World Federation
of
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Centers

2007
ULTRASONIC BENCHMARKS

Problems for 2007

This year we have two components of the ultrasonic benchmark study. The first component is a repeat of some of the previous studies we performed on the pulse-echo responses of side-drilled holes. In those studies we saw larger than expected differences, particularly in the shear wave responses of the side-drilled hole. From carefully examining those results, we now believe the water path length was specified incorrectly. In later experiments, this water path distance was corrected with time-of-flight measurements. We would like to now compare these corrected measurements with model predictions.

The second component of the benchmark study is a study of the effects of surface curvature on the ultrasonic response of flat-bottom holes. The objective here is to compare various model-based predictions on how the curvature of an interface changes the measured flat-bottom hole response and compare model predictions to some experimental results

2007 Benchmark Problems

Side-drilled hole (SDH) study

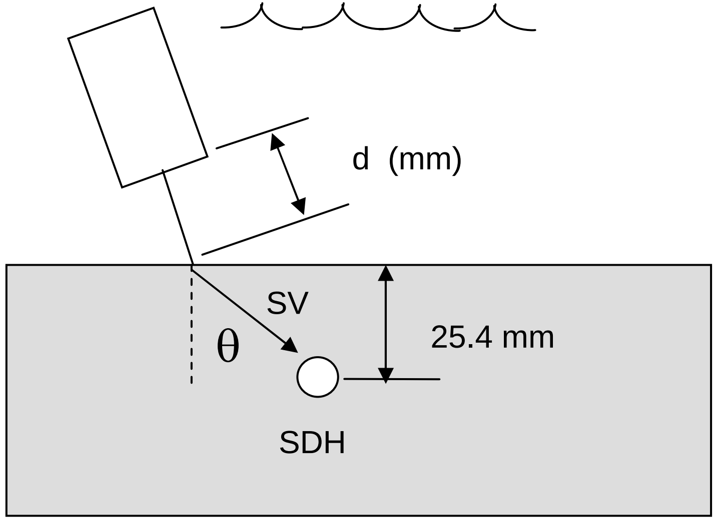
The samples used in this study are the same two aluminum side-drilled hole (SDH) blocks used in the 2004 study. One contains a 1 mm diameter SDH and the other a 4 mm diameter SDH, both at the 25.4 mm depth shown in Figs.1 and 3 (the depth is measured to the center of the hole). The two transducers used (one planar and one spherically focused) were also the same transducers used in the 2004 study. The planar transducer was a 5 MHz, 12.7 mm diameter transducer and the focused transducer was a 5 MHz, 12.46 mm diameter with a geometrical focal length of 172.9 mm. These focused probe parameters were "effective" values as measured experimentally to give a best fit diameter and geometrical focal length that can be reliably used in beam models to reproduce the transducer wave field.

For both blocks the transducer was oriented to produce refracted SV waves at two refracted angles ($\theta = 45, 60$ degrees). These are cases where there were significant differences seen between experiments and models in the 2004 study but they are not cases where major differences would be expected since they are not near critical angles or high grazing angles. We set the incident angle of the transducer relative to the interface normal which theoretically would produce a refracted angle of 45, 60, etc. as predicted by Snell's law. Keeping that angle fixed we then adjusted the orientation of the transducer about the interface normal so as to peak up the signal and align the transducer beam with the plane normal to the SDH axis. We then translated the transducer back and forth parallel to the interface to obtain the maximum peak-to-peak response of the signal. The waveform received from the SDH at this transducer location was recorded. The water path length, d, was determined in this final location from the time-of-flight measurement of the signal received from the SDH.

For each block a reference A-scan response (at the same system settings as for the SDH responses) was obtained from the front surface of the block at normal incidence (see Figs. 2 and 4).These front surface responses were used to determine the "system efficiency" factor as a function of frequency for the tests.

