

## NDE OF INTERFACES IN THE TUBE GEOMETRY WITH PIEZOFILM TRANSDUCERS

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JAN 22 1992

### ABSTRACT

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 the evaluation of interfaces in coaxially extruded Zirconium-Zircaloy tubes and the clamping condition of Nitinol couplers over stainless steel tubing. Detailed description will be given for the evaluation of an interface in a Zirconium-Zircaloy tube, on which the same transducer was used both as the transmitter and the receiver. The multiple echo 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.

### I. INTRODUCTION

Piezoelectric polymer films such as polyvinylidene fluoride (PVDF) are widely known to be efficient receivers of ultrasound but inefficient transmitters. The low acoustic impedance of the film makes it a good match with water and hence useful in medical ultrasonics. In nondestructive evaluation (NDE) of metal parts, PVDF film transducers have found some use but are generally considered too low in efficiency. However, in certain NDE applications the advantage due to the flexibility nature of the film transducers can more than compensate their disadvantage of low efficiency. One such case is the inspection of interfaces in cylindrically symmetric components such as pipes or tubes. Because the piezofilm transducer conform to the surface curvature and may be wrapped around a pipe, normal incidence is ensured everywhere and mode conversion problems are avoided. This feature greatly helps the interpretation and analysis of the ultrasonic signals and makes accurate, quantitative

determination of the interface parameters possible. In this paper, PVDF film transducers were applied to evaluate the interface condition in two metal components: a coaxially extruded Zirconium-Zircaloy tube and Nitinol couplers clamped over stainless steel tubing. Detailed results and quantitative analysis will be given for the co-extruded Zirconium tube. For the clamping condition of the Nitinol coupler, only qualitative correlation will be given.

### II. EVALUATION OF INTERFACE IN CO-EXTRUDED ZIRCONIUM TUBE

#### (1) Sample Description and Test Method

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.

Since the reflection coefficient of the interface depends on the acoustic impedances of the two adjoining materials, mass density and speed of sound data were sought for pure Zr and for Zr-2. For pure Zr, the density is 6.505 and the speed of longitudinal wave is 4.70 km/sec [2]. The acoustic impedance of pure Zr is therefore 30.6 MRyl. For Zr-2, the density and the longitudinal wave speed were determined experimentally on pieces cut from the tube and the results are 6.51 g/cm<sup>3</sup> and 4.66 km/sec, respectively. Based on this results, the acoustic impedance of Zr-2 is 30.3 MRyl. Within measurement errors, the acoustic impedances of Zr and Zr-2 are essentially equal. This implies that the reflectivity is very low and that which material has the greater acoustic impedance will determine the phase of the reflected signal.

Experimentally, a rectangular-shaped piezofilm transducer [3] (Pennwalt SDT1-028K, 28mm x 14mm) was coupled to the outer surface of the tube with oil and pressed against the tube with a piece of rubber as a backing. The transducer was driven by a

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Panametrics 5052PR broad band pulser/receiver and the received RF signals were displayed on a LeCroy 9400 digital oscilloscope for measurements

## (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.

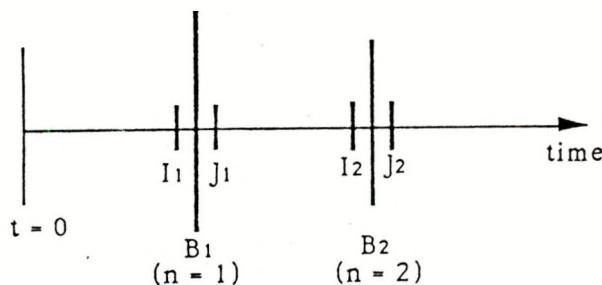


Fig. 1 The Multiple Reflected Echoes

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.

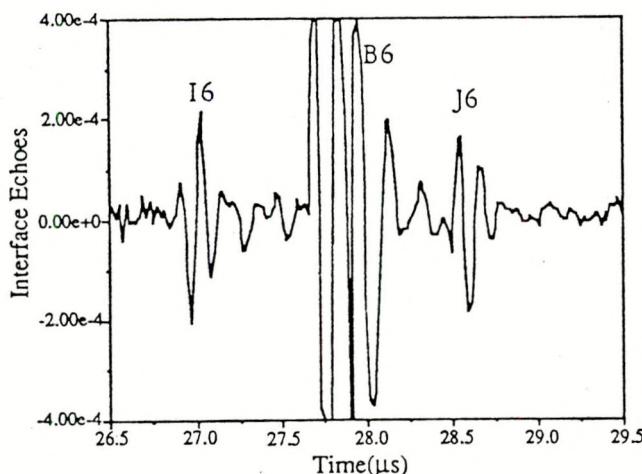


Fig. 2 The 6th Round Trip Echoes on the Zr-Zircaloy tube

## (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  $J_2$ .

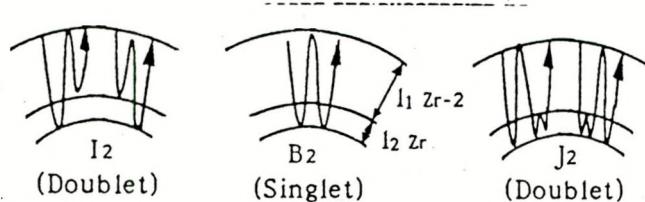


Fig. 3 Wave Paths of 2nd Round-trip Echoes

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  $\alpha$ . 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  $n$ th 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.

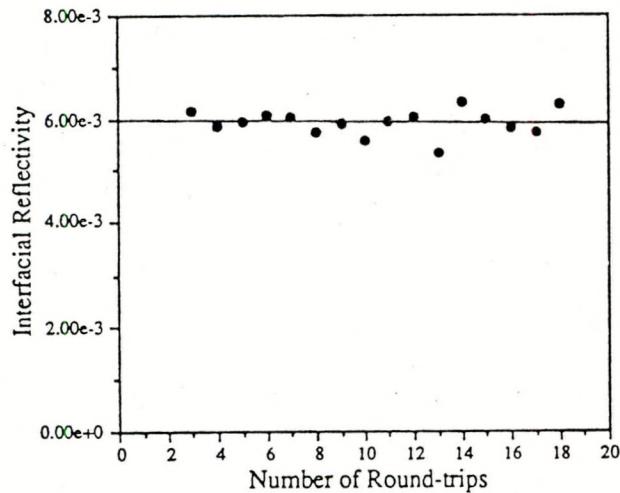


Fig 4 Interfacial Reflection Coefficient of Zr-Zircaloy Tube

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

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

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

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

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

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

Substituting  $\alpha$  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.

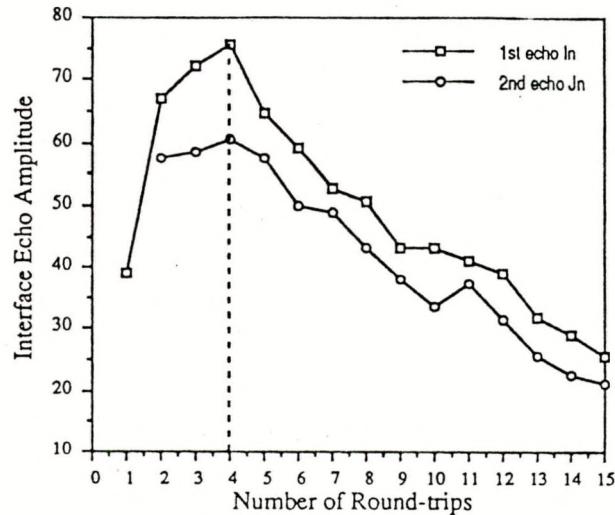


Fig 5 The Interfacial Echo versus Number of Round-trips

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:

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

#### (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.

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.

### III. 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[4,5], 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).

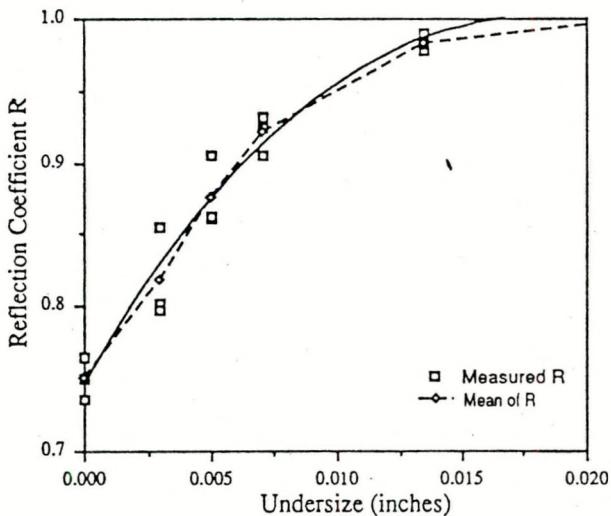


Fig. 6 The Reflection Coefficient of the Nitinol Coupler Interface

### 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 tube, weakly reflecting interfaces ( $R \sim 0.006$ ) 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.

### ACKNOWLEDGEMENT:

This work was supported by the Director for Energy Research, Office of Basic Energy Sciences of the US Department of Energy under Contract No. W-7405-ENG-82, and was conducted at Ames Laboratory.

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