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Bolt axial stress measurement based on a mode-converted ultrasound method using an electromagnetic acoustic transducer

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ABSTRACT

A method is proposed to measure the stress on a tightened bolt using an electromagnetic acoustic transducer (EMAT). A shear wave is generated by the EMAT, and a longitudinal wave is obtained from the reflection of the shear wave due to the mode conversion. The ray paths of the longitudinal and the shear wave are analyzed, and the relationship between the bolt axial stress and the ratio of time of flight between two mode waves is then formulated. Based on the above outcomes, an EMAT is developed to measure the bolt axial stress without loosening the bolt, which is required in the conventional EMAT test method. The experimental results from the measurement of the bolt tension show that the shear and the mode-converted longitudinal waves can be received successfully, and the ratio of the times of flight of the shear and the mode-converted longitudinal waves is linearly proportional to the bolt axial tension. The non-contact characteristic of EMAT eliminates the effect of the couplant and also makes the measurement more convenient than the measurement performed using the piezoelectric transducer. This method provides a promising way to measure the stress on tightened bolts.

1. Introduction

High-strength bolt joints are widely used in large-scale bridges and machine structures. The high strength friction grip bolt joints use the friction force of the contact surface to support the structures and have strict requirements for the axial load of the bolt [1]. The axial load is generated by the preload in the bolt joint assembly. An incorrect preload is harmful to the quality of the bolt joints. Insufficient load can reduce the carrying capacity of the joint and conversely, and excessive preload can create fatigue failures in the bolt. Even if the preload is appropriate, the bolt axial load may decrease in service due to vibration or alternating load, and the structural integrity may be threatened. Thus, the estimation of the bolt axial load is necessary during the bolt joint assembly and maintenance.

There are several ways of estimating the axial load such as the torque method, turn-of-nut method, and stretch method [1,2]. However, these ways of estimating the axial load are indirect, and the result is affected by dozens of variables such as friction coefficient, and material properties. These methods are also inconvenient in the course of performance of the bolt joint maintenance. The ultrasonic method of axial stress measurement is a non-destructive and direct method for control of the bolt axial load [3–8]. The ultrasonic method is based on the acoustoelastic effect: the ultrasonic velocity can be changed by the stress state [9,10]. According to this principle, the instruments for the ultrasound axial stress measurement have been developed [3–5]. The disadvantage of these instruments, based on the test method of single mode ultrasound, is that the time of flight of the unstressed state must be known before testing because the influence of the bolt length must be eliminated in the axial stress measurement. Due to this requirement, the tightened bolt cannot be measured unless the joint is loosened. To overcome this disadvantage, the combined longitudinal and shear wave test methods are applied in the axial stress measurement [6,7]. The ratio of velocities of the longitudinal and the shear waves, which is unrelated to the bolt length, is used to estimate the axial stress [11]. Although use of the ratio of velocities is a significant achievement, some problems must be solved to perform the ultrasonic measurement of the axial stress. The couplant required in the use of the piezoelectric transducers leads to a significant error in the axial stress measurement [12,13]. The mode-converted ultrasound is applied to detect the longitudinal and the shear waves using one piezoelectric transducer and reduce influence of the error caused by the couplant [14]. However, the influence of the couplant still exists and blocks the application of the ultrasound axial stress measurement in practice.

The electromagnetic acoustic transducer (EMAT) generates and detects the ultrasound through the electromagnetic field and does not need couplant or contact with the specimen [15]. Because of

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the noncontact characteristic, the EMAT is applied to the bolt axial stress measurement and shows good performance [16–18]. However, it is difficult for the EMAT to generate the longitudinal wave in ferromagnetic bolts due to the low efficiency of the longitudinal wave generation [19–21]. The EMAT is only applied in the axial stress measurement using the shear wave test method. As previously mentioned, the single mode wave method cannot measure the axial stress of the tightened bolt. This disadvantage limits the application of EMAT to the bolt axial stress measurement.

In this paper, an EMAT is proposed to measure the axial stress of the tightened bolt without loosening that bolt. The EMAT can generate only shear waves in the bolt. However, the EMAT can receive both the longitudinal and the shear waves reflected from the bolt end due to the mode conversion of ultrasound. This method avoids the inefficiency of generation of the longitudinal wave based on the electromagnetic acoustic transduction and obtains the longitudinal wave indirectly. First, the ray paths of the longitudinal and the shear waves in the bolt are analyzed, and then, the ratio of the times of flight of the longitudinal and the shear waves is obtained by mathematical derivation. This ratio is linear with the bolt axial stress. Second, the structural parameters of the EMAT and selection of the operating frequency are studied to improve the signal to noise ratio of the longitudinal wave. Finally, the bolt axial tension load experiment is performed to verify the proposed method. The experimental results show that the ratio of the time of flight of the longitudinal and the shear wave is linearly proportional to the bolt axial tension, which agrees well with the prediction of the theory.

