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Influence factors analysis and accuracy improvement for stress measurement using ultrasonic longitudinal critically refracted (LCR) wave

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ABSTRACT

Generally, material stress measurement using ultrasonic longitudinal critically refracted (LCR) wave is inevitably influenced by ambient temperature and coupling condition, which limits its industrial application. In this article, the sensitivity of stress measurement accuracy to temperature variation and coupling condition is discussed analytically and numerically. Based on this, the ultrasonic signal-detecting mode is improved by one-transmitter-two-receiver signal-detecting configuration. Meanwhile, a novel coupling condition is also created by directly filling with couplant between the ultrasonic probe and the measured surface. The testing results showed that the temperature sensitivity could be reduced to 0.81 ns/°C compared with −16.82 ns/°C of the traditional one-transmitter-one-receiver signal detecting configuration, and less distortion and attenuation of the detecting LCR wave signals could also be obtained. Further, a pre-stretched aluminum alloy with uniaxial stress was employed to verify the feasibility of the developed method and probe. The stress measurement accuracy could achieve 20 MPa compared with the simulation results.

1. Introduction

There is no doubt that the machine components and/or structures always work in complex stress state, including tensile stress, compressive stress and their combination. In addition, the stress has great effect on work-piece fatigue life, service security and equipment maintenance. Therefore, in order to evaluate the service reliability of the machine components, it is essential to characterize its stress state [1].

Up to now, many nondestructive stress measurement methods have been developed. As one of the main methods, the diffraction method mainly focuses on the stress that varies over the atomic or the grains scale, which uses high energy beam (e.g. X-ray, electron or neutrons) to detect the change of Bragg scattering angle to determine elastic strain [2]. However, either a strict testing environment is required, or the testing equipment and/or process is very complex and time consuming. By contrast, the magnetic method based on the Barkhausen effect is limited within ferromagnetic materials [3]. In recent years, ultrasonic method using piezoelectric transducer has been developed to detect and identify damage in complex structures [4,5].

Compared with other non-destructive methods, ultrasonic has the potential of low cost and high efficiency for stress measurement, and also good prospect to meet the in-site stress measurement requirements in industrial applications [5]. Essentially, stress measurement using ultrasonic is based on acoustoelasticity effect, which denotes that the ultrasonic velocity changes in stressed state [6]. Actually, the average stress along ultrasonic propagation path can be obtained, which mainly relates to macro stress. Generally, the longitudinal critically refracted (LCR) wave is widely adopted for stress measurement [7], since its velocity is more sensitive to material stress than other ultrasonic waves. The LCR wave was firstly used to measure the third order elastic constants [8,9]. Recently, the most common application of LCR wave is residual stress measurement after welding, in which case, not only the weld defect need to be detected [10] but also residual stress need to be evaluated due to complex thermo-plastic deformation in the materials [11–15]. Further, the experimental results were verified by the hole-drilling method and theoretical analysis [16].

Actually, the effect of material internal stress on the variation of ultrasonic velocity (or the TOF) is always tiny, i.e. weak acoustoelastic effect. For example, the stress of the yield level only causes the ultrasonic velocity to be changed by 3‰ for AA7075-T6 metal [16]. As a result, a small detecting deviation of ultrasonic velocity (or the TOF) would result in large stress measurement error. Unfortunately, the stress measurement using ultrasonic is always affected by multiple factors, including anisotropic property [17], micro-texture [18], temperature [19], and coupling conditions [14,20]. Among these factors, the temperature variation and ultrasonic distortion and attenuation due

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Nomenclature

C_{IJKL}	second order elastic constants(Pa)
K	wave number (/m)
k	acoustoelastic constant
k_W	temperature sensitivity of V_W(m/s/°C)
k_L	temperature sensitivity of V_L(m/s/°C)
L_M	distance between the transmitter and the first receiver(m)
ΔL_M	distance between the first receiver and the second receiver (m)
L_W	distance from the transducer to material surface (m)
l	Murnaghan constant(Pa)
m	Murnaghan constant(Pa)
N_J	directional cosine of ultrasonic propagation direction
T_0	reference temperature(°C)
ΔT	temperature change with respect to T_0 (°C)
t	TOF in stressed state(s)
t_0	TOF in stress free state(s)
t_1	TOF from the transmitter and the first receiver(s)
t_2	TOF from the transmitter and the second receiver(s)
t^i_{JL}	cathy stress in initial configuration (Pa)
u_K	displacement in X_K direction(m)
U_K	polarization amplitude of ultrasonic(m)
V	ultrasonic phase velocity(m/s)
V_L	LCR wave velocity in the material(m/s)
V_{L0}	LCR wave velocity in stress free state(m/s)
V_{LT_0}	LCR wave velocity in material at T_0(m/s)
V_W	longitudinal wave velocity in wedge(m/s)
V_{WT_0}	longitudinal wave velocity in incident wedge at T_0(m/s)
X_J	spatial position of a material point in initial configuration (m)

