NDE OF CYLINDRICALLY SYMMETRIC COMPONENTS WITH PIEZOFILM TRANSDUCERS

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INTRODUCTION

The flexible polymer piezofilms such as polyvinylidene fluoride[1] (PVDF) possess distinct advantages as ultrasonic transducers for inspecting cylindrically symmetric components, including rods, pipes, cladding, and tube interfaces. The flexibility and contour conforming nature of the film transducer ensure normal incidence and avoid mode conversion. In this work, PVDF transducers are used in several applications, including the evaluation of interfaces in coaxially extruded Zirconium/Zircaloy-2 tubes, the inspection of the clamping condition of Nitinol coupler and the detection of artificial flaws in Aluminum rods. Detailed description will be given for the valuation of an interface in a Zirconium/Zircaloy tube, on which the same transducer was used both as the transmitter and the receiver. The observed signals were analyzed and reflection coefficient as small as 0.006 was accurately measured. Comparison will be made with the measurement results of conventional transducers.

EVALUATION OF INTERFACE IN CO-EXTRUDED ZIRCONIUM TUBE

(1) Sample Description

The Zirconium tube was coaxially extruded. It consisted of a thin inner layer of pure Zirconium and a thicker Zircaloy-2 outer layer. The outer diameter of the tube was 2.50", and the wall thicknesses of the inner and outer layers were roughly 0.07" and 0.36", respectively. In the measurement, a Pennwalt SDT1-028K transducer[2] was placed on the outside wall of the tube with a piece of rubber as the backing.

(2) Experimental Results

In the measurement, the multiple echoes of the interface and the backwall of the tube can be observed up to 18th round trip. The schematic picture of the echoes on an oscilloscope is drawn in Fig. 1.

It can be seen from Fig.1 that the nth interfacial echoes I_n and J_n appear before and after the back wall echo B_n. A typical group of the 6th round-trip echoes, acquired with a LeCroy 9400 digital oscilloscope, is shown in Fig. 2.

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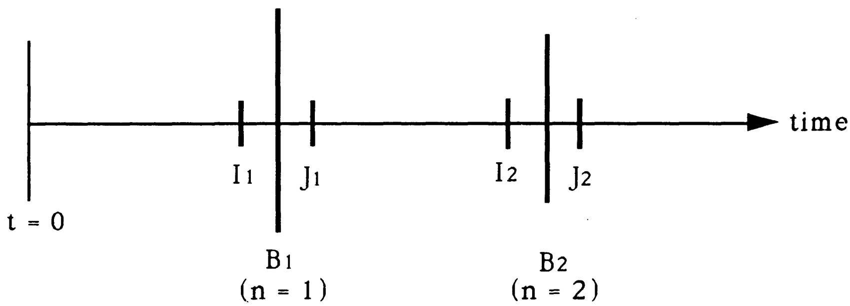

