Evaluation of Acoustical Holography for the Inspection of Light Water Reactor Weld Assemblies

**H. D. Collins
R. P. Gribble**

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FOREWORD

This report describes the work conducted at Pacific Northwest Laboratory to evaluate acoustical holography techniques for the characterization of light water reactor weld surface signatures in the nuclear safeguards program.

Special thanks are due Dr. James M. McKenzie for his excellent cooperation, guidance and support in this program.

CONCLUSIONS

The primary objective of this program was the evaluation of acoustical holography techniques for characterization of the light water reactor weld surface signatures in the nuclear safeguards program.

The accurate characterization of weld surface irregularities and vertical deviations was achieved using acoustical holographic interferometric techniques.

Preselected weld surfaces were inspected and the vertical deviations characterized by phase measurements or fringe densities in the image. Experimental results on Sandia samples verify depth deviation sensitivities of 0.11 μm to 0.16 μm .

The two point interferogram technique (see Section 3.3) is recommended for surveillance of the weld surface associated with fuel rod removal in the nuclear safeguard program. The use of this unique holographic signal processing provides essentially a fail-safe method for surveillance of clandestine fuel rod removal.

Statistical analysis in Section 4 indicates 99.99% (weld surface deviation) confidence interval between 2 μm and 3 μm can be achieved. These results illustrate the extremely high resolution capabilities of the surveillance technique employing coherent signal processing.

EVALUATION OF ACOUSTICAL HOLOGRAPHY FOR THE INSPECTION OF LIGHT WATER REACTOR WELD ASSEMBLIES

INTRODUCTION

This report describes work by Pacific Northwest Laboratory to assist Sandia National Laboratories to meet its general requirement for investigating new safeguard inspection techniques for light water reactor weld assemblies. The present technique employs three acoustical focused transducers positioned in a unique jig above the security fuel rod weld cap. Two sensors interrogate the weld surface with broadband pulses and the return echoes are analyzed to determine weld integrity. Fuel rod removal through the cap requires destruction of the existing weld and rewelding to prevent theft detection. The theft is revealed by the new weld structure that is detected by amplitude correlation techniques during the next inspection period.

The reliability of the inspection procedure is determined by the ability of the acoustical amplitude correlation technique to reveal subtle changes between the two weld surfaces (i.e., old and new).

The research conducted at PNL employs the use of "acoustical holography" for the inspection of weld surface integrity. The holographic technique uses coherent signal processing of the reflected signals to characterize surface deviations. The apparatus used for weld crown surface inspection is a holographic system operating in the focused hologram mode employing an electronic simulated or acoustic reference beam. The definition of this class of hologram is simply the interference pattern between object and reference beams with the condition that the object is in focus at the hologram plane. The variable simulated inclination angle provides the capability of controlling the fringe density without the use of different frequencies, as with the more conventional optical techniques.

External surfaces such as irregular weld surfaces, etc., can be inspected with the deviations in fringe density representing the height or depth of the irregularities. The use of multiple acoustic paths (i.e., echoes) dramatically increases the depth resolution by changing the fringe spacing criterion. The spacing between fringes represents $\lambda/2k$ deviations in depth where k is the number of multiple paths or echo returns. Thus, simply the going from the first to the sixth echo, the depth deviation between fringes decreases from $\lambda/2$ to $\lambda/12$.

Experimental results on preselected Sandia weld samples indicate surface deviations can be detected within 0.11 to 0.16 μm . The 99.99% confidence interval using 20 measurements is approximately 3 μm .

The results illustrate the unique resolution capabilities of the holographic technique applied to weld surface surveillance.

1.0 ACOUSTICAL INTERFEROMETRY THEORY

Acoustical interferometry techniques usually parallel those previously done in the field of optics. Naturally there are special cases in acoustics which are impossible to duplicate in optics because the detectors, sources, etc. are physically different. The method described in this report employs a simultaneous focused source-receiver scanning technique with a simulated or acoustic reference. This system coupled with a focused transducer and multiple path echo selection represents a very unique interferometry imaging device. The fringe density or spacing criterion can be controlled without changing the insonification frequency.

Figure 1.1 shows the geometry for constructing an acoustical interferogram using a focused source-receiver transducer. The phase at the receiver point (x, y, z) is

Figure 1.1. Interferogram Construction Geometry.

$$\phi_1(x,y,z) = \phi_0(x,y,z) - \phi_r(x,y,z) \quad (1)$$

and

$$\phi_1(x,y,z) = \frac{2\pi}{\lambda s}(Z_0+Z_1) - \phi_r(x,y,z) \quad (2)$$

where λs = acoustic wavelength in the medium

Z_1 = object to receiver distance

Z_0 = object to source distance.

The resultant phase (ϕ_1) is a function of both the object and the reference phases. The reference phase is simulated electronically and thus the reference fringe density in the interferogram is selectable. The operator has complete control over the fringe density using only one illumination frequency. Fringes are produced when the resulted phase (Eq. 3) equals $2\pi n$ radians. Equation 3 defines the condition mathematically

$$\frac{2\pi}{\lambda s}(2Z_1) - \phi_r(x,y,z) = \pm 2\pi n \quad (3)$$

where $n = 1, 2, \dots$

1.1 MULTIPLE PATH TECHNIQUE

If we employ multiple path techniques (i.e., gating on the k th signal return or echo) the fringe spacing criterion is changed. Equation 3 can be rewritten in the following form

$$\frac{2\pi}{\lambda s}(2kZ_1) - \phi_r(x,y,z) \approx 2\pi n \quad (4)$$

$k = 1, 2, 3, \dots$

where k is the number of multiple paths or signal echoes. The fringe or contour generation criterion is given by the following equation

$$\Delta Z = \frac{\lambda S}{2k} \quad (5)$$

where the reference phase is assumed constant. Equation 5 shows the fringe density is also selectable depending on the number of multiple paths or echoes.

1.2 FRINGE SPACING CRITERION

Equation 3 can be written for two object points at different elevations in the "z" direction

$$\begin{aligned} \phi_1(x,y) &= \frac{2\pi}{\lambda S}(2Z_1) - \phi_r(x,y) \\ \phi_2(x,y) &= \frac{2\pi}{\lambda S}(2Z_2) - \phi_r(x,y) \end{aligned} \quad (6)$$

The simulated acoustic reference phase can be expressed in the following form

$$\phi_r(t) = \frac{2\pi t}{T} = \frac{2\pi x}{d_x} \quad (7)$$

where d_x is the reference spacing or grating for a flat plate parallel to the scanning aperture. Equations 6 and 7 are rewritten in terms of the object positions (x,z)

$$\phi_1(x,y) = \frac{2\pi}{\lambda S}(2Z_1) - \frac{2\pi x_1}{d_x} = 2\pi n \quad (8)$$

$$\phi_2(x,y) = \frac{2\pi}{\lambda S}(2Z_2) - \frac{2\pi x_2}{d_x} = 2\pi(n+1) \quad (9)$$

where $n = 1, 2, 3, \dots$

The difference between Equations 8 and 9 represent the criterion between fringes (n, n+1) and the vertical change in elevation. The resultant equation is:

$$\Delta\phi(x,y) = \frac{2\Delta Z_1}{\lambda s} + \frac{\Delta x}{d_x} = 1$$

$$\Delta Z = \frac{\lambda s}{2K} \left(1 - \frac{\Delta x}{d_x} \right) \quad (10)$$

where k = number of multiple paths

$d_x = V_x T_p$ (reference grating)

ΔX = fringe spacing on the interferogram.

