ACOUSTIC INTERFEROMETER FOR LOCALIZED RAYLEIGH WAVE VELOCITY MEASUREMENTS

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ABSTRACT. Two instrumentation systems for measurement of Rayleigh surface wave (RSW) velocity are described. The first system consists of a more conventional methodology using matched RF amplifiers and phase detector/mixer circuits. In the second system, a lock-in amplifier, operating at high frequency, replaces the matched RF amplifiers and phase detector/mixer circuit, therefore simplifying the instrumentation. Both systems have been used to measure relative Rayleigh wave velocity using a cylindrically focused acoustic transducer consisting of three elements. A high-precision relative velocity measurement of Rayleigh surface waves is performed by exciting the central element and one of the outer elements with a tone burst signal and measuring the phase difference between the two received signals.

INTRODUCTION

Rayleigh Surface Wave (RSW) velocity measurements in localized regions are usually performed using acoustic lenses that focus acoustic waves on the surface of a sample in presence of a liquid (water) medium [1,2]. An acoustic lens while bringing acoustic waves into focus also generates RSW, for the waves incident at the Rayleigh critical angle on the surface of the sample. These RSW, while propagating on the surface of the sample, reradiates energy at the same angle, and the piezo-electric transducer of the acoustic lens can detect them. Acoustic waves that are not incident at the critical angle are reflected by the sample as direct reflected waves. The capability of detecting both direct reflected waves and the RSW by the transducer of the acoustic lens offers a methodology for quantitative determination of RSW velocity in localized regions. For quantitative determination of the Rayleigh wave velocity two methods are often used. The classical method is the so called “V(z)” curve method [3,4]. In this technique, distance between the acoustic lens and the sample is reduced and the variation of the amplitude of the reflected signal is measured. In the presence of RSW this amplitude exhibits oscillations as a function of distance. The oscillation in amplitude is due to the interference between the direct reflected signal and the RSW signal. The periodicity of the oscillation is related to the RSW velocity and the frequency of the acoustic waves. Employing sophisticated software techniques and controlling the temperature of water between the lens and sample,
absolute RSW velocity has been determined, with high precision and sensitivity of 1 part in 10⁴ [5]. In the second methodology, same transducer detects both direct reflected and the RSW signal. Since the RSW travels on the surface of the material, it can be separated from the direct reflected signal in time domain. Different techniques are used to measure the time separation between the signals and to measure the absolute RSW velocity [6-11]. In this method since the time separations are measured, the velocity of sound in water can be measured as an independent parameter and avoids the necessity to control the temperature of water. The precision and sensitivity of this methodology is very similar to that of the V(z) curve.

The V(z) curve and time difference methods are based on the observation of the amplitude of the signals. However, it is well known in physical acoustics that the phase measurements of the signals can provide very high precision in relative sound velocity measurements. Liang et al.[12] utilized phase measurement methodology in focused acoustic beams to measure RSW velocity in materials. In phase measurements, the phase of two signals traveling through the same environment are compared. When the acoustic lens is defocused, the RSW arrives later time compared with the direct reflected signal. The RSW and the direct reflected signal travel through the same environment. Hence, using a tone burst excitation, when sufficient time separation between the two signals is generated; the phase difference between the two signals can be measured and used for high precession RSW velocity determination. The fractional change in the RSW ($\Delta V_R$), is related to the phase difference ($\Delta \phi$) between the direct reflected signal and the RSW signal [12] as,

$$\Delta V_R/V_R = (\lambda_w/4\pi \Delta z \cos \theta_R) \Delta \phi$$  

where, $\lambda_w$ is the wavelength in water and $\Delta z$ is the defocus. The Rayleigh critical angle, $\theta_R = \sin^{-1}(v_w/v_R)$ where $v_w$ is the velocity of sound in water.

Liang et al [12] designed an acoustic microscope operating at 50 MHz, recorded the phase measurements and demonstrated the high sensitivity of the system for RSW velocity measurement. In a more recent investigation Meeks et al [13] developed a double pulse interferometer using an acoustic lens with a transducer capable of generating both longitudinal and shear waves to perform phase measurements. The applicability of system operating at 600 MHz for imaging residual variation has been demonstrated.