Greek symbols

λ	Lame constant(Pa)
μ	Lame constant(Pa)
σ	uniaxial stress magnitude(Pa)
θ_i	the first critical angle(°)
δ_{IK}	the Kronecker delta
ρ	material density (kg/m^3)

Abbreviation

LCR	longitudinal critically refracted
TOF	time-of-flight

to poor coupling have become the main obstacle in the in-situ stress measurement. The LCR probe device with one transmitter and one receiver is widely applied for stress measurement. The velocity variation is usually reflected by the TOF variation in a fixed ultrasonic path, including the wedge and the tested material. What's more, the TOF is linear with material internal stress within the elastic range [21]. The ultrasonic velocities of the wedge and the tested material are influenced by the temperature at the same time. Besides, before LCR wave propagates along the material surface layer, the longitudinal wave needs to propagate through the hard-to-hard coupling interface, which will cause ultrasonic attenuate and distortion.

For temperature aspect, ultrasonic velocity in 6063-T4 aluminum alloy was measured at different environmental temperatures [22], from 160 K to 280 K under four magnitudes of pre-stress respectively, which showed that the ultrasonic propagation velocity in 6063-T4 decreased with temperature and increased with compressive stress linearly. Further, Chaki [23] compensated the temperature induced error using the linear relationship between TOF and environmental temperature and measurement accuracy has been improved practically. However, an ultrasonic velocity calibration at different temperatures needs to be performed experimentally for both the tested material and the incident wedge. In the aspect of coupling condition, Yashar [14] compared contact and immersion ultrasonic method in welding residual stress measurement of dissimilar joints. It showed that the coupling condition of the immersion method was more stable. In addition, laser ultrasonic measurement without coupling has also been developed [24], but it required high surface quality and the thermo-induced ultrasonic signal was weak due to the limited energy of exciting laser.

There may be two effective approaches to improve stress measurement accuracy using ultrasonic, one is to suppress the negative influence of the environment temperature and the coupling condition on TOF; the other is to optimize the probe structure and compensate its negative influence. The structure of the article is: the stress measurement equations and the linear relation between TOF and stress are derived based on acoustoelasticity effect in Section 2; the influence of temperature variation and coupling condition on TOF are analyzed analytically and numerically in Section 3; a series of experiments are planned and implemented to verify the feasibility of the developed method and probe in Section 4, and the experiment result was also discussed in this section. Conclusions were drawn in Section 5.

2. Theory of stress measurement using ultrasonic LCR

2.1. Measurement equations based on acoustoelasticity

By introducing the material constitutive model into the ultrasonic propagation dynamic equation based on finite deformation theory, the acoustoelasticity equation is [6],

$$\frac{\partial}{\partial X_J}\left[(\delta_{IK}t^i_{JL}+C_{IJKL})\frac{\partial u_K}{\partial X_J}\right]=\rho\frac{\partial^2 u_I}{\partial t^2} \tag{1}$$

where δ_{IK} represents the Kronecker delta function, ρ represents the mass density in the initial configuration. X_J represents spatial position of a material point in the initial configuration, u_K represents the displacement in X_K direction, and C_{IJKL} represents the elastic constants in the Cathy stress field t^i_{JL}. When a plane wave propagates in solid material, the particle vibration can be expressed as,

$$u_I=U_I\exp[jK(N_J X_J-Vt)] \tag{2}$$

where U_I represents the polarization amplitude in X_I direction, N_J represents the directional cosine of ultrasonic propagation direction, K represents the wave number of ultrasonic, and V represents the phase velocity. The characteristic equation of ultrasonic propagation in stressed material can be obtained by Eqs. (1) and (2),

$$[(\delta_{IK}t^i_{JL}+C_{IJKL})N_J N_L-\rho V^2\delta_{IK}]U_K=0 \tag{3}$$

Eq. (3) indicates that the phase velocity V is not only related to the elastic constants C_{IJKL} but also the material stress t^i_{JL}. For isotropic material, when the longitudinal elastic wave propagates in the direction of uniaxial stress, the relation between longitudinal velocity V and stress magnitude σ can be expressed as,

$$\rho V^2=\lambda+2\mu+\sigma\frac{1}{3\lambda+2\mu}\left(\frac{\lambda+2\mu}{\mu}(4\lambda+10\mu+4m)+\lambda+2l\right) \tag{4}$$

where λ and μ are Lame constants, l and m are Murnaghan constants, and σ is the magnitude of uniaxial tension stress.

2.2. Linear relation between TOF and stress using LCR wave

Generally, piezoelectric transducer is used to excite an ultrasonic pulse, and a wedge is inserted between the transducer and the tested