If we scan in the y direction, the equation is the same except Δy and d_y are substituted for Δx and d_x respectively.

2.0 DESCRIPTION OF SCANNED HOLOGRAPHIC IMAGING SYSTEM

2.1 BASIC HOLOGRAPHIC SYSTEM

Figure 2.1 is the block diagram of the scanning acoustical holographic system showing the various components. A brief description of the salient features of the imaging system will be discussed. Probably the most expedient method of describing the system is to simply follow the signal from the start (i.e., oscillator) to the final interferogram.

Figure 2.1. Block Diagram of Acoustical Holography System.

The output of the high frequency oscillator which represents the coherent source is divided or split into two signals, the object and reference, which parallels optical interferometry or holography. The oscillator signal is gated to produce short pulses which are amplified and drive the source transducer after impedance matching networks. The acoustic energy is focused by the transducer on the object and weld surface deviations are imaged.

If we let the object signal at the receiver be described by the following equation

$$S_o(x,y) = P_o(x,y) \cos [\omega t + \phi_o(x,y)] \quad (11)$$

where $P_o(x,y)$ is the amplitude modulus and ϕ_o the phase. The acoustic reference signal is simulated electronically and can be expressed as

$$S_r(x,y) = P_r(x,y) \cos [\omega t + \phi_r(x,y)] \quad (12)$$

where $P_r(x,y)$ and $\phi_r(x,y)$ are selectable. The two signals are multiplied and then time averaged. The resultant holographic signal is given by the following equation

$$S_i(x,y) = \frac{1}{T_o} \int_0^{T_o} S_o(x,y) S_r(x,y) dt = \\ 1/2 P_r(x,y) P_o(x,y) \cos [\phi_o(x,y) - \phi_r(x,y)]. \quad (13)$$

Fringes or contour lines occur when the resultant phase equals $\pm 2\pi n$ radians. This signal drives the "Z" axis of the storage oscilloscope. The focused image interferogram is then constructed on either the storage tube or television screen.

2.2 INTERFEROMETRIC MODE

The use of interferometry in weld imaging provides extremely high depth resolution and reveals very small surface deviations. The rather unique feature of this technique is its ability to differentiate between convex and concave defects with the programmed electronic simulated reference beam. Figure 2.2 shows the construction geometry and interferograms of a convex defect on a flat plate. The elevation between fringes is easily calculated using the following equation:

$$\Delta Z = \frac{\lambda s}{2K} \left(1 - \frac{\Delta X}{d_x} \right) \quad (14)$$

where K = number of multiple paths

$d_x = V_x T_p$ (reference fringe spacing)

ΔX = fringe spacing in the interferogram

λs = acoustic wavelength

The reference spacing is the distance between fringes on the zero slope area with respect to the scanning plane and the convex defect is easily identified by the increase and decrease in fringe density (scanning left to right). Very small anomalies and other defects are easily detected using this imaging technique.

Figures 2.3a, b, c, and d are photographs and acoustic images of two pennies. These objects were imaged using the system operating at 50 MHz with the simulated reference. The fringe lines are extremely close on the head of the Indian and have merged together on the head of Lincoln (see Figures 2.2b and d). The fringe density across either the Indian or Lincoln penny is selectable by varying the inclination angle of the simulated reference electronically. Thus, the operator has complete control of the fringe density without changing the frequency.

ACOUSTICAL
 FREQUENCY: 3.23MHz
 SCAN RATE (v_x): 7.62cm/sec
 PHASE SHIFTER
 PERIOD (T_p): 20m sec.
 REFERENCE ANGLE (α_x) $18^\circ, 0^\circ$

Figure 2.2. (a) Interferogram Construction Geometry, (b) Interferogram ($\alpha_x = 17.2^\circ, 0^\circ$), and (c) Interferogram ($\alpha_x = 17.2^\circ$).

(a)

(b)

OBJECT: INDIAN HEAD PENNY
 ACOUSTIC FREQUENCY: 50MHz
 MAGNIFICATION: 0.9
 ELEVATION BETWEEN FRINGES: 0.015mm

(c)

(d)

OBJECT: LINCOLN HEAD PENNY
 ACOUSTIC FREQUENCY: 48MHz
 MAGNIFICATION: 3.6
 ELEVATION BETWEEN FRINGES: 0.016mm

Figure 2.3. (a) & (c) are the Optical Images and (b) & (d) the Focused Acoustical Interferograms.

2.3 ELECTRONIC SIMULATED ACOUSTIC REFERENCE

If we assume an acoustic plane wave reference beam, then the reference beam can be expressed as

$$S_r(x,y) = P_r(x,y) \cos \left(\omega t - \frac{2\pi}{\lambda S} x \sin \alpha_x \right) \quad (15)$$

where $\phi_r(x,y) = \frac{2\pi}{\lambda S} x \sin \alpha_x$.

No loss of generality results in only considering two dimensions with the object located on the (x-z) plane. The signal contribution to the acoustic receiver by the reference beam is

$$P_r(x,y) \cos \left(\omega t - \frac{2\pi}{\lambda S} \sin \alpha_x V_x t \right) \quad (16)$$

where V_x is the scanning velocity of the acoustic receiver and

$$\omega_x = \frac{2\pi}{\lambda S} V_x \sin \alpha_x \quad (17)$$

Equation 16 represents a sinusoidal wave whose phase (ϕ_r) is a function of the scanning velocity (V_x) and the inclination angle (α_x). Thus, the acoustic plane wave reference beam can be simulated with an electrical signal of this form and combined with the object signal in a balanced mixer or multiplier. If the direction of propagation of the plane wave reference is perpendicular to the x axis, then $\omega_x = 0$ and the reference signal is simply $(P_r(x,y) \cos \omega t)$. This electrical signal, when combined with the object signal in a mixer, would simulate an on-axis plane wave acoustic reference beam. Now, if the inclination angle is not zero, then the electrical reference signal must be phase shifted to simulate an off-axis acoustic reference beam. The simulated

inclination angle is a function of the scanning velocity, wavelength of sound, and the phase shifter control voltage frequency. Naturally, in three dimensions skewed beams are possible with phase shifting and time delay circuits. The phase of the electronic reference can be shifted with respect to time by the following voltage waveform shown in Figure 2.4.