Note: In all the testing cases the transducer location and orientation was changed until a maximum response was obtained. For the oblique incidence cases considered here the reflector may not lie on the central axis refracted ray of the transducer since the maximum point for the incident wave field may not occur on that central ray .

experimental arrangements for measuring the responses of the 1 mm and 4 mm diameter SDHs with a planar transducer



planar transducer
5 MHz
6.35 mm radius (nominal)

$\theta = 45^{o}$, d = 86.6 mm
$\theta = 60^{o}$, d = 106.2 mm

Fig. 1 Planar Transducer setup for SDH specimens

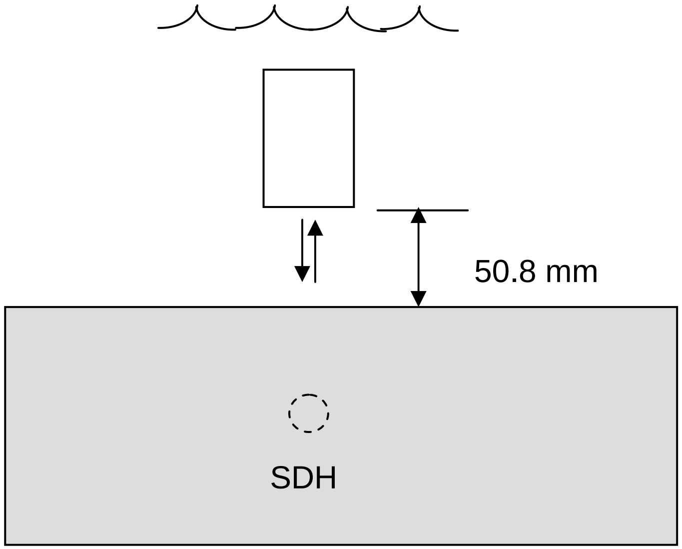
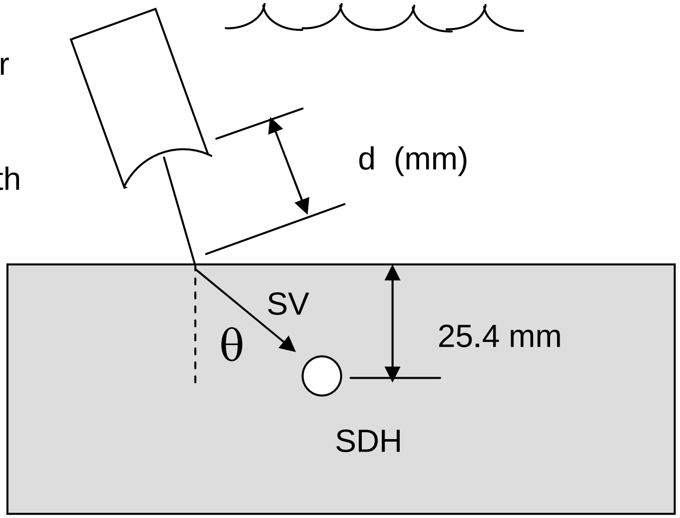


Fig. 2 Reference experiment for a planar transducer and SDH specimens
(planar front surface reflection)

The I mm and 4 mm diameter SDHs were also interrogated with a spherically focused transducer as shown in Fig. 3



spherically focused transducer
5 MHz
12.46 mm effective diameter
172.9 mm effective focal length

$\theta = 45^{o}$, d = 86.6 mm
$\theta = 60^{o}$, d = 106.2 mm

Fig. 3 Spherically focused transducer setup for SDH specimens

For the spherically focused probe, a reference scattering experiment again was performed at the same system settings as for the SDH cases. However, in this case the transducer is placed at a water path length equal to the geometrical focal length of the transducer, as shown in Fig. 4, and the A-scan response of the front surface is measured at normal incidence.