2. Method for bolt axial stress measurement based on the mode-converted ultrasound

2.1. Principle of the combined shear and longitudinal wave testing

The preload on the bolt causes a tensile stress along the bolt axis. Due to the acoustoelastic effect, the velocities of the ultrasonic waves in the bolt vary depending on the stress state. In the case of the axial stress measurement, the ultrasonic wave propagates in the same direction as the stress, and the ultrasonic velocities can be written as [6,9]:

$$v_\sigma^L = v_0^L(1 + C^L\sigma) \tag{1a}$$

$$v_\sigma^S = v_0^S(1 + C^S\sigma) \tag{1b}$$

where v^L and v^S are the ultrasonic velocities of the longitudinal and the shear waves, respectively. The subscript labels 0 and σ designate the unstressed state and stressed state, respectively. The parameter σ is the bolt stress. C^L and C^S are the acoustoelastic coefficients of the longitudinal and the shear waves, respectively, and can be expressed as follows [6]:

$$C^L = \frac{\lambda + 2l + (\mu + \lambda)(4\lambda + 10\mu + 4m)/\mu}{2(\lambda + 2\mu)(3\lambda + 2\mu)} \tag{2a}$$

$$C^S = \frac{4\lambda + 4\mu + m + \lambda n/4\mu}{2\mu(3\lambda + 2\mu)} \tag{2b}$$

where λ and μ are the second-order Lame's constants, and l, m and n are the third-order Murnaghan's constants. The parameters T_σ^L and T_σ^S are the times of flight of the longitudinal wave and shear wave propagating along the axis of the stressed bolt. Because the two mode waves propagate along the same ray path, the ratio of the time of flight of the longitudinal and the shear wave M can be written as

$$M = \frac{T_\sigma^L}{T_\sigma^S} = \frac{v_\sigma^S}{v_\sigma^L} \tag{3}$$

Combining Eqs. (1a), (1b), and (3) yields the following expression.

$$M = \frac{v_0^S}{v_0^L} \cdot \frac{1 + C^S\sigma}{1 + C^L\sigma} \tag{4}$$

The expression of the ratio of the times of flight can be simplified by noting that the term C_σ^L is much smaller than 1. The first order Taylor Series Expansion of Eq. (3) gives

$$M \approx \frac{v_0^S}{v_0^L}[1 + (C^S - C^L)\sigma] \tag{5}$$

where v_0^S, v_0^L, C^S and C^L are constants and can be obtained before the measurement is performed. According to Eq. (5), the stress of the bolt can be determined by measuring the parameter M, and the bolt length is eliminated

2.2. Method for bolt axial stress measurement based on the mode-converted ultrasound

The EMAT generates the longitudinal wave in ferromagnetic materials only with difficulty. However, using the mode conversion, the longitudinal wave can be obtained from the reflection of a shear wave when the angle of the shear wave incidence is smaller than the third critical angle. Fig. 1 shows the ray paths of the radially polarized shear wave in the cylindrical specimen. The cylindrical specimen is used to simulate the bolt, and two end faces are assumed to be parallel with each other. Due to the radial polarization, the ray path S_1 makes an angle α with the axis of the specimen. The angle α depends on the parameters of the transducer. According to the geometrical conditions and Snell's law, the ray path should satisfy the following relationship:

$$\alpha = \theta_S \tag{6a}$$

$$\theta_S = \gamma_S \tag{6b}$$

$$\frac{\sin\theta_s}{v_0^S} = \frac{\sin\gamma_L}{v_0^L} \tag{6c}$$

where θ_S is the angle of incidence of the shear wave, and γ_L and γ_S are the angles of reflection of the longitudinal wave and the shear wave, respectively. Because there is no stress at the end of the bolt, the subscript labels of the ultrasonic velocities are *0*. The time of flight of path S_1–S_2 can be given by

$$T_{1-2} = \frac{L}{\cos\alpha \cdot v_\sigma^S} + \frac{L}{\cos\gamma_S \cdot v_\sigma^S} \tag{7}$$

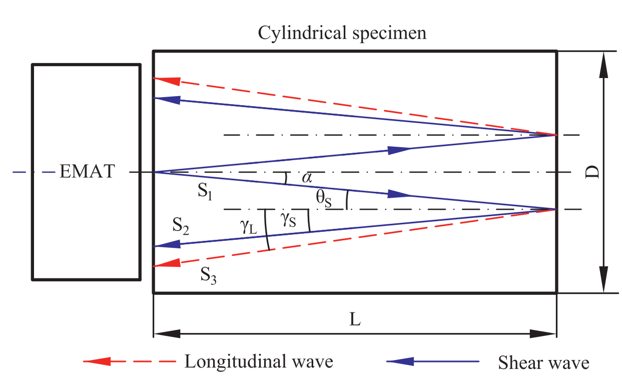

Fig. 1. The ray paths of the radially polarized shear wave of the cylindrical specimen.