Figure 2.4. Phase Shifter Control Voltage.

The control voltage radian frequency (ω_p) can be expressed in terms of ω_x :

$$\omega_p = 2\pi f_p = \frac{2\pi}{\lambda s} V_x \sin \alpha_x \quad (18)$$

If the simulated plane wave is inclined with respect to a planar object (i.e., $\alpha_x > 0$), then a linear fringe grating will be imposed on the interferogram. The fringe spacing is a function of the scanning velocity (V_x) phase shifter frequency (f_p) and the image magnification (m). The fringe spacing on the interferogram is

$$d_x = \frac{V_x T_p}{m} = \frac{V_x}{m f_p} = \frac{\lambda s}{\sin \alpha_x} \quad (19)$$

where $\alpha_x = \sin^{-1} \left(\frac{\lambda s m f_p}{V_x} \right)$

Figure 2.5 is a graph illustrating the fringe spacing as a function of the scanning velocity and the phase shift voltage. It should be obvious that any grating spacing or fringe

Figure 2.5. Fringe Spacing Versus Phase Shifter Period.

density can be imposed on the interferogram by proper adjustment of the phase shifter control voltage frequency or scanning velocity. The grating spacing can be less than a wavelength which indicates the electronic simulation is more versatile than using an acoustic reference beam. The contour lines are usually constructed perpendicular to the scanning lines in rectilinear scanning. Figure 2.6 is a typical ref-

lines in rectilinear scanning. Figure 2.6 is a typical reference grating imposed on the interferogram (rectilinear scanning).

ACOUSTIC FREQUENCY: 48.2MHz
SCAN RATE: 1.2mm/sec
PHASE SHIFTER PERIOD: $T_p=40\text{m sec}$
FRINGE SPACING: 1.6mm
REFERENCE ANGLE: $\alpha_x=41^\circ$

Figure 2.6. Acoustical Interferogram of a Flat Surface Parallel to the Scanning Aperture at 48.2 Mhz.

3.0 EXPERIMENTAL RESULTS WITH LIGHT WATER REACTOR WELD ASSEMBLIES

The acoustic experiments consisted of imaging various weld surface samples using focused interferometry technique. The fringe structure is determined by Equation 14 with $d_x = \infty$ and $K = 1$. The distance between fringes represents an elevation change of $\lambda s/2$ (i.e., 0.075 mm at 20 MHz). The sample weld surface interferograms illustrate the extremely high depth resolution capabilities of this technique. A low F-number focused transducer was used to provide excellent lateral resolution across the weld structure.

3.1 INTERFEROGRAMS OF SANDIA SAMPLE WELD SURFACE STRUCTURES

Figures 3.1a and 3.1b are the weld surface geometries of two selected samples (SPL-1 and SPL-2) and the outlined inspection areas. The welds are approximately 6 mm in width and less than 1 mm in height above the plate surfaces. The two plates are approximately 3 mm thick.

Figure 3.1c is the SPL-1 focused hologram or interferogram of the outlined area. The vertical elevation or weld surface deviation between fringes is 0.075 mm. The fringes across the weld surface illustrate the unique contour pattern or signature produced by the welding process. The flat connecting plates also contain a series of parallel fringes of different density. This simply indicates the two plates are tilted at different angles with respect to the scan plane.

Figure 3.1d is the interferogram of sample SPL-2 and the weld signature again appears extremely complicated with respect to vertical deviations, etc. The left side plate is tilted in a direction perpendicular to the weld centerline as indicated by the fringe structure. The vertical elevation between the weld and the outer inspection area is 0.525 mm

Figure 3.1. Selected Sandia Weld Samples and Their Associated Interferograms Constructed at 20 MHz in H_2O : (a) Sandia Weld Sample SPL-1; (b) Sandia Weld Sample 2; (c) Interferogram of SPL-1; and (d) Interferogram of Sample 2. Elevation between fringes is 0.075 mm.

(i.e., 8 fringes). The right plate is essentially parallel to the scanning plane as indicated by the fringe density.

Figure 3.2 shows the Sandia weld samples (#3 & #4) and their associated interferograms of the outlined inspection areas. The acoustic interferograms illustrate the various tilt angles of the connecting plots and the weld surface deviations. Each interferogram represents a unique weld surface correlation pattern that uniquely identifies the 64,000 sample point structure. Thus, each sample point is related to a specified phase value.

The typical safeguard application involves only two or three sample points with their associated phase values. The phase sensitivity at 20 MHz in water is approximately 0.1 μ meters/degree. Using two or three sample points for weld identification provides a unique high resolution phase detection system. Weld falsification will be virtually impossible using this system.

3.2 INTERFEROGRAMS OF REACTOR (PWR) TUBE PLATE

Figure 3.3 shows the PWR tube plate assembly, interferogram and C-scan of the local area around holes 3, 4 and 5. the construction frequency was 20 MHz with vertical elevation of 0.075 mm between fringes. Inspection of the smooth tube plate requires a higher frequency to adequately reveal small deviations around the circular tube holes. the fringe density near the holes 3, 4 and 5 is insufficient for characterization. The overall fringe density appears quite uniform and indicates the structure is tiled with respect to the scanning plane. The area around holes 3 and 4 is a typical C-scan illustrating amplitude information for comparison with the interferogram.

Figure 3.2. Selected Sandia Weld Samples and Their Associated Interferograms Constructed at 20 MHz in H_2O :
 (a) Sandia Weld Sample #3; (b) Sandia Weld Sample #4; (c) Interferogram of Sample #3; and (d) Interferogram of Sample #4.

Figure 3.3. PWR Reactor Tube Plate, Interferogram and C-Scan:
(a) Tube Plate; (b) Tube Plate Inspection Area;
and (c) Interferogram and C-Scan

3.3 TWO POINT INTERFEROGRAMS OF NUCLEAR SAFEGUARD WELD ASSEMBLY

Figure 3.4a illustrates the dual transducer two point interferogram construction geometry. The nuclear safeguard weld assembly is located directly below the transducer jig with its water coupling reservoir. Each transducer samples a unique point on the weld surface. The point size or area is determined by the transducer F-number and illumination frequency. The transducers supplied by Sandia operating at 13.5 MHz illuminated a 0.2mm^2 circular area. The depth deviation sensitivity (Δd) at 13.5 MHz in water is $0.16 \mu\text{meters/degree}$.