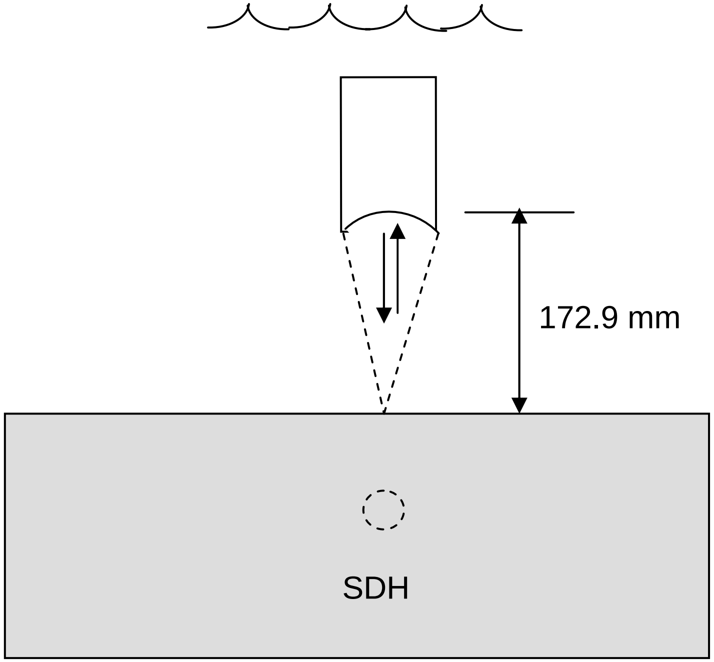


Fig. 4 Reference experiment for spherically focused probe and SDH specimens

This year we have used the front surface reference experiments to extract the system efficiency factors for the experiment and provided those factors as part of the data files. Here, we will describe in detail how those system efficiency factors were obtained. For the reference experiment one can model the received voltage as a function of frequency, $V_R(f)$, as

$$V_R(f) = \beta(f)\frac{\langle p(f)\rangle}{\rho_1 c_1 v_0}$$

where <p(f)> is the average pressure received from the front surface, ρ_1 is the density of the water, c_1 is the wave speed of the water, and v_0 is the velocity on the face of the transducer (assumed to act as a piston). However, the average received pressure in these reference experiments can be modeled for the planar transducer as:

$$\frac{\langle p(f)\rangle}{\rho_1 c_1 v_0} = \mathrm{R}\exp\left(-2\alpha(f)D\right)\left\{1-\exp\left(i\,ka^2/2D\right)\left[J_0\left(ka^2/2D\right)-iJ_1\left(ka^2/2D\right)\right]\right\}$$

where R is the P-wave plane wave reflection coefficient for the water/block interface given by

$$R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}$$

D = 50.8 mm is the distance of the transducer from the block, k is the wave number for waves traveling in the fluid, α (f) is the attenuation of the water, and *a* is the radius of the planar transducer. J_0 and J_1 are ordinary Bessel functions. Note that a phase term corresponding to the time delay in traveling to the front surface of the block and back has been omitted in these results since it only changes the time of arrival.

For the spherically focused transducer, a similar model for the received average pressure gives

$$\frac{\langle p(f)\rangle}{\rho_1 c_1 v_0} = -R\exp\left(-2\alpha(f)D\right)\left\{1-\exp\left(i\,ka^2/2D\right)\left[J_0\left(ka^2/2D\right)-iJ_1\left(ka^2/2D\right)\right]\right\}^*$$

where note there is now a minus sign in the result and $\{\}^{*}$ denotes the complex conjugate. For the spherically focused transducer case, however, the distance D must be the geometrical focal length of the transducer so here D = 172.9 mm.

If we let

$$\frac{\langle p(f)\rangle}{\rho_1 c_1 v_0} = P(f)$$

in either the planar or focused cases then we see that the system efficiency factor is given in both cases by deconvolution of the received voltage with this model-based average pressure, i.e.

$$\beta(f) = \frac{V_R(f)}{P(f)}$$

However, as is well known, deconvolution is sensitive to noise, so that a Wiener filter is used instead of the simple division shown, i.e. we obtain the system efficiency factor from

$$\beta(f) = \frac{V_R(f)\{P(f)\}^{*}}{|P(f)|^2 + e^2 \max\left(|P(f)|^2\right)}$$

where $\{\}^{*}$ again denotes the complex conjugate, | | denotes the magnitude, and e is a noise parameter. In the cases considered here we have used e = 0.03 for the planar probe cases and e = 0.09 for the focused probe cases. The results, however, are not sensitive to these choices.

Since the same transducer and system settings were used in the SDH measurements as in the reference experiments, the SDH measurements have the same system efficiency factor and so if one can model the average received pressure from the SDH with an appropriate beam model and flaw scattering model, one can predict the received voltage as a function of frequency, i.e.

$$\{V_R(f)\}_{SDH} = \beta(f)\frac{\langle p(f)\rangle_{SDH}}{\rho_1 c_1 v_0}$$

where $\{V_R(f)\}_{SDH}$ is the received voltage as a function of frequency of the SDH, and $<p(f)>_{SDH}$ is the modeled average received pressure (including the effects of the attenuation of the water for those cases).

An inverse FFT of this received voltage then gives an absolute prediction of the voltage versus time (A-scan) of the SDH.

We have placed the efficiency factors calculated in this manner in the folders as shown in Fig. 5. The data for these factors are all contained in text files. The format of those files is very simple. It is just a three column format, where the sampled frequency values (in MHz) are given in the first column, the real part of the measured system function (in Volts/MHz) is given in the second column, and the imaginary part in the third column, i.e.

f1	r1	i1
f2	r2	i2
f3	r3	i3

etc.