Fig. 1 The Multiple Reflected Echoes

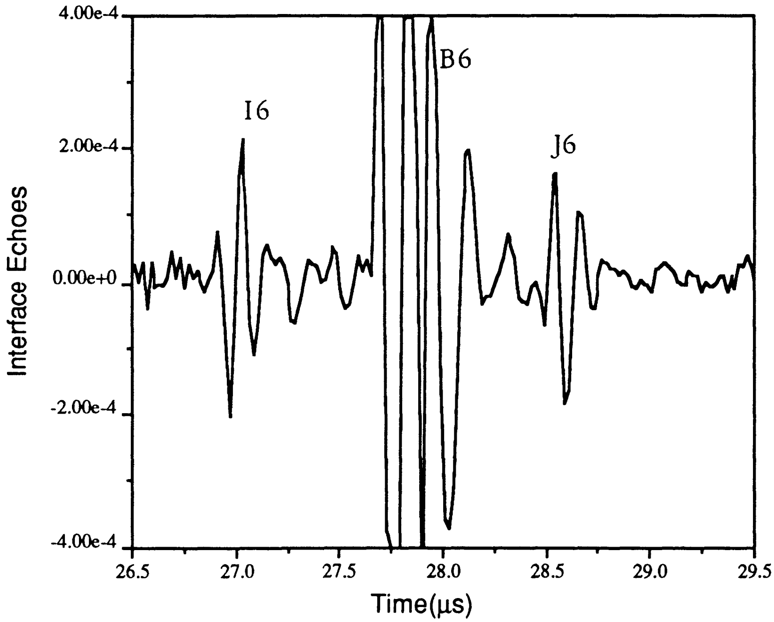

Fig. 2 The 6th Round Trip Echoes on the Zr/Zircaloy-2 tube

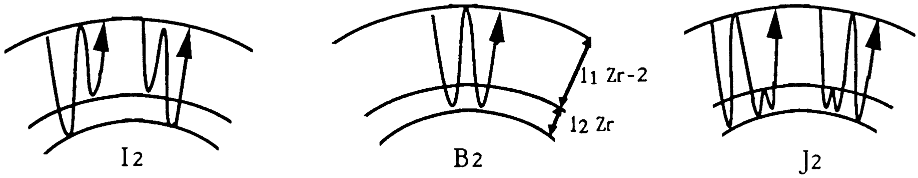

Fig. 3 Wave Paths of 2nd Round-Trip Echoes

3) Analysis

In the pulse-echo measurement, when n is larger than one, the multiple interfacial echoes will add in phase. Shown in Fig. 3 are the wavepaths for the 2nd round-trip echoes. It is clear that the two wavepaths add in phase for echoes I_2 and J_2.

Assume that the thicknesses of the Zircaloy-2 and pure Zirconium layers in the tube are l_1 and l_2, and that they have the same attenuation coefficient α. We further assume that R_a, R_f and R_i are the reflection coefficients for the Zirconium-air, Zircaloy-PVDF, and Zircaloy-Zirconium interfaces, respectively, then it is easy to write down the amplitudes of the nth round-trip echoes I_n, B_n and J_n as follows:

$$I_n = n\, R_a^{n-1} R_f^{n-1} R_i\, T_i^{2(n-1)}\, e^{-2(n-1)(l_1+l_2)\alpha}\; e^{-2l_1\alpha}\;; \quad (1)$$

$$B_n = R_a^{n} R_f^{n-1} T_i^{2n}\, e^{-2n\,(l_1+l_2)\alpha}\;; \quad (2)$$

$$J_n = n\, R_a^{n+1} R_f^{n-1} R_i\, T_i^{2n}\, e^{-2n\,(l_1+l_2)\alpha}\, e^{-2l_2\alpha}\;. \quad (3)$$

From Eqs. (1) and (3), we expect that the amplitudes of interfacial echoes I_n and J_n first increase when n increases, then decrease due to the effect of the attenuation.

By setting

$$\frac{\partial I_n}{\partial n} = 0 \quad \text{or} \quad \frac{\partial J_n}{\partial n} = 0\,,$$

and assuming $R_a = 1$ and $R_f \approx 1$, the maximum amplitude can be predicted to occur for the following value of n:

$$n = \frac{1}{2\,\alpha\,(l_1 + l_2) - 2\ln(T_i)}\,. \quad (4)$$

Dividing Eq. (1) and Eq. (3) by Eq. (2), we have

$$\frac{I_n}{B_n} = n \frac{R_i}{T_i^2 R_a}\, e^{2l_2\alpha} \quad (5)$$

and

$$\frac{J_n}{B_n} = n\, R_a R_i\, e^{-2l_2\alpha}\,. \quad (6)$$

Noticing that $T_i^2 = 1-R_i^2$ and $R_a = 1$, the reflection coefficient at the Zircaloy-2 and Zirconium interface can be determined by multiplying Eq. (5) and Eq. (6) together, that is,

$$R_i = \frac{1}{\sqrt{1 + n^2\left(\frac{B_n}{I_n} \cdot \frac{B_n}{J_n}\right)}} \quad (7)$$

The multiplication of Eq. (5) and Eq. (6) cancelled out the attenuation coefficient and the reflection coefficient of the Zirconium-Zircaloy interface is therefore a function of n, and the amplitude ratios of the nth group of echoes. The interfacial reflection coefficient R_i can then be computed from the echo amplitude ratios of each group. Figure 4 shows the calculated interfacial reflection coefficient up to 18th round trip echoes. The average reflection coefficient based on the data is

$R_i = 0.006 \pm 5\%$.

This implies that impedances of Zirconium and Zircaloy-2 differ by approximately 1.2% and the transmission coefficient T_i at their interface is approximately unity.

Dividing Eq. (1) by Eq. (3), we arrive at the relationship

$$\frac{I_n}{J_n} = \frac{1}{T_i^2 R_a} e^{4 l_2 \alpha} . \quad (8)$$

Since T_i^2, $R_a \approx 1$, the apparent attenuation coefficient, which includes all the energy