Figure 3.4. (a) Two Point Interferogram Construction Geometry and (b) Holographic Signal Processing of Weld Crown Data.

Figure 3.4b is the simplified block diagram of the signal processing modification to the basic system described in Section 2.0. The object and reference transducers (#1 and #2) interrogate two points on the weld surfaces. The return signals are multiplied and time averaged to produce the holographic signal

$$S_{1,2}(x,y) = A_1(x_1,y_1)A_2(x_2,y_2) \cos [\phi_1(x_1,y_1)-\phi_2(x_2,y_2)] \quad (20)$$

The amplitudes $A_1(x_1,y_1)$ and $A_2(x_2,y_2)$ are considered to be constant in the analysis. In practice we use high gain amplification and clip the resulting signals or automatic gain control to eliminate amplitude variations. The zero-crossing information is used to extract the phase information between the two signals. The output signals can then be expressed in the following form

$$S_{1,2}(x,y) = K \cos \frac{4\pi}{\lambda} (Z_1 - Z_2) \quad (21)$$

where $Z_1 - Z_2$ is the vertical distance between the two points.

The phase between the two sample points is read directly from the digital phase meter as shown in Figure 3.4b.

Two-point interferograms were constructed using the nuclear safeguard assembly and four preselected Sandia transducers (K-8, K-9, K-10 and K-11). Twenty discrete measurements were obtained with transducers K-9, K-10 and K-11 using K-8 as the reference. The experimental data are shown in Figure 3.5 and illustrate the phase variations between measurements and transducers. The weld was simulated with a flat sample for evaluation of the safeguard weld assembly position accuracy. The assembly was repositioned over the

K-8, K-9

I	X(I)	X(I + 1)
1	89.5	92.5
3	91.0	90.0
5	91.0	89.0
7	86.5	89.5
9	85.0	86.0
11	91.0	91.0
13	91.0	93.0
15	65.0	91.5
17	90.0	86.0
19	91.0	87.5

K-8, K-10

I	X(I)	X(I + 1)
1	76.0	60.0
3	86.0	65.0
5	87.0	85.0
7	88.0	84.0
9	84.0	87.0
11	70.0	67.0
13	75.0	82.0
15	85.0	87.0
17	86.0	86.0
19	87.0	85.0

K-8, K-11

I	X(I)	X(I + 1)
1	87.0	87.0
3	90.0	90.0
5	89.0	87.0
7	87.0	90.0
9	86.0	50.0
11	86.0	78.0
13	88.0	90.0
15	85.0	90.0
17	90.0	82.0
19	89.0	87.0

Figure 3.5. Transducers Experimental Phase Data on Light Water Weld Crown Reactor Assemblies.

sample and liquid couplant supplied for each measurement. Section 4.0 describes the statistical analysis used to define the 99.99% confidence interval (C.I.) for each data set. The 99.99% C.I. for the safeguard assembly was approximately 3 μ meters illustrating the measurement resolution of the device.

4.0 STATISTICAL ANALYSIS OF THE TWO POINT INTERFEROGRAMS

We shall assume in this analysis that the parent measurement populations are normal; otherwise the t distribution that we use will be only approximately valid.

4.1 DISCUSSION OF THE CONFIDENCE INTERVAL

In estimating a population mean μ with a sample mean $\bar{X}$, we generally have no information on the population standard deviation σ ; hence, we use the estimated S, the sample deviation. Thus, the 99.99% confidence interval can be expressed as

$$\mu = \bar{X} \pm Z_{5 \times 10^{-5}} \frac{S}{\sqrt{n}} \quad (22)$$

$$\text{where } S^2 = \frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2 \quad \text{and} \quad \bar{X} = \frac{1}{n} \sum_{i=1}^n X_i.$$

Provided the sample is large (i.e., 25-50 measurements), this will be a reasonably accurate approximation. But with a smaller sample size, this expression with $Z_{5 \times 10^{-3}}$ (normal variable) introduces an appreciable source error. If we wish to be 99.99% confident, the interval estimate must be broadened.

By analogy, we introduce Student's "t" variable

$$t = \frac{\bar{X} - \mu}{S/\sqrt{n}} \quad (23)$$

The similarity between Z and t is immediately evident. The only difference is that Z involves σ , which is usually unknown; but t involves S, which can be calculated from the sample.

As expected, the t distribution is more spread out than the normal (see Figure 4.1) since the use of S rather than

Figure 4.1. The Standard Normal and t Distributions Compared.

σ introduces a degree of uncertainty. Moreover, while there is one standard normal distribution, there is a whole family of t distributions. With a small sample size, this distribution is considerably more spread out than the normal; but as the sample size increases, the t distribution approaches the normal, and for samples of 50 or more, the normal becomes very accurate approximation.

The t distribution is not tabled according to the sample size n , but according to the divisor in S^2 , which is called "degrees of freedom."

The 99.99% confidence interval for the population measurement mean is given by the following expression

$$\mu = \bar{X} \pm t_{5 \times 10^{-5}} \frac{S}{\sqrt{n}} \quad (24)$$

where $t_{5 \times 10^{-5}}$ is the critical t value leaving 0.005% of the probability in the upper tail, with $n-1$ degrees of freedom.

4.2 PRACTICAL RULES FOR USE OF THE "t" DISTRIBUTION

The important practical question is: When do you use the t distribution and when do use the normal? If σ is known, the normal distribution is appropriate; if σ is unknown, then the t distribution is appropriate, regardless of sample size. However, if the sample size is large, the normal is an accurate enough approximation of the t. So in practice, the t distribution is used only for small samples where σ is unknown.

Figure 4.2 illustrates the weld crown statistical model where the population is assumed normal with population parameters μ and σ^2 . These parameters are constants, but generally unknown. By contrast, the sample mean $\bar{X}$ and sample

WELD CROWN STATICAL MODEL

- $\mu = \bar{X} \pm \epsilon$ (SAMPLING ERROR)

$$\text{WHERE } \bar{X} = 1/n \sum_{i=1}^n x_i$$

- CRUCIAL QUESTION IS: HOW WIDE MUST THE PHASE INTERVAL BE TO CAPTURE THE TRUE MEAN PHASE 95 OF A 100 MEASUREMENT?

Figure 4.2. Weld Crown Statistical Model.

variance S^2 are random variables, varying from sample to sample. A random variable such as $\bar{X}$ or S^2 is calculated from the measurements in the sample (i.e., subset).

We wish to estimate the average phase or deviation of all measurements with a nuclear safeguard assembly using a reference flat weld. The population (i.e., all measurements with the assembly) mean (μ) is a fixed, but unknown parameter. We estimate it by taking a sample of 20 discrete measurements. This is our best single estimate of μ , but as we know from sampling theory, that unless we are extremely lucky this estimate $\bar{X}$ will be either a little high or a little low (see Figure 4.3). If we want to be reasonably confident that our inference is correct, we cannot claim that μ is precisely equal to our observed $\bar{X}$; instead we must make a confidence interval (see Equation 4).

