrmann, et al.[15] obtained an expression for acoustic nonlinearity parameter in terms of measured normal surface displacement components as

$$\beta = \frac{8A_2}{\omega^2 A_1^2 X} \frac{c_1 \sqrt{c_1^2 - c_R^2}}{2\left(\frac{c_s}{c_R}\right)^2 - 1}, \tag{1}$$

where c_R, c_l and c_s are the Rayleigh wave velocity, longitudinal wave velocity and shear wave velocity, respectively; A_1 and A_2 are the amplitudes of the fundamental and second-order harmonic signals, respectively; X is the propagation distance of the Rayleigh wave in a solid material; and ω is the angular frequency.

In actual experiments, c_R, c_l, c_s and X remain unchanged. Therefore, the nonlinearity parameter is only related to the fundamental and second-order harmonic amplitudes, and the relative nonlinearity parameter can be used to represent the variation of nonlinearity parameter of Rayleigh wave, as expressed by

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

The relative nonlinearity parameter β' is used as an evaluation parameter for fatigue specimens that are subjected to cyclic loading, and a curve that is based on Eq. (2) versus fatigue cycles has been recognized by Kim[9], Cantrell[10] and other researchers. In this research, the relative nonlinearity parameter is also taken as a parameter to evaluate the corrosion fatigue of metal specimens.

2 Experimental procedure

2.1 Sample preparation

An experimental specimen of Q235A steel is machined into a shape with a stress-concentration zone in the middle.

The specimen dimensions are provided in Fig. 1, where the specimen thickness is approximately nine times the wavelength of the Rayleigh wave at 5 MHz, which satisfies half free space for generated condition of Rayleigh waves.

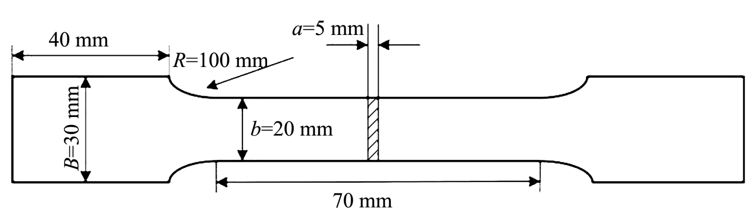

Fig. 1 Geometric dimensions of specimen

A corrosion-fatigue specimen is produced by the immersion-corrosion method with NaCl solution being the corrosion medium. The concentration of corrosive-medium is 10%, and the time for immersion is 20 days. A 20 Hz sine-wave cyclic loaing is obtained by a PA-100 fatigue machine. The ratio of the maximum stress to minimum stress is 0.25, and the center power and load amplitude is 10 kN. To observe the material nonlinearity at different stages of fatigue life, fatigue testing is from 1×10^5 to 7×10^5 cycles of cyclic loading, and finally the corrosion-fatigue specimen shows bending deformation.

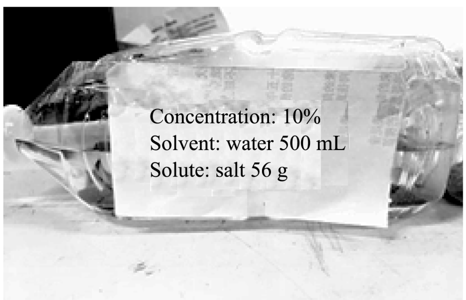

Fig. 2 Corrosion medium

2.2 Experimental setup

Excitation and reception system based on Rayleigh surface wave detection method is built, and the schematic of experimental platform is shown in Fig. 3.