Each system efficiency factor data set contains 1000 sampled points, with a sampling spacing of 0.1 MHz

The file naming format for the system efficiency factors is:

EFF_1_U.txt

transducer type (U = unfocused (planar) , F = focused)

block containing SDH of specified size (4 = 4 mm diameter, 1 = 1 mm diameter)

Note: Only the positive frequency components of the system efficiency factor were calculated here over a frequency range of roughly 0 – 20 MHz and zeros appended to these results to give 1000 samples over the full frequency range of 0 – 100 MHz. Thus, if these positive frequency components of the system efficiency factor are multiplied by the corresponding positive frequency components of the modeled average pressure received by the transducer from the SDH, the product will again only contain the positive frequency components of the received voltage, $V_R(f)$. To recover the time domain signal from only positive frequency components, Fourier transform theory says that one must divide the zero frequency (dc) value by two and compute twice the real part of the inverse FFT.

Also Note: In all the frequency domain results given here, the forward and inverse Fourier transforms were defined as:

$$V(f) = \int_{-\infty}^{+\infty} v(t)\exp(2\pi i f t)\,dt$$

$$v(t) = \int_{-\infty}^{+\infty} V(f)\exp(-2\pi i f t)\,df$$

so that to be consistent with these definitions the FFTs of the discrete forward and inverse Fourier transforms of the sampled functions must be computed from:

$$V(f_n) = \Delta t \sum_{j=1}^{N} v(t_j)\exp\left[2\pi i (j-1)(n-1)/N\right] \quad (n = 1, 2, \ldots, N)$$

$$v(t_k) = \frac{1}{N\Delta t}\sum_{n=1}^{N} V(f_n)\exp\left[-2\pi i (n-1)(k-1)/N\right] \; (k = 1, 2, \ldots, N),$$

where $i = \sqrt{-1}$, N is the number of sampling points and Δt is the time interval between samples.

We have included the MATLAB scripts (and necessary supporting MATLAB functions) used to calculate the system efficiency factors present in the folders of the 2007 benchmark (see Fig. 5). From these files one can see exactly how the steps that were just described were implemented.

Some remarks:

The attenuation of the water (at the temperature under which all the experiments were conducted) was calculated as

$$\alpha = 24.79\times 10^{-6}\ f^{2} \quad \text{Np/mm} \qquad \text{where } f \text{ is the frequency in MHz}$$

The P-wave attenuation of one of the aluminum blocks was measured but found to be negligible, so that we have assumed that both the P-wave and SV-wave attenuation of the blocks can be ignored.

If one wants to replace the system efficiency factors given here by a simpler function (such as a Gaussian), the magnitude of the amplitude, amp, (in Volts/MHz), bandwidth, bw, (in MHz), and center frequency, fc, (in MHz) for these factors is given below. Note that such a replacement will cause the waveform shape to be different from the measured value.

EFF_1_U	EFF_4_U	EFF_1_F	EFF_4_F
amp = 0.161	amp = 0.1616	amp = 0.2139	amp = 0.2158
bw = 3.0	bw = 3.0	bw = 2.4	bw = 2.4
fc = 4.8	fc = 4.8	fc = 4.0	fc = 4.0

SDH study for the 2007 Benchmark:

Use the system efficiency factors given to make absolute comparisons of your model-based A-scan wave forms to the experimental wave forms. Alternatively, use a model-based system efficiency factor (such as a Gaussian) that approximates the center frequency and bandwidth of the functions given here for making the comparisons.

Also, report the peak-to-peak differences (in dB) between the experiments and model predictions.

The A-scan and other data for the various cases is located in the folder hierarchy shown in Fig. 5. The READ ME file contains a copy of these notes. Since separate blocks were manufactured for the 1mm and 4 mm SDHs the results for these two flaw sizes were placed in separate sub-folders BLOCK 1 (1mm SDH block) and BLOCK 2 (4mm SDH block).

The files in each of the final sub-folders include a text file named PARAMETERS.doc that lists all the pertinent parameters (wave speeds, transducer properties, etc.) for the experimental results of that final sub-folder.

In each final sub-folder a text file containing the A-scan results from a front-surface reflection experiment, as described previously, is in a file named REF.txt. This front surface reflection measurement was performed at exactly the same system settings used for the other A-scan measurements contained in the same sub-folder.