Figure 4.3. Construction of Twenty Interval Estimates: Typical Results.

Figure 4.3 illustrates the typical results for 95% confidence interval using 20 interval estimates with the true mean (μ) unknown to the statistician. We observe that 19 of these 20 estimates bracket the constant μ . We only miss bracketing μ one time (i.e., 95% C.I.).

In practice, we usually take one sample not 20 and once this interval estimate is made, it is either right or wrong; this interval brackets μ or it does not. The important point to recognize is that we are using a method with a known probability of success.

4.3 STATISTICS USING TRANSDUCERS K-8 AND K-9

The major objective of the experiments is to evaluate the measurement repeatability (i.e., confidence interval) with assembly using a holographic interferometric signal processing technique.

Figure 4.4 is the 20 measurement sample and basic statistics using transducers K-8 and K-9 in the nuclear safeguard assembly with the simulated flat weld. Each measurement was obtained by removal and replacement of the flat weld into the assembly. This procedure simulates the typical safeguard inspection scenario.

Phase measurements are shown in Table 1 (Figure 4.4) and translated into deviation measurements.

The mean phase ($\bar{X}$) is calculated to be 85.4 degrees and the coefficient of variation 10.38%. The standard deviation (S) is 8.9 degrees).

The 99.99% confidence interval is 70° to 95° (i.e., width of 15°). Converting to vertical deviation, the interval is $12\mu\text{m}$ to $15\mu\text{m}$ (i.e., $3\mu\text{m}$ width). This means we will capture the true mean μ 9,999 times out of 10,000.

**TRANSDUCERS K-8;K-9
FLAT SAMPLE
2-PROBE DIFFERENTIAL PHASE
SANDIA
20 MEASUREMENTS
STUDENT T DISTRIBUTION**

I	X(I)	X(I+1)
1	87.0	87.0
3	90.0	90.0
5	89.0	87.0
7	87.0	90.0
9	86.0	50.0
11	86.0	78.0
13	88.0	90.0
15	85.0	90.0
17	90.0	82.0
19	89.0	87.0

BASIC STATISTICS

N = 20
 STD ERROR OF THE MEAN = 1.98
 MEAN = 85.4000
 COEF OF VARIATION = 10.38%
 VARIANCE = 78.5684
 STANDARD DEVIATION = 8.8639
 SKEWNESS = -3.4187
 KURTOSIS = 14.1501
 99.00% C.I. FOR MEAN:
 (79.7285, 91.0715)
 ONE-TAIL t (19, 0.005) = 2.86137557851

99.99% C.I. FOR MEAN: 76° TO 95°
 $\Delta\phi = 19^\circ$
 471 μ INCH TO 589 μ INCH
 $\Delta d = 118 \mu$ INCHES

Figure 4.4. Statistics Using Transducers K-8 and K-9.

4.4 STATISTICS USING TRANSDUCERS K-8 AND K-10

Figure 4.5 is the 20 phase measurement sample and basic statistics using transducers K-8 and K-10 with the same nuclear safeguard assembly. Transducer K-8 is used as the reference with all three transducers. The measurement procedure is the same as described for the K-8, K-9 sample.

The calculated mean is 81.6° and the coefficient of variation 9.9%. The standard deviation is 8.1° .

The 99.99% confidence phase interval is 74° to 90° (i.e., width of 16°). The deviation interval is $11.7\mu\text{m}$ to $14.2\mu\text{m}$ (i.e., width of $2.5\mu\text{m}$).

TRANSDUCERS K-8;K-10
 FLAT SAMPLE
 2-PROBE DIFFERENTIAL PHASE
 SANDIA
 20 MEASUREMENTS
 STUDENT T DISTRIBUTION

I	X(I)	X(I + 1)
1	76.0	60.0
3	86.0	65.0
5	87.0	85.0
7	88.0	84.0
9	84.0	87.0
11	70.0	67.0
13	75.0	82.0
15	85.0	87.0
17	86.0	86.0
19	87.0	85.0

BASIC STATISTICS

N = 20
 STD ERROR OF THE MEAN = 1.81
 MEAN = 81.6000
 COEF OF VARIATION = 9.91%
 VARIANCE = 65.4105
 STANDARD DEVIATION = 8.0877
 SKEWNESS = -1.5541
 KURTOSIS = 4.1710
 99.00% C.I. FOR MEAN:
 (76.4252, 86.7748)
 ONE-TAIL t (19, 0.005) = 2.86137557851

99.99% C.I. FOR MEAN: 74° TO 90°
 $\Delta\phi = 16^\circ$
 459 μ INCH TO 558 μ INCH
 $\Delta d = 99 \mu$ INCHES

Figure 4.5. Statistics Using Transducers K-8 and K-10.

The confidence interval has remained essentially constant using a different transducer indicating the technique does not require elaborate transducer matching.

4.5 STATISTICS USING TRANSDUCERS K-8 AND K-11

Figure 4.6 is the 20 phase measurement sample and basic statistics using transducers K-8 and K-11. The mean phase is 88.4° and the coefficient of variation 6.73%. The standard deviation is 5.94° .

The 99.99% confidence interval is 82° to 95° (i.e., width of 13°). The deviation interval is $13\mu\text{m}$ to $15\mu\text{m}$ (i.e., width of $2\mu\text{m}$). The confidence interval again is approximately the same as with transducer K-8 and K-10.

TRANSDUCERS K-8;K-11
 FLAT SAMPLE
 2-PROBE DIFFERENTIAL PHASE
 SANDIA
 20 MEASUREMENTS
 STUDENT T DISTRIBUTION

I	X(I)	X(I + 1)
1	89.5	92.5
3	91.0	90.0
5	91.0	89.0
7	86.5	89.5
9	85.0	86.0
11	91.0	91.0
13	91.0	93.0
15	65.0	91.5
17	90.0	86.0
19	91.0	87.5

BASIC STATISTICS

N = 20
 STD ERROR OF THE MEAN = 1.33
 MEAN = 88.3500
 COEF OF VARIATION = 6.73%
 VARIANCE = 35.3184
 STANDARD DEVIATION = 5.9429
 SKEWNESS = -3.2092
 KURTOSIS = 13.2640
 99.00% C.I. FOR MEAN:
 (84.5475, 92.1525)
 ONE-TAIL t (19, 0.005) = 2.86137557851

99.99% C.I. FOR MEAN: 82° TO 95°
 $\Delta\phi = 13^\circ$
 508 μ INCH TO 589 μ INCH
 $\Delta d = 81 \mu$ INCHES

Figure 4.6. Statistics Using Transducers K-8 and K-11.