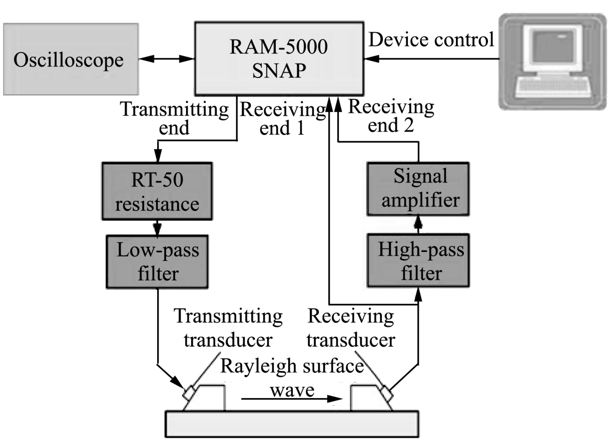

Fig. 3 Experimental setup

A tone burst signal of 20 cycles with a center frequency at 5 MHz is generated by RETIC RAM-5000 SNAP using a high-power gated amplifier, and then passes through a RT-50 resistance, which can suppress transient behavior from a mismatch between the amplifier and the transducer[2]. A low-pass filter of 5 MHz and a high-pass filter of 10 MHz are used to reduce noise and nonlinearity of detection system[3]. Two commercial PZT-based piezoeletric transducers with center frequencies of 5 and 10 MHz respectively are aligned on one side of the specimen in a straight line as a transmitter and a receiver. The ultrasonic wave is excited by the emission transducer into the organic glass wedge, and then Rayleigh surface wave at the interface of the wedge and the specimen is generated to propagate on the specimen surface. The nonlinear Rayleigh surface wave is received by the organic glass wedge and the receiver transducer. The two wedges at the launching and receiving positions have the same angle, and all contact interfaces are coupled with the couplant.

Because of surface damage of the corrosion-fatigue that causes a distortion in time domain during the Rayleigh surface wave propagation process, the second-order harmonic signal is generated, and the power of which is so weak that it can be submerged in the fundamental signal and noise. Therefore, the fundamental and second-order harmonic signal should be received separately. The fundamental signal is backed to the reception end of the RETIC RAM-5000 SNAP. The second-order harmonic signal needs to pass firstly through a 10 MHz high-pass filter and a 20 dB signal amplifier before being sent back to the detection system. All acquired ultrasonic signals are displayed as synchronized on the oscilloscope.

2.3 Angle of wedge

A Rayleigh wave is excited by the wedge method. The longitudinal wave excited by a emission transducer propagates through the wedge at a certain angle, and Rayleigh surface wave is generated and propagated along the specimen surface. The incident angle and the refraction angle at the wedge and specimen interface are shown in Fig. 4 and satisfy Snell's Law was

$$\frac{c_1}{c_2}=\frac{\sin\theta_1}{\sin\theta_2}, \tag{3}$$

where c_1 is the longitudinal wave velocity of 2 680 m/s in the organic glass wedge and c_2 is the Rayleigh wave velocity of 3 013 m/s on the specimen surface. Therefore, the incident angle of the longitudinal wave in the wedge is

$$\sin\theta_1=\frac{c_1}{c_2}\sin 90^\circ=\frac{c_1}{c_2}. \tag{4}$$

By substituting the values of c_1 and c_2 into Eq. (4),

$\theta_1 = 60°$ is obtained. Therefore, when the incident angle is 60°, the Rayleigh surface wave as a detection signal can be excited.

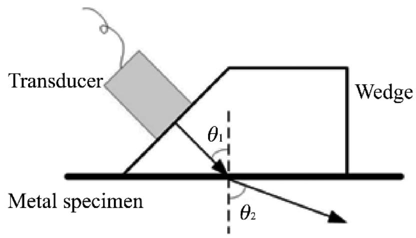

Fig. 4 Wedge angle

3 Results and analysis

The time-domain wave signal of fundamental and second-order harmonic waves are acquired according to the experimental procedure as shown in Figs. 5 and 6, respectively.