Also, in each final sub-folder all the A-scan results for the cases considered are contained in text files having a naming convention that will be described below.

The A-scan data are all contained in text files. The format of those files is very simple. It is just a two column format, where the sampled time values (in μsec) are given in the first column and the measured A-scan voltage (in volts) is given in the second column, separated by a tab, i.e.

```
t1      v1
t2      v2
t3      v3
```

etc.

All A-scan data contain 1000 sampled points. The sampling frequency used was always 100 MHz.

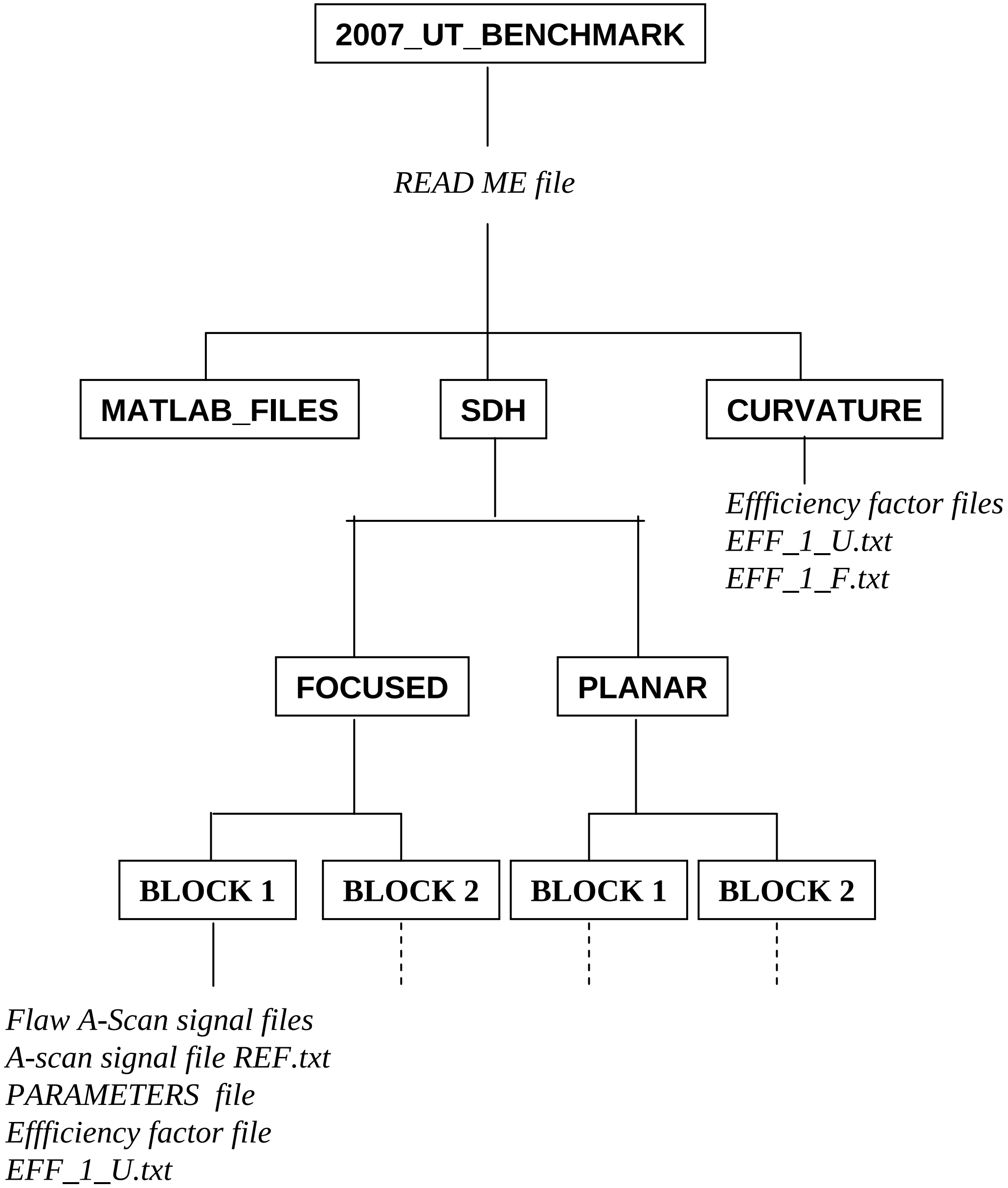
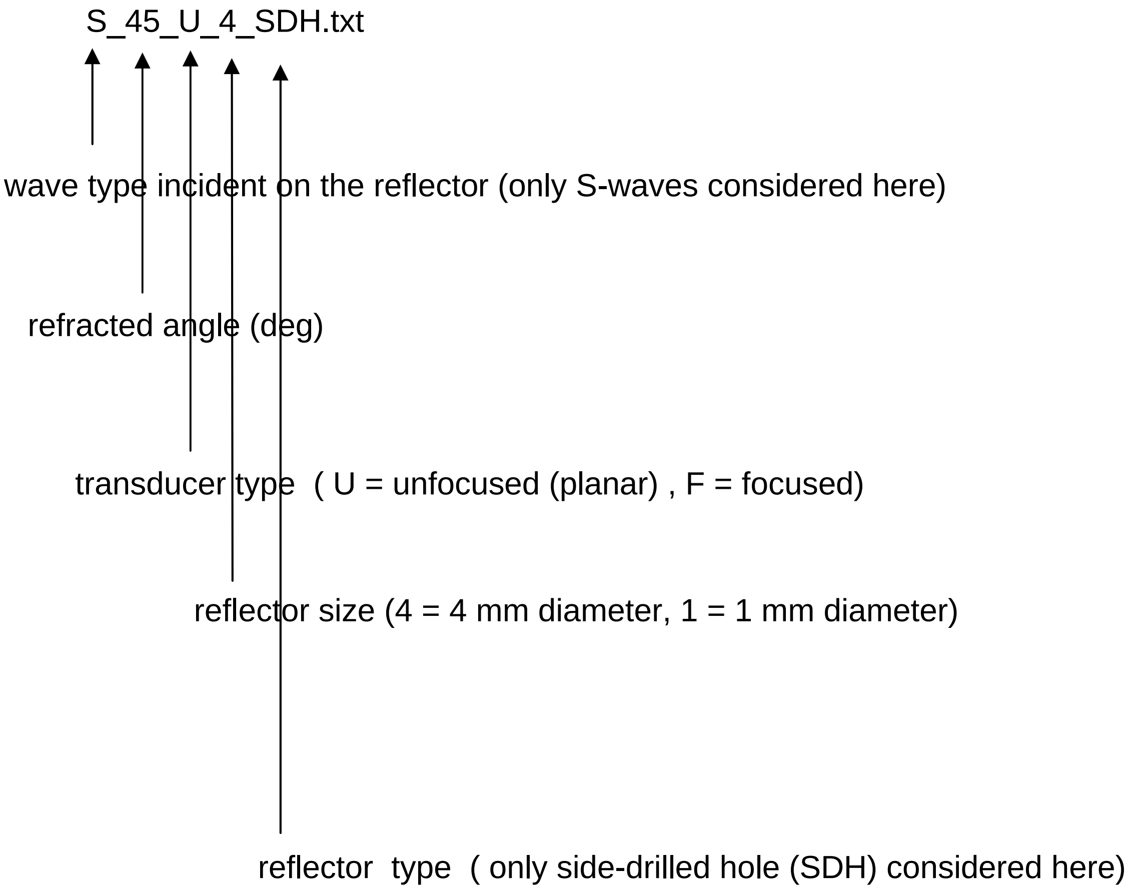