Liang et al [12] and Meeks et al [13] used single element transducer acoustic lenses for measurements of phase difference between the direct reflected signal and the RSW signal. The time separation between the two signals is quite small and hence the defocus and the number of cycles in the excitation tone burst must be carefully chosen. The amount of overlap between the two signals and the number of cycles determine the sensitivity and the phase noise of the measurement system. Recently, Sathish et al [14] have developed a Three Element Focusing Ultrasonic Transducer (TEFUT) that eliminates several limitations of the single element transducers. In TEFUS a tone burst signal excites both the central element and one of the outer element. At a defocus the central element receives only direct reflected signal. The outer element excites the RSW and the other outer element is used to detect only RSW. By mixing the two signals an acoustic interferometer was developed to measure the phase difference and hence the RSW velocity. The TEFUT and the phase measurement methodology were used to measure the residual stress across a weld line. The instrumentation for phase measurement involves several amplifiers and moreover is an analog method. In this paper we present a new method of acoustic interferometer using TEFUS and a high frequency lock-in amplifier to measure the RSW. Measurement of changes in the phase difference between the direct reflected signal and the RSW across an electron beam weld line in a sample of Ti-6Al-4V are presented. The results are compared
with the measurement performed on the same sample using analog phase measurement instrumentation and x-ray diffraction residual stress measurements.

This paper first presents a brief discussion of the TEFUT and the analog instrumentation for phase difference measurements for the sake of continuity. Then the high frequency lock-in amplifier methodology is discussed in detail. Measurement of phase difference performed on electron beam welded Ti-6Al-4V sample using lock-in-amplifier methodology and analog instrument the are discussed in the results along with the residual stress measured on the same sample using x-ray diffraction.

THREE-ELEMENT-FOCUSED-ULTRASONIC-TRANSUDER (TEFUT)

Figure 1 shows a schematic diagram of the three-element-focused-ultrasonic-transducer. The transducer has cylindrical geometry and hence produces line focus beams. The details of the design and construction have been discussed elsewhere [14]. The transducer is constructed using polymeric piezo-electric PVDF film. It has a focal length of 20 mm and a width 10 mm. It operates at a center frequency of 20 MHz and has a bandwidth of 15 MHz. The central element (CE) when excited generates a line focus on the surface of the sample. The aperture of the element is chosen such that there is no surface acoustic wave generation of any type. The same transducer detects the reflected signal. One of the outer elements (OE1) when excited produces also focused acoustic line on the sample surface. The aperture and the position of the element is designed such that major portion of the beam is incident at the Rayleigh wave critical angle. When the transducer is defocused RSW are generated at the interface between water and the sample. The RSW while propagating on the sample reradiate energy at the same angle and they are detected by the outer element, OE2.

FIGURE 1. Split Aperture Three Element Acoustic Lens.
INSTRUMENTATION FOR PHASE MEASUREMENT

Conventional Analog Instrumentation

A block diagram of the analog instrumentation used for phase measurement is shown in figure 2. Detailed description can be found elsewhere [14]. A brief description is provided here for continuity. A tone burst signal is generated by chopping a continuous wave signal. This is amplified and used to drive the central element (CE) and one of the outer elements (OE1) of the TEFUT. Acoustic waves generated by the central element focus on the surface of the sample along a line. The reflected signal travels back to the central element and detected by the same element and further amplified. When the lens is defocused the outer element excites RSW on the surface of the sample. The reradiated RSW signal is received by the other outer element (OE2) and further amplified. The two signals are combined in a mixer circuit. The output of the mixer is low pass filtered and displayed on a digital oscilloscope. The output of the mixer is proportional to the phase difference between the input signals. It will be maximum when the two signals are in phase while minimum for out of phase condition. A software gate is placed at the point in time where the two signals overlap and the phase output is digitized. The specimen is raster scanned while the voltage in the gate is scaled and used to create a phase image of the specimen.