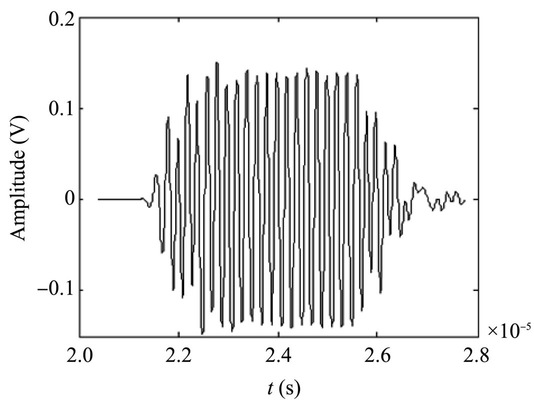

Fig. 5 Time signal of fundamental wave

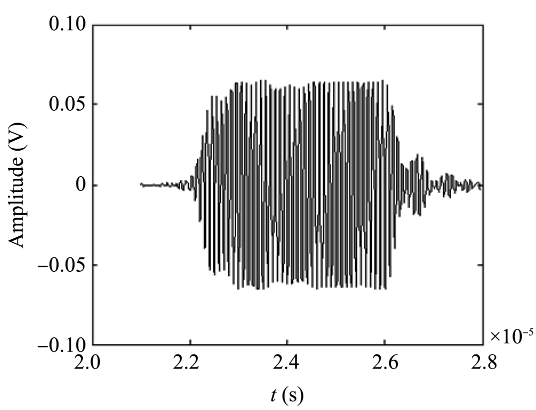

Fig. 6 Time signal of second-order harmonic wave

To remove the influence of random noise from experimental detection and to guarantee the accuracy and reliability of experimental results, the above detection process is repeated three times, and the average experimental data are used as an evaluation parameter.

The fundamental and second-order harmonic signals are windowed, and a fast-Fourier transform is used to obtain the fundamental amplitude A1 and the second-order harmonic amplitude A2, as shown in Fig. 7. The dashed line is the spectrum of second-order harmonic wave signal.

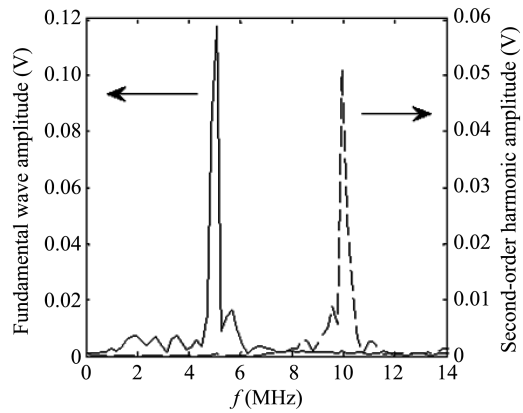

Fig. 7 Fundamental and second-order harmonic waves' amplitudes

The amplitude of fundamental and second-order harmonic wave of Rayleigh surface wave signal from Fig. 7 are substituted into Eq. (2) to obtain the relative nonlinearity parameter. The relative nonlinearity parameter of the initial specimen without corrosion fatigue is recorded as β_0. The relative nonlinearity parameters of the corrosion-fatigue specimen are regularized by using a ratio of β/β_0, which can reveal a variation of material nonlinearity that is caused by corrosion fatigue.

To ensure that measured nonlinearity results mainly from material inherent rather than from system noise, a linear relationship between the wave propagation distance and the amplitude of second-order harmonic wave from Eq. (1) is obtained, as shown in Fig. 8.

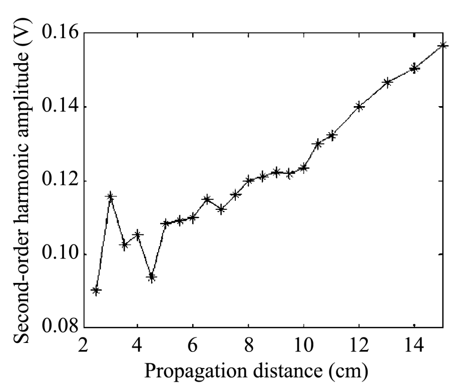

Fig. 8 Second-order harmonics amplitude as a function of propagation distance

Fig. 8 shows that the second-order harmonic amplitude is accumulated from the propagation distance of Rayleigh wave. From 2 cm to 4 cm, the amplitude of the second-order harmonic is unsteady because of the influence of near field transducer. From 4 cm to 15 cm, the second-order harmonic amplitude is almost linear with increasing distance due to amplitude cumulative effect. Therefore, the distance between the emitting and receiving transducers must exceed 4 cm to avoid measurement inaccuracies in the near field of the transducer.

Based on the measurement method, a relationship between the regularized relative nonlinearity parameters and the fatigue cycle of the corrosion fatigue specimen is plotted as a fitted curve in Fig. 9.