Fig. 5 The file structure for the 2007 ultrasonic benchmark data

All the data files for the A-scan responses of the reflectors in the various cases considered follow the following format, which is the same as in the 2004 study.

File name format for a "flaw" A-scan signal files



S_45_U_4_SDH.txt

wave type incident on the reflector (only S-waves considered here)

refracted angle (deg)

transducer type (U = unfocused (planar) , F = focused)

reflector size (4 = 4 mm diameter, 1 = 1 mm diameter)

reflector type (only side-drilled hole (SDH) considered here)

The file PARAMETERS.doc contains a comprehensive list of all the parameters needed to model a given setup (those that are not contained in the data filename just shown). The parameters contained in this text file are listed below.

Parameters given in PARAMETERS.doc

Transducer

Transducer center frequency (MHz)
transducer diameter (mm)
transducer focal length (effective geometrical value) (mm)

Geometry-Setup

water path (mm)
reflector depth (normal to the interface – to reflector center (or front surface for the FBH)) (mm)

Material Properties

velocity of water (mm/μsec)
density of water (gm/cm$^{3)}$
attenuation of water $\alpha = 24.79 \times 10^{-6} f^2$ Np/mm (*f* is in MHz)
P- wave speed of block (mm/μsec)
S- wave speed of block (mm/μsec)
density of block (gm/cm$^{3)}$

Data

sampling frequency (100 MHz)
Number of data points in A-scans (1000)

Surface Curvature Corrections Study

There are two parts to the study. The first part is a purely model-based study of the effects of curvature and hole size on the response of planar and focused probes. The second study is a comparison of model-based results to experiments.