Lock-in Amplifier Instrumentation

The instrumentation utilized for measurement of phase with a lock-in amplifier is shown in figure 3 as a block diagram. A continuous sine wave is sent to the reference input of the lock-in amplifier. A Tone burst waveform of 5-cycle duration and repetition rate of

FIGURE 2. Instrumentation for Analog Mixer phase measurement.
4000 per second generated using a function generator (Agilent Model #33250A) is delivered to a “Transmit Switch”. This switch is used to direct the tone burst to either the central or one of the outer elements of the TEFUT. Currently the switch is operated manually, but soon will be controlled using a computer. One output of the switch is fed to the central element (CE) of the TEFUT. The “Receive Switch” must also be set for the center element. The signal received by the central element after reflection from the sample is amplified and supplied to the input channel of the high frequency lock-in amplifier (SRS Model #SR844). The phase difference between the center element channel and the continuous wave reference channel is recorded. The other output of the “Transmit Switch” (if selected) sends the tone burst to one of the outer elements of the transducer (OE1). The “Receive Switch” is set to outer element (OE2). The reradiated RSW signal detected by the outer element (OE2) is amplified and sent to the input channel of the lock-in amplifier. The Lock-in amplifier displays the phase difference between the RSW and the continuous wave reference input signals. This phase difference is recorded. The measurements described above provide a) the difference in phase between the direct reflected tone burst and the reference signal and b) the phase difference between the RSW tone burst and the reference signal. The difference between the two-phase differences yields the phase difference between the direct reflected wave and the RSW wave. This phase difference is utilized to compute the relative change in the Rayleigh wave velocity using equation (1). By scanning the transducer across the sample, the phase difference and the relative change in the RSW velocity can be mapped.

**FIGURE 3.** Instrumentation for Lock-in amplifier phase measurement.
RESIDUAL STRESS MEASUREMENT ACROSS A WELD LINE

One of the motivations for the development of TEFUT has been to measure small changes in RSW velocity caused by residual stress. An ideal sample for the cylindrical geometry of the TEFUT is a straight weld line. It is well known in welding that the residual stress in the heat-affected zone is generally tensile and reduces away from the weld line. In a recent investigation [14] the variation in relative phase difference between the direct reflected and RSW signal was measured across an electron beam welded titanium (Ti-6Al-4V) sample using the TEFUT. An analog instrumentation described earlier was used for the measurements. The same specimen was utilized for measurements of phase difference using the high frequency lock-in amplifier methodology. The sample has an optically polished flat surface that eliminates topography contribution to the phase difference measurements. The acoustic lens and the sample were immersed in a large water tank to minimize the effect of temperature variations. The results of the phase difference measurements across the weld line performed using lock-in amplifier at an acoustic frequency of 14 MHz are shown in figure 4. At each location the phase difference is an average over entire width of the acoustic beam. The figure 4 also shows the phase difference measurements performed using analog instrumentation when the TEFUT was excited at a frequency of 15 MHz. Figure 4 also shows the x-ray diffraction residual stress measurements performed at fixed locations along the same line. These measurements were acquired using a rectangular x-ray collimator (5 mm x 1mm). All the measurements were performed approximately on the same region on the sample.

![Graph showing phase difference and residual stress across a weld line](image)

**FIGURE 4.** Variation of Phase difference and Residual stress across a weld line.
The x-ray diffraction residual stress measurement shows a broad peak with maximum tensile stress (32 Ksi) at the center of the weld line. It also exhibits another maximum that is close to zero (0 Ksi) residual stress. Far from the central weld line the residual reaches compressive stress of -15 to 20 Ksi. It is well known that the RSW velocity in a material under compressive stress is higher than the unstressed state. For a material under tensile stresses it is less than the unstressed state. Based on this fact it is expected that the phase difference increase when the stress is tensile while it decreases for the case of compressive stress. The phase difference between the direct reflected and the RSW signal measured using the high frequency lock-in-amplifier and the analog instrument follow the same behavior as the residual stress variation. Far from the weld line on the left side the phase difference is maximum and it decreases reaching a minimum when the residual stress reaches first small maximum. Further the phase difference increases and reaches small maxima when the stress is minimum. The phase difference reaches a large minimum when the residual stress reaches maximum tensile stress. On the other side as the tensile stress decreases the phase difference increases. Thus the phase difference across the weld line mimics the residual stress variation. The phase difference measurements performed by high frequency lock-in amplifier method is good agreement with the analog measurements.

CONCLUSIONS

In conclusion, we have developed an acoustic interferometer based on high frequency lock-in-amplifier to measure phase difference between the direct reflected and RSW signal in a three-element focused ultrasonic transducer. The phase difference measurements across an electron beam weld line follows, the x-ray diffraction residual stress measurements. Lock-in amplifier measurements have been found to be in good agreement with the analog acoustic interferometer measurements. Both lock-in amplifier method as well as the analog instrumentation is capable of measuring small changes in the RSW velocity caused by residual stress.

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