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Velocity measurements of cylindrical surface waves with a large aperture line-focus acoustic transducer

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ABSTRACT

Acoustic microscopy has been widely applied in the measurements of the mechanical properties. However, the measurement of wave velocity on a curved cylindrical surface by acoustic microscopy was seldom reported. In this paper, we adopted a large aperture line-focus PVDF transducer and a defocusing measurement system to measure the velocity of a cylindrical surface waves. The theoretical model was established to study the relationship among the propagation path of surface waves, the geometric parameters of a transducer, and the diameter of a shaft specimen. Based on theoretical deduction and mathematical modeling, theoretical oscillation curves of phase difference were obtained. According to the improved $V(f,z)$ analysis method, the $V(f,z)$ curves were obtained through analyzing experimental data at different frequencies by Fourier transform. Then the surface wave velocity of the cylindrical tungsten steel specimen (Ø 20 mm) could be determined by fitting the $V(f,z)$ curves with the theoretical curves. The measurement results were consistent with the theoretical values, indicating that the measurement method was feasible. This study laid the basis for the ultrasonic measurement of the mechanical properties on the layer-coated cylinders.

1. Introduction

Shaft-like structures, such as aerospace engine shafts, ship propeller shafts, and automobile crankshafts, are widely applied in engineering fields. Due to friction and corrosion, a shaft is vulnerable and its precision and service life will be gradually decreased. Moreover, mechanical properties of the surfaces of shaft-like parts directly affect their performances. Therefore, it is necessary to evaluate the mechanical properties of shaft-like parts.

Ultrasound techniques play an important role in characterizing the elastic properties of materials. The surface acoustic waves (SAW) are most commonly used to characterize the surface properties of materials. To increase the inversion precision of the approach of the surface acoustic waves, a high-frequency ultrasound measurement system, such as an acoustic microscopy or a laser ultrasound system, is usually required to generate and detect the high-frequency SAW. However, the laser ultrasound systems are usually expensive and complicated. Furthermore, in the surface acoustic wave method, it is usually required to accurately measure the wave velocity over a fairly wide frequency range. Compared with the laser ultrasound systems, the acoustic microscopy method has become a technique widely used in the material characterization and the measurements of the surface wave velocity and the longitudinal wave velocity in block or plate structures [1]. In addition, there are some other means to evaluate the material properties [2,3].

Song et al. [4,5] developed an acoustic microscopy system to perform the non-destructive evaluation of the elastic constants of bulk small-size materials based on the defocusing measurement method. Due to the relatively limited research data and the cylindrical rotating rod structure of a shaft, it is difficult to evaluate the surface wave velocity of a shaft [6]. However, considering the high requirements of surface mechanical properties of the shafts during the operation, it is necessary to measure surface wave velocity of the cylindrical specimen for the evaluation of corresponding mechanical properties [7]. This study focused on the theoretical analysis and experimental measurements of the cylindrical surface wave velocity of the shaft-like structures.

2. Theoretical modeling of cylinder surface wave propagation

Many researchers described the applications of the ultrasonic microscopic method in the measurement of surface wave velocity on smooth flat specimens [8,9]. The surface wave velocity differs

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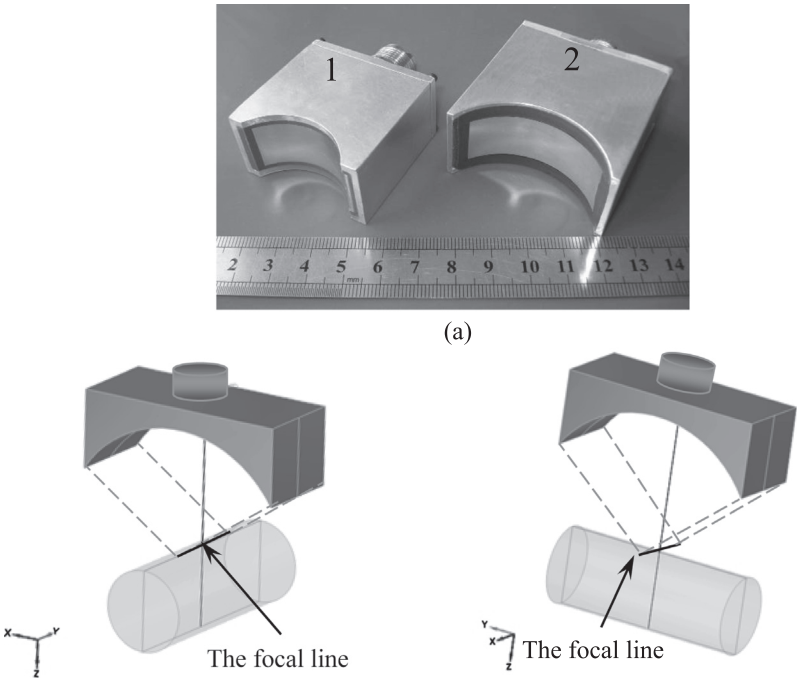