Part 1: Model-Based Study

Here, we will examine the on-axis normal incidence P-wave response of a flat-bottom hole (FBH) in an immersion setup through a cylindrically curved interface (Fig. 6). The distance of the transducer from the interface in the water will be fixed as 50.8 mm, as shown, and the flat face of the FBH will be located 25.4 mm below the surface. The sizes of the hole that will be considered are: # 1, # 2, # 3, # 4, # 5, # 6, # 7, # 8 , where # n means a FBH diameter of (n/64) inches. The radius of the curvature of the cylindrical interface will be taken to be -1 in., -2 in, -3 in., -4 in., -5 in., -6 in., infinity (planar), +6 in., +5 in., +4 in., +3 in., +2 in., +1 in. where the meaning of plus and minus curvatures are shown in Fig. 6.

The two transducers will be used in this study are the same ones used in the benchmark study just described, a 5 MHz, 6.35 mm radius planar transducer and a 5 MHz, 12.46 mm radius focused transducer with a focal length of 172.9 mm. Note that there was no attempt here to place the FBH in the center of the focal region of the focused transducer.

In this study $\langle p\rangle/\rho c v_0$ should be modeled as a function of frequency for the cases indicated, where $\langle p\rangle$ is the average received pressure from the FBH, ρ , c are the density and wave speed of the water, and v_0 is the velocity on the face of the sending transducer, which is assumed to act as a piston . This normalized average pressure should then be multiplied by a system efficiency factor that represents the limited bandwidth present in a simulated inspection. The resulting product will yield the frequency components of the measured voltage. Performing an inverse FFT of the results will give simulated A-scan wave forms (see the discussion in the SDH benchmark).

The values for the system efficiency factor we will use here are specific cases obtained from the reference studies described in the first part of the benchmark. The magnitude of these functions for both the planar and focused transducer cases are shown in Fig. 7. The values of these system functions are the text files described previously named EFF_1_U for the planar probe and EFF_1_F for the focused probe. Both of these files were placed in the folder named CURVATURE (see Fig. 5). The data format in these files is discussed in the SDH study .

If the user wishes to replace these experimentally measured system efficiency factor functions by a purely model-based function, a simple function having a maximum amplitude of 0.161 Volts/MHz , a center frequency of 4.80 MHz, and a -6dB bandwidth of 3.0 MHz will reproduce the major characteristics of this function for the planar probe case (see Fig. 7). These are the same values given previously for EFF_1_U.

For the focused case, the spectrum is less symmetric but a simple function with a maximum amplitude of 0.2139 Volts/MHz, a center frequency of 4.0 MHz and a -6dB bandwidth of 2.4 MHz will generate similar characteristics to the function in Fig. 7. These are the same values given previously for EFF_1_F. In this study the absolute amplitudes of these functions are not essential since only amplitude ratios will be obtained. In both cases the functions used to represent the system efficiency factor should be tapered to zero at zero frequency so that no significant dc component is present.

For this part of the benchmark study the peak-to-peak values, PP, of these simulated A-scan waveforms should be calculated and divided by the peak-to-peak value, PPR, of a reference response, which we will take here as the # 4 FBH as measured through the planar interface. The ratio PP/PPR should be calculated in decibels (dB) and placed in a matrix of values as follows:

	-1	-2	-3	-4	-5	-6	plane	+6	+5	+4	+3	+2	+1
# 1													
# 2													
# 3													
# 4							0 dB						
# 5													
# 6													
# 7													
# 8													

Such a matrix should be generated for both the focused and planar transducers.

Since the water path and metal path is the same in all case, the results in the matrix are independent of the attenuation in the water and metal. The wave speeds and densities in the water and solid component were taken as the same as the SDH benchmark study just described.

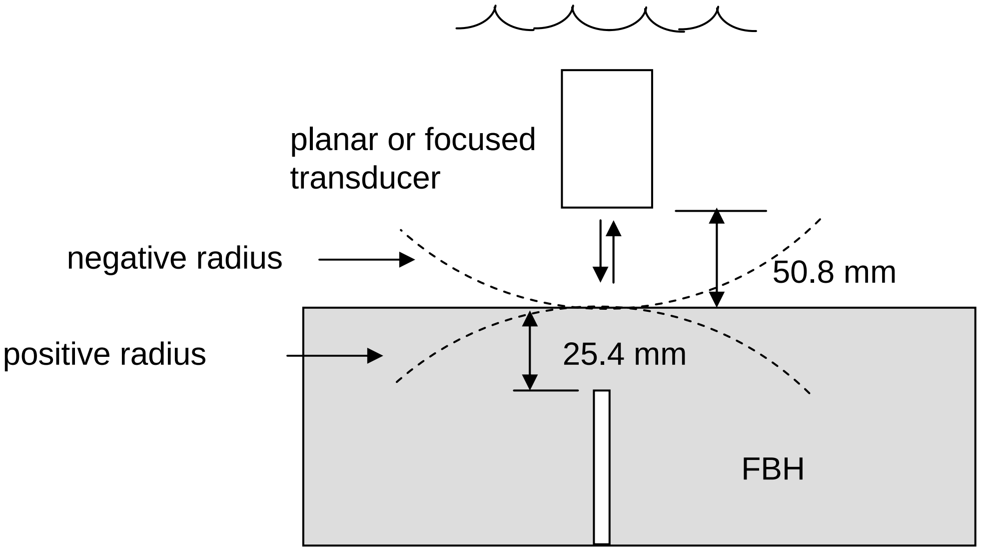


Fig. 6 The FBH setup for the interface curvature study

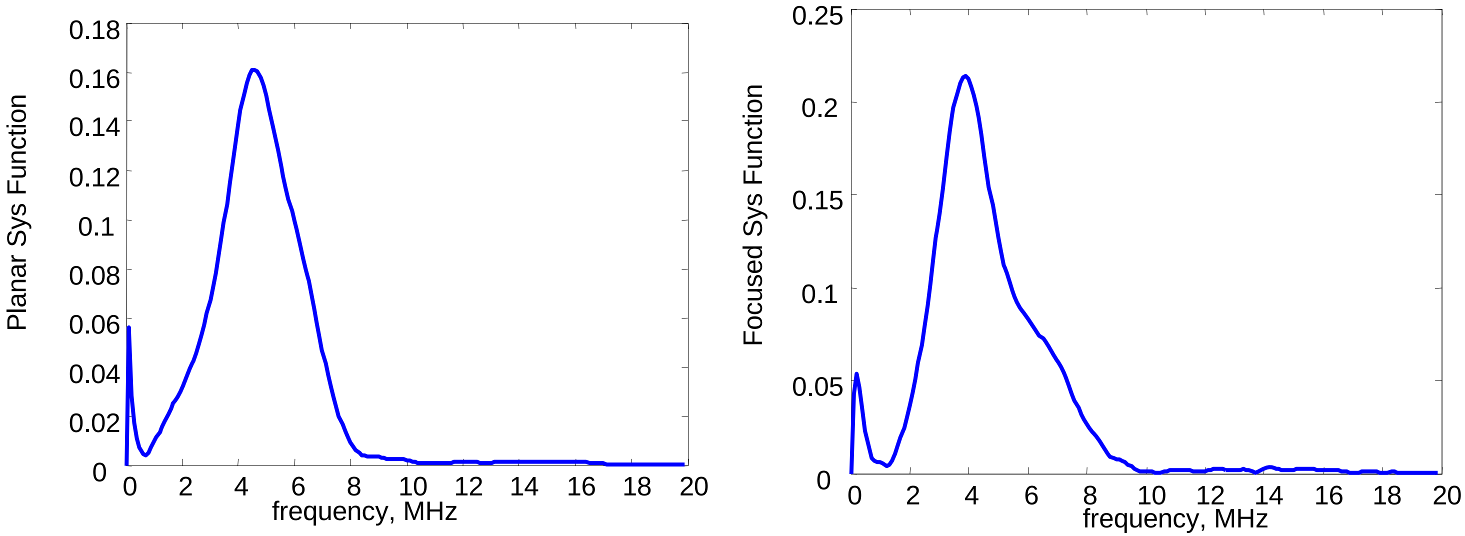


Fig. 7 The magnitude of the system efficiency factors for a planar transducer (EFF_1_U) and a focused transducer (EFF_1_F).