5.0 APPENDIX

5.1 ELECTRICAL CHARACTERISTIC EVALUATION TECHNIQUE FOR ULTRASONIC SEARCH UNITS

This technique describes measurement procedures for evaluating ultrasonic search units used with ultrasonic systems and provides means for obtaining performance data which describes the electrical responses of the search unit and associated coaxial cable as a separate component or subsystem of the ultrasonic inspection system.

The procedures are designed to evaluate single element piezoelectric search units designed for immersion, contact straight or angle beam ultrasonic inspections, and are applicable to search units within the frequency range of 0.4 MHz to 30 MHz.

The technique is not intended to define performance limits but to provide standardized procedures for making measurements from which limits may be established.

The measurement data obtained may be employed to selectively specify, evaluate or provide performance criteria for procurement, quality assurance or service evaluation of operating characteristics of ultrasonic search units.

Parameters to be measured: electrical characteristics of ultrasonic search units can be described from data obtained by measuring the following parameters:

- A. Acoustic Frequency Response (Frequency Spectrum)
- B. Bandwidth (Percentage)
- C. Relative Pulse Echo Sensitivity
- D. Time Domain Response
- E. Electrical Impedance.

Acoustic Frequency Response is a measure of the pulse echo amplitude response of the search unit as a function of

frequency. This measurement provides performance data relating to the intrinsic acoustic parameters of the unit. There are two procedures established for generating the acoustic frequency response; namely, sinusoidal burst and shock excitation. The frequency response is the pulse echo (or pulse reflection) response obtained from a specific target.

Bandwidth (Percentage) is defined as the bandwidth of the pulse echo response from a target measured at a value of 6 dB (50%) below the peak of the frequency response (fp). Bandwidth is expressed as a percentage and is calculated from the following formula:

$$BW = \frac{f_u - f_l}{f_c} \times 100$$

where f_u and f_l are the upper and lower values selected at 6 dB below f_p and f_c is the center of the upper and lower bandwidth values. As the peak frequency may not be centered between f_l and f_u , a value for the center frequency, f_c , is calculated. The formula for this calculation is:

$$f_c = \frac{f_l + f_u}{2}$$

Relative Pulse Echo Sensitivity (S_{rel}). Values for applied and received power, from which true insertion losses might be determined, are not obtainable with the technique described. Consequently, a relative measure is used to establish a figure of merit or sensitivity of search units. Relative pulse echo sensitivity is obtained by measuring the applied voltage and the received echo voltage and calculating the value using the following formula:

$$S_{rel} = -20 \log \frac{E_e}{E_a}$$

where E_e = echo voltage and E_a = applied voltage. Section 5.6 describes means for measuring relative pulse echo sensitivity.

Time Domain Response. Time domain responses provide means for defining acoustic signal-to-noise and depth resolution capability. The search units may be shock excited with square wave or single cycle sine wave or spike pulse. The time domain signals are recorded from specific targets which are chosen for the type of search unit being evaluated (e.g., immersion, contact, straight or angle beam).

Electrical Impedance. The magnitude of the electrical impedance of the search unit is obtained by using the sinusoidal burst technique and measuring the applied voltage and the applied current and calculating the value using the formula:

$$Z = \frac{E_a}{I_a}$$

where E_a is the applied voltage and I_a is the applied current.

An alternate means for measuring the electrical impedance is with a vector impedance meter or impedance bridge. With these techniques, all measurements must be made in the frequency range of the search unit and under a condition where no standing acoustic waves are present. Standing waves in the test tank or test block can give erroneous results. The complex impedance obtained with the impedance meter provides the magnitude and phase angle of the search unit impedance at specific operating frequencies. The value for magnitude of electrical impedance is especially important in comparing the electrical driving criteria of different search units and in establishing the minimum driving criteria of

different search units and in establishing the minimum driving characteristics of pulser used in conjunction with specific search units. Different search units may have values as $Z = 10$ ohms, 50 ohms, 100 ohms, etc., depending on frequency, diameter and design and still be effectively used, provided the pulser is compatible with that load.

NOTE: All impedance measurements must be performed with the search unit and coaxial cable of an appropriate length.

5.2 ACOUSTIC FREQUENCY RESPONSE MEASUREMENT

The acoustic frequency response is a measure of the pulse echo response from a given target as a function of frequency. This response is used as the basis for establishing other operating parameters of the search unit including bandwidth and sensitivity. Typical response curves are shown in Figure 5-1. The two curves are used to describe conditions in which a search unit has a response that is symmetrical about a center frequency, and a condition in which the peak response (f_p) and the center frequency (f_c) are not identical. Means for measurement of bandwidth are given in Section 5.3. The response may be recorded by camera from the oscilloscope picture or by hard copy digital recorder instrument. The importance is to obtain an accurate recording of the response curve from which a measure of performance may be established.

Two means are described for obtaining the acoustic frequency response of ultrasonic search units as separate components of the ultrasonic system. They are: (a) sinusoidal burst, and (b) shock excitation. Within controlled limits the responses obtained by each procedure provide like results, however, reproducibility is dependent on factors such as generator driving impedance, search unit impedance, pulse

Figure 5-1. Acoustic Frequency Response.

shape and measurement systems. Care should be exercised in selection of the measurement system and system components.

Sinusoidal Burst Technique: The sinusoidal burst technique is shown in Figure 5-2 and provides a simple but basic means for obtaining acoustic frequency response. The principle is to apply a sinusoidal burst of a known voltage and frequency to the search unit and determine its response at that frequency. By varying the frequency across the operating range of the search unit and recording the response at each frequency, a plot of the acoustic frequency response is obtained. The procedure may be performed manually by varying the frequency of the function generator or automatically by configuring the function generator to sweep through a preset range and recording the swept frequency response.

Figure 5-3 is a block diagram for a system for automatically recording acoustic frequency response. The function generator (typically Tektronix, Wavetek, HP) is adjusted to produce sinusoidal bursts at the various frequencies anticipated from the operating frequency of the search unit (e.g., 1-5 for 2.5 MHz, 1-10 for 5 MHz, etc.). The pulse width generator is adjusted to provide a minimum of 10 cycles at the lowest measurement frequency. The sinusoidal burst is applied to the search unit and the pulse echo response from a given target is recorded for a specific frequency. The frequency of the bursts is swept through the frequency range and the pulse echo voltage response is recorded at each frequency. The returning echo is intensified only in center one-half of the echo response to insure that the incoherent ends do not influence the measurements. Both the amplitude of the applied voltage and the amplitude of the echo response are plotted as a function of frequency. These plots are used to determine search unit sensitivity.