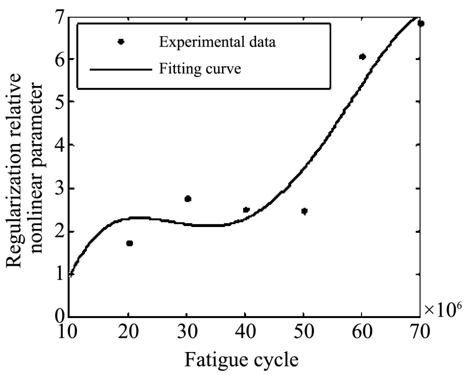

Fig. 9 Relationship between regularized relative nonlinearity parameters and fatigue cycles

Fig. 9 shows that this curve can be divided into two stages. In the first stage before 5 106 times, the relative nonlinearity parameter increases initially with fatigue cycles, and then the trend remains steady. This is possibly because of little material degradation occurs compared with the perfect state during the first stage of the fatigue life, then the relative nonlinearity parameter variation is not obvious. In the second stage after 5 106 times, the relative nonlinearity parameter has a rapidly increasing tendency, which may be due to a so rapid deterioration in the late fatigue of the corrosion-fatigue specimen that macroscopic cracks emerge in the material. The fitted curve of the relative nonlinearity parameter of corrosion-fatigue specimen is very different from that of Kim and Cantrell, which shows that the nonlinearity parameter of a fatigue specimen with cyclic loading only is approximately proportional to the number of cyclic loading. This occurs because of a gradual accumulation of dislocation and persistent slip bands with an increasing number of cyclic loads, as reflected in the monotonically increasing tendency of the nonlinearity parameter. However, corrosion fatigue specimens are subjected to not only cyclic loading, but also corrosion medium, and this leads to the fitted curve of the nonlinearity parameter not increasing monotonically, but increasing rapidly and suddenly, although it appears that the specimen is almost perfect at first. Thus, corrosion fatigue with a combined interaction of corrosion and cyclic loading is more dangerous than fatigue only with a single cyclic loading, and the nonlinear acoustic method by using Rayleigh wave can monitor the health of metal materials and potentially predict the remaining fatigue life.

4 Conclusion

The nonlinear Rayleigh surface wave detection method is used to achieve non-destructive detection for corrosion fatigue damage of a Q235A steel specimen. Experimental results show that the relative nonlinearity parameter based on Rayleigh surface wave can characterize the corrosion fatigue damage of Q235A steel specimen very well, and therefore this non-destructive detection technique is very useful for the assessment for corrosion fatigue damage and life prediction in industrial components.

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Q235 钢材腐蚀疲劳损伤的非线性 Rayleigh 表面波评价方法研究

李海洋[1]，王召巴[1]，潘强华[2]

（1. 中北大学 电子测试技术重点实验室，山西 太原 030051；
2. 中国特种设备检测研究院，北京 100029）

摘　要： 本文研究了 Q235A 钢腐蚀疲劳的评价方法。在腐蚀和循环载荷共同作用下，试样表面退化，并导致 Rayleigh 波沿试样表面传播过程中产生二次谐波，这种现象可以用于腐蚀疲劳损伤的早期评价。以楔形换能器为基础，搭建了 Rayleigh 波信号的发射和接收实验平台，测量了相对非线性参数的变化趋势。在 10%NaCl 溶液和 20 Hz 循环载荷的共同作用下进行腐蚀腐蚀试验，制备腐蚀疲劳试样，每 10^5 次疲劳周期测量一次相对非线性参数，直至疲劳周期数为 7×10^5 次。然后绘制试样腐蚀疲劳试验中表面退化产生的相对非线性参数与疲劳载荷循环的测量曲线，该曲线显示出初始稳定，之后迅速增加的变化趋势。实验结果表明，腐蚀疲劳会导致 Q235A 钢试样的突然破坏，非线性 Rayleigh 表面波测量技术可用于定量表征 Q235A 钢的疲劳寿命。

关键词： 腐蚀疲劳损伤；非线性声学；表面波；Q235 钢材

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