(a)

(b)

(c)

Fig. 1. (a) Line-focus PVDF transducer. Measurement in the (b) parallel direction and (c) perpendicular direction.

from the velocity of the leaky surface wave due to the load effect on coupled liquid (water). However, the densities of measured samples are much higher than that of coupled liquid. Therefore, the difference between surface wave and leaky surface wave is negligible. In this paper, we did not distinguish surface wave from leaky surface wave.

Types 1 and 2 of line-focus transducers [10] are shown in Fig. 1 (a). Because of the curved cylindrical structure of a shaft, there are only two ways to measure its surface wave velocity by the line-focus transducer. Firstly, the focal line of the transducer is parallel to the axis of the cylinder (the parallel mode in Fig. 1(b)). Secondly, the focal line of the transducer is perpendicular to the axis of the cylinder (Fig. 1(c)).

The measurement principle in the perpendicular mode is the same to that in the flat specimens. That is to say, the surface wave propagates along a straight line. However, the echo signal is weak and not easily utilized because the focal line of the transducer cannot be completely focused on the cylindrical surface. When the line-focus transducer is used to measure surface wave velocity in the parallel mode, the surface waves propagate along the circumferential direction of the cylindrical specimens. Therefore, the more energy is concentrated on the cylindrical surface. Therefore, the geometric relationship between cylindrical specimens and the transducer can be fully utilized. The arrangement in the parallel mode can be used to measure the surface wave velocity of cylindrical specimens. However, the propagation of the cylindrical surface wave is different from the plane Rayleigh surface wave. The principle of concentric measurement should be further studied.

When the line-focus transducer is focused on the surface of the shaft-like structures in the parallel mode, the focal line overlaps the cylinder axis of the specimen surface. In defocusing conditions, according to Snell's theorem, the Rayleigh Angle θ_R, can be determined as:

$$\sin\theta_R = \frac{V_W}{V_R} \tag{1}$$

where V_w is the acoustic wave velocity in water; V_R is the surface wave velocity of the specimens [11–15].

The schematic diagram of defocusing measurement is shown in Fig. 2(a). During the defocusing measurement, the acoustic waves have two major propagation paths. Firstly, on Path D, the directly incident waves are reflected by the cylindrical specimens. Secondly, on Path B, the incident waves at Rayleigh Angle travel along the cylindrical surface and finally received by the transducer. The two reflected signal waveforms in time domain can be continuously recorded at different defocusing distances (z). The waveform processing method is described below.

The mathematical model for the propagation path of the acoustic wave excited and received by line-focused PVDF transducer during defocusing measurement is shown in Fig. 2(b). In Fig. 2, according to the relationship among the propagation path of Rayleigh waves, the geometric parameters of a transducer, and the diameter of a shaft specimen, we can conclude:

$$\theta_A = \sin^{-1}\left[\frac{r\sin\theta_R}{r-z}\right] \tag{2}$$

where θ_A is the wave incident angle to generate Rayleigh waves and z is the defocusing distance. In this paper, we call θ_A in Fig. 2 "azimuth angle".

According to Fig. 2(b), Eqs. (3) and (4) can be respectively deduced as follows:

$$L_w = R - r\frac{\sin(\theta_A - \theta_R)}{\sin\theta_A} \tag{3}$$

where L_w represents the transmission distance of ultrasonic wave in water,

$$L_R = 2r(\theta_A - \theta_R) \tag{4}$$

where L_R represents the transmission distance of the surface wave along the circumferential direction.