Figure 5-2. Tone Burst Sweep Frequency Transducer Electrical Characterization.

Figure 5-3. Block Diagram of Tone Burst, Swept-Frequency Measurement System.

Shock Excitation Technique: The shock excitation technique for obtaining acoustic frequency response follows the principle that a shock pulse applied to the search unit produces a broad spectrum of energies to the unit and that the echo from a given target produces the frequency distribution that is characteristic of that search unit. Figure 5-4 describes the test setup for employing the shock excitation procedure. The system consists of a shock excitation generator (square wave, or spike pulse), preamplifier, echo gate that can be adjusted to capture the echo, search unit, oscilloscope and a spectrum analyzer. The excitation pulse is applied to the search unit and an echo obtained from a specific target. This echo is selectively gated to eliminate extraneous acoustic energies. The gated echo is fed to the oscilloscope and to the spectrum analyzer. The record from the spectrum analyzer describes the acoustic frequency response of the search unit. Both square wave and spike excitation pulses may be used.

Square Wave Pulser: The square wave pulse from a low impedance generator provides a highly reproducible response. The procedure is to adjust the duration of the square wave to the half period of the center frequency of the search unit and use this pulse to excite the search unit.

The feature of low impedance establishes a constant driving spectrum to the majority of search units covered under this recommended practice. As the impedance of search units used in industrial practice may range from a few ohms (e.g., 10) to several hundred ohms (e.g., 500), a low impedance generating source permits maximum transfer of power to the load (search unit).

Spike Pulse Generator: Fast rise time shock excitation pulsers produce a broad spectrum of energies. It is common

Figure 5-4. Functional Block Diagram for Employing Shock Excitation Procedure.

practice to use a fast rise time (e.g., 5-10 nanosecond) pulse circuit with a variable "damping" circuit to control the recovery time of the pulse. Unfortunately, these types of pulsers may have both a variable spectrum and a variable output impedance, thus making it difficult to determine the actual power density of the spectrum applied to the search unit. The search unit impedance may influence the actual spectrum delivered by the pulse generator which in turn may produce a measurement error or discrepancy.

Care must be exercised when employing either square wave or spikes to insure that the applied spectrum covers the operational bandwidth of the search unit. The variable length control of the square wave and the damping control of the spike pulse generators must be properly adjusted in order to achieve both reproducible and meaningful measurements. Low impedance source generators are recommended.

The sinusoidal burst and shock excitation procedures are applicable to all types of search units. The procedures for evaluating the various styles are outlined below.

1. Immersion. Figure 5-5 shows the test setup for obtaining acoustic frequency response for immersion units.

a. Immersion Flat. Flat or nonfocused search units are adjusted so that the distance from the face of the search unit to the target (X_0) is approximately two inches (50 mm). A flat and smooth glass block of not smaller than three inches by three inches (75 mm x 75 mm) by one inch (25 mm) thick can be used as the target. A manipulation should be used for alignment to obtain a maximum amplitude response from the target. The frequency response of flat search units is independent of distance. The two inch (50 mm) distance is chosen as a compromise to accommodate a variety of frequencies and sizes of search units.

TO TEST SYSTEM

Figure 5-5. Test Setup for Establishing Acoustic Frequency Response for Immersion Search Units.

b. Focused Search Units. Acoustic frequency response for focused search units follow the same procedure as described for flat search units except that the distance X_0 is adjusted to the focal length of the search unit. This exception is made to provide consistency in measurement.

2. Contact Straight and Angle Beam Search Units. Measurements for contact search units may be made with the unit coupled to the test part. Couplant shall be glycerin or similar (but specified) fluid.

a. Straight Beam. Figure 5-6 shows the test setup for contact straight beam search units. A one and one-half inch (38 mm) flat rolled aluminum block is used for the frequency response measurements. The back surface of the block is used as the target and the echo response from this target is recorded. Thicker blocks may be used for lower frequency and/or larger diameter search units.

Figure 5-6. Contact Straight Beam Test.

b. Angle Beam Search Units. Figure 5-7 shows the test setup for determining acoustic frequency response for

Figure 5-7. Angle Beam Test.

angle beam search units. The peak echo response from a corner reflection of a flat straight aluminum test block shall be used for this measurement. The search unit shall be adjusted to obtain the maximum amplitude echo from the corner reflection and the frequency response shall be recorded. Suggested block thickness for various angles is listed in Table I.

TABLE I

45° Search Unit - 1.0 inch (25 mm) thick
 60° Search Unit - 0.75 inch (19 mm) thick
 70° Search Unit - 0.5 inch (13 mm) thick

Thicker test blocks may be used for lower frequency, larger diameter search units. Specific block thickness should be recorded on the test sheet.

Alternate Means for Measuring Frequency Response of Angle Beam Search Units: Frequency response for angle beam search units with integral or attached plastic refraction blocks may be obtained using the identical procedures used for flat immersion search units. A fixture designed to hold the search unit is placed so that the sound beam can be manipulated to obtain maximum response from the target. The distance X_0 is fixed at 2.0 inches (50 mm) for all angles of search units. The frequency response is identical to that obtained using the contact angle beam block. The amplitude of the response is somewhat higher (e.g., 4-6 dB), thus the written procedure used should clearly identify the approach used.

Caution: The immersion procedure is not valid for straight beam contact search units which incorporate a hard wear face surface. This style of search unit is designed to couple into a solid material.

Special Notice for Acoustic Frequency Response Measurement: When adjusted to optimum settings, the results from the sinusoidal burst and the two pulse excitation procedures will produce identical results. However, because of the multiple variables associated with electronic components and adjustments, some differences may result. It is important that the quality control records reflect the specific procedure and test configuration employed so that variations resulting from manufacture, use or aging can be correctly assessed.

5.3 BANDWIDTH MEASUREMENTS

Bandwidth is defined as the spectrum contained within 6 dB of the peak response of the acoustic frequency response curve. Typical frequency curve is shown in Figure 5-8. The peak amplitude response is chosen as the reference mark even

Figure 5-8. Determination of Operational Bandwidth.

though it may not be at the anticipated frequency. This reference is identified as the frequency f_p and all bandwidth measurements are related to this peak.

Values for the lower (f_l) and the upper (f_u) frequencies are determined as the frequencies at the 6 dB (50%) amplitude response above and below the peak frequency. In the Figure 5-8 example, BW is established as follows:

$$BW = \frac{f_u - f_l}{f_c} \times 100\%$$

$$f_u = \text{upper frequency (6 dB level)} = 6.7 \text{ MHz}$$

$$f_l = \text{lower frequency (6 dB level)} = 2.9 \text{ MHz}$$

$$f_c = \frac{f_l + f_u}{2} + \frac{2.9 + 6.7}{2} = 4.8 \text{ MHz}$$

$$BW = \frac{6.7 - 2.9}{4.8} \times 100 = 79\%$$

5.4 RELATIVE PULSE ECHO SENSITIVITY MEASUREMENT

Relative pulse echo sensitivity (S_{rel}) is defined as follows:

$$S_{rel} = -20 \log \frac{E_e}{E_a}$$

where: E_e is the voltage response of the echo from the reflector and E_a is the voltage applied to the search unit at the bandwidth center frequency (f_c).