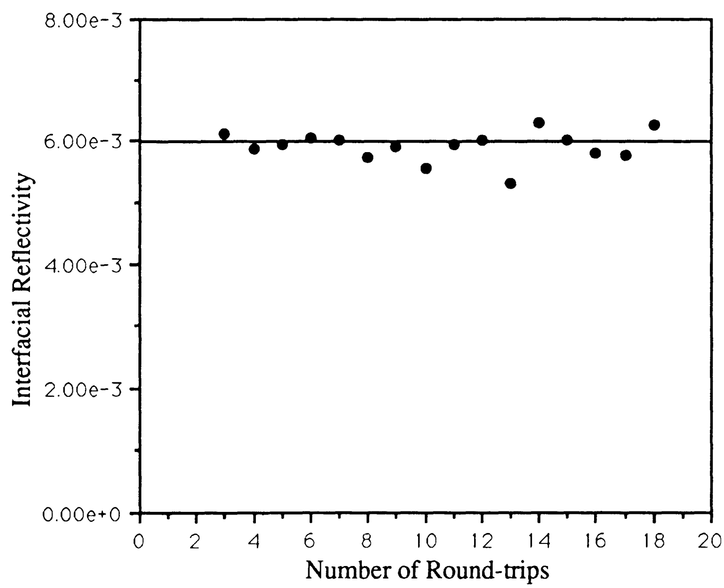

Fig 4 Interfacial Reflection Coefficient of Zr/Zircaloy-2 Tube

losses other than that due to reflection and transmission at the interfaces, can be determined from the interfacial echoes I_n and J_n. That is,

$$\alpha = \frac{1}{4 l_2} \ln\left(\frac{I_n}{J_n}\right) . \tag{9}$$

The experimental results of I_n and J_n at a typical location on the tube give that

$$\alpha = 0.13 \pm 0.04 (\mathrm{cm}^{-1}) .$$

Substituting α and T_i into Eq. (4), we then determine the value of n corresponding to the maximum echo amplitude. The value was 3.5. Since the value must be an integer, it is taken to be 4. This prediction based on Eq. (4) agrees well with the experimental results, which are shown in Fig. 5.

In the measurements, the interfacial echoes I_n and J_n are always out of phase due to the impedance difference of Zr and Zircaloy-2, but I_n is always in phase with B_n. This implies that the acoustic impedance of pure Zirconium is smaller than the impedance of Zircaloy-2. Using the pulse overlap technique, the time interval between I_n and J_n can be precisely measured. This then allows a determination of the thickness of the Zr layer l_2 to a good accuracy. At one location on the tube, it is measured to be:

$$l_2 = 0.0738 \pm 0.0002'' .$$

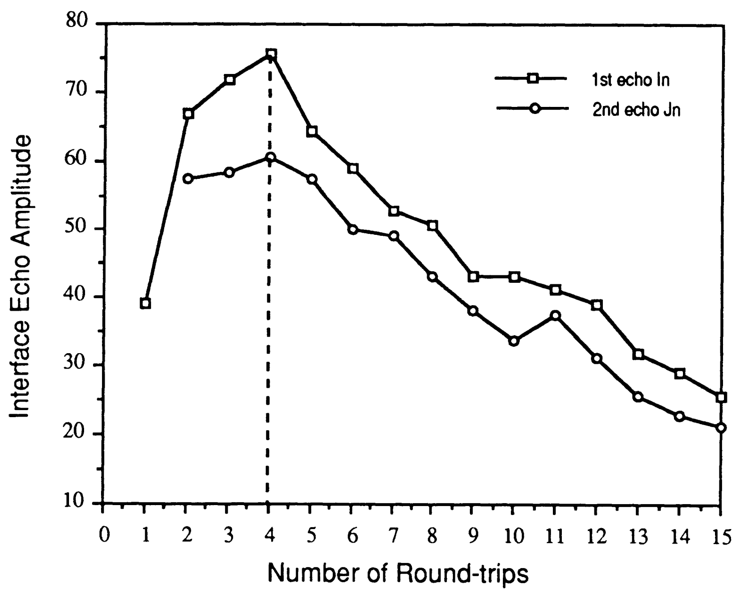

Fig 5 The Interfacial Echo versus Number of Round-trips

(4) Comparison with Conventional Transducers

In addition to using PVDF film transducers in contact mode, other methods were also used to evaluate the interfacial echoes of the same Zr/Zr-2 tube. The quality of the echo signals (i.e., the S/N ratio), ranked from the best to the worst, in the following order (Cylindrically focused probes were not evaluated in this study.):

1. PVDF film transducer in contact;
2. PVDF film transducer in immersion, curved to be concentric with tube;
3. Spherically focused probe in immersion, focused on the interface;
4. Contact, planar prob with circumferential wedge coupler;
5. Planar immersion probe.

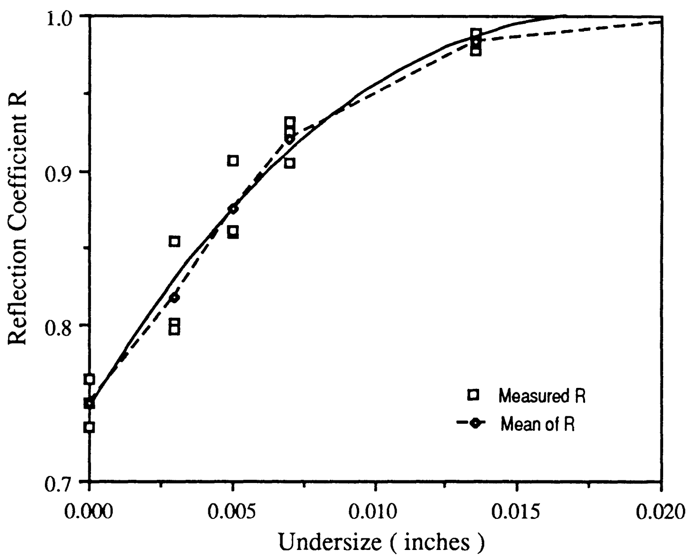

Fig. 6 The Reflection Coefficient of the Nitinol Coupler Interface

The flexible PVDF film transducers have the contour conforming advantage and produce normal incidence everywhere on the tube, thus avoiding mode conversions. In this application, although the efficiency of PVDF transducer was not as good as that of a ceramic transducer, but the signal/noise ratio and the measurement accuracy of PVDF transducer outperformed conventional transducers.

OTHER APPLICATIONS

(1) Evaluation of the Clamping Condition of Nitinol Coupler

The tube couplers used in this study were made from Nitinol, a so called "shape memory" material. At room temperature, they had an outer diameter of

0.82" and were about 1.2" long. There were four lands on the inner wall of the coupler so as to clamp two stainless steel tubes (held end to end) together by shrinkage. In previous investigations[3-4], the reflection coefficient of the coupler-tubing interface, obtained in immersion measurements, was related to the stress level of clamping. In this study, PVDF transducers were used to examine the coupler tubing interface. The interfacial clamping stress was varied by machining the tubes to different undersizes. The interfacial reflection coefficients were calculated from the amplitudes of the interfacial echoes. The results were shown in Fig. 6, where the dashed line is the average reflection coefficient at three different locations of each sample, and the solid line is a polynomial best fit of the measured interfacial reflectivity. It is clear in Fig. 6 that the reflection coefficient increases when the undersize increases (and the interfacial stress decreases).

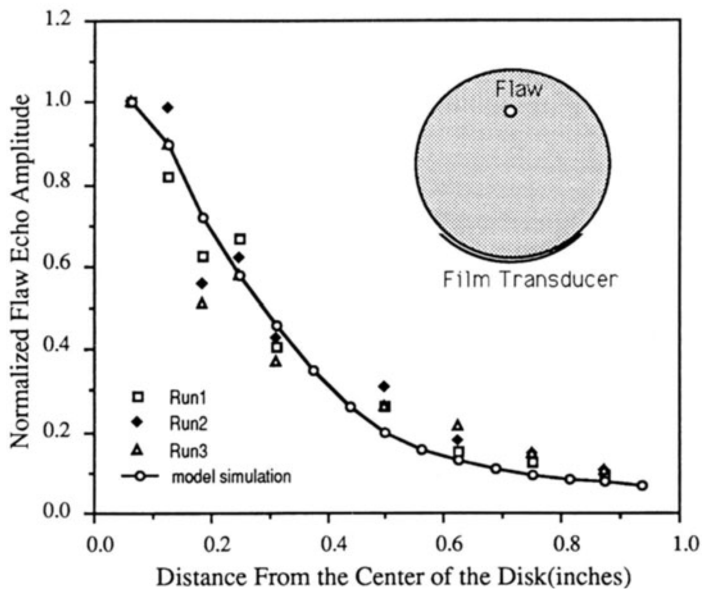

Fig. 7 The Measured and Predicted Flaw Amplitude

(2) Detection of Artificial Flaws in Circular Aluminum Disks

Taking its advantage of flexibility, PVDF film transducers were also used to detect artificial flaws in 2" dia., 1" thick aluminium disks. The flaws were 1/16" dia. through holes drilled at a different distance d from the center of each disk. In the measurement, a PVDF film transducer was placed symmetrically with respect to the flaw by maximizing the flaw signal. The flaw echo amplitudes in three different runs were shown in Fig. 7 as a function of flaw location. A model has been developed[5] to predict the target echo signal by computing the impulse response of this geometric configuration. The predicted (and normalized) signal amplitude was also displayed in Fig. 7 as a solid line in comparison with the experimental data.

CONCLUSIONS

The PVDF film transducers have the advantages of flexibility and curvature conforming ability in the inspection of parts with curved surfaces. Although they are less efficient than rigid ceramic transducers and do not match the acoustic impedance of metals as well as ceramic transducers, the advantages can still outweigh the disadvantages in some applications in tubes and rods.

In the interface measurement of Zirconium/Zircaloy-2 tube, weakly reflecting interfaces (R ~ 0.006) can be evaluated in detail, and the thickness of the cladding can be measured accurately. The experimental results and observations were successfully interpreted with model.

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