Sinusoidal Burst Procedure. Figure 5-9 describes the procedure for establishing S_{rel} from the test results obtained with the sinusoidal burst procedure. The value for S_{rel} is established at f_c . In the example shown:

$$E_e = 700 \text{ Mv}$$

$$E_a = 6.5 \text{ V}$$

$$S_{rel} = -20 \log \frac{0.7}{6.5} = -19.3 \text{ dB}$$

Shock Pulse Procedure. Figure 5-10 shows the waveforms for obtaining a value for S_{rel} using the shock pulse procedure. The shock excitation generator, search unit, specific target and a sensitive oscilloscope (shown in Figure 5-4) are required for obtaining a value of S_{rel} . The driving waveform response is measured and used for the value E_a . The amplitude value of the echo response is used for E_e . The calculation for S_{rel} follows the same formula as defined above.

Note: No interposing preamplifier is to be used to amplify the echo signals.

Figure 5-9. Sinusoidal Burst Technique (1/2 of waveform displayed).

Figure 5-10. Shock Excitation Technique.

The range of values determined for relative pulse echo sensitivity can vary from -5 dB to -60 dB or more. The value is dependent on many variables such as search unit design, frequency and style. The S_{rel} value is primarily used to establish an initial value for each search unit so that it may be monitored as a function of use and time and so that it may be compared to like units obtained from one or more vendors.

The values for S_{rel} from the sinusoidal burst procedure may differ from those obtained from the shock excitation procedure. In the shock excitation procedure, only the values of the applied pulse voltage and the echo voltage are available. As the frequency distributions of the applied waveform may fall outside the actual operational bandwidth of the search unit and as the echo response is measured without regard to frequency, the values obtained for certain types of search units (particularly broadband) will be dependent on the procedure chosen.

5.5 TIME DOMAIN RESPONSE MEASUREMENTS

The time domain response is the measurement of the acoustic signal-to-noise ratio and the range resolution capability of a search unit. Figure 5-11 shows the experimental setup for this measurement. A shock excitation generator (square wave, spike or single cycle of a sine wave) is used to excite the search unit. The pulse is adjusted to $1/2\lambda$ and the echo response from the appropriate target is recorded (e.g., flat glass plate for immersion back echo for straight beam or corner reflector for the angle beam units). The echo recorded shall provide an evaluation of signal-to-noise or time response to the 40 dB level. If required, an intermediate preamplifier may be used to amplify the signal.

Figure 5-11. Recording of Time Domain Responses.

Caution: All measurements must be made with the cable attached to the search unit as would occur in practice.

5.6 ELECTRICAL IMPEDANCE MEASUREMENTS

The magnitude of the electrical impedance of a search unit and the coaxial cable as a transmitter may be made by using the sinusoidal burst technique and measuring the voltage and current applied to the search unit. The absolute value of electrical impedance may be obtained using a vector impedance bridge.

Electrical Impedance (Sinusoidal Burst Technique). Figures 5-2 and 5-3 describe the setup for measuring ultrasonic frequency response of a search unit. This same setup may be used for measuring the magnitude of the impedance of a search unit. The initial measurements provide values for applied voltage and bandwidth center frequency. By substituting a current probe for the voltage probe, a measurement of applied current as a function of frequency may be obtained. The value for the magnitude of the electrical impedance of the search unit is made at bandwidth frequency (f_c).

$$Z = \frac{E_a}{I_a}$$

where E_a is applied voltage and I_a is applied current.

Figure 5-12 shows typical results from which the impedance measurement is determined.

Figure 5-12. Typical Voltage and Current Recordings for Determining Impedance.

Electrical Impedance (Vector Impedance Bridge). Please refer to the instruction manuals for commercial impedance bridge measurement instruments for procedures necessary for obtaining curves from which absolute values for complex impedance may be determined.

All impedance measurements must be made under conditions which simulate operational conditions. Immersion units must be measured in water and straight beam contact units must be made with the search unit coupled to a test block. Angle beam units are designed to load into plastic; therefore, impedance measurements may be made in water or on the test block.

Electrical Impedance (Shock Excitation). Results from measurements of the voltage and current of applied shock excitation pulses are not effective in determining electrical impedance and are not recommended.

5.7 EVALUATION EXAMPLES

Figure 5-13 shows a typical 5.0 MHz transducer with simple parallel inductor tuning.

Figure 5-14 is Sandia transducer No. K-10 without parallel inductor and Figure 5-15 is No. K-10 with parallel inductor. Note the change in bandwidth and electrical impedance.

FREQUENCY RANGE 1 - 10 mHz

FREQUENCY, mHz

$f_p = 5.7$
 $f_l @ -6 \text{ dB} = 3.1$
 $f_u @ -6 \text{ dB} = 7.0$
 $f_c = 5.05$
 $\text{B.W.} @ -6 \text{ dB} = 77\%$
 $S_{\text{rel}} = -12.4 \text{ dB}$
 $Z_l @ f_c = 45.5 \Omega$
 $\text{D.C.R.} = 0.7 \Omega$

FREQUENCY, mHz

Figure 5-13. Typical Waveforms for a PZT 5.0 MHz Immersion Search Unit with a Parallel Inductor.

WITHOUT PARALLEL INDUCTOR

$f_p = 14.0$
 $f_l @ -6 \text{ dB} = 10.0$
 $f_u @ -6 \text{ dB} = 16.0$
 $f_c = 13.0$
 $B.W. = 46\%$
 $S_{rel} = -47 \text{ dB}$
 $Z = 23\Omega$

Figure 5-14. Search Unit K-10 without Parallel Inductor.

WITH PARALLEL INDUCTOR

$f_p = 14.4$
 $f_l @ -6 \text{ dB} = 12.4$
 $f_u @ -6 \text{ dB} = 16.4$
 $f_c = 14.4$
 $\text{B.W.} = 28\%$
 $S_{\text{rel}} = -52 \text{ dB}$
 $Z = 187 \Omega$

Figure 5-15. Search Unit K-10 with Parallel Inductor.

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9088 S. Cass Avenue
Argonne, IL 60439
- 10 Dr. James McKenzie
Sandia National Laboratories
International Safeguards Division 1754
Albuquerque, NM 87185
- 27 DOE Technical Information Center

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R. P. Gribble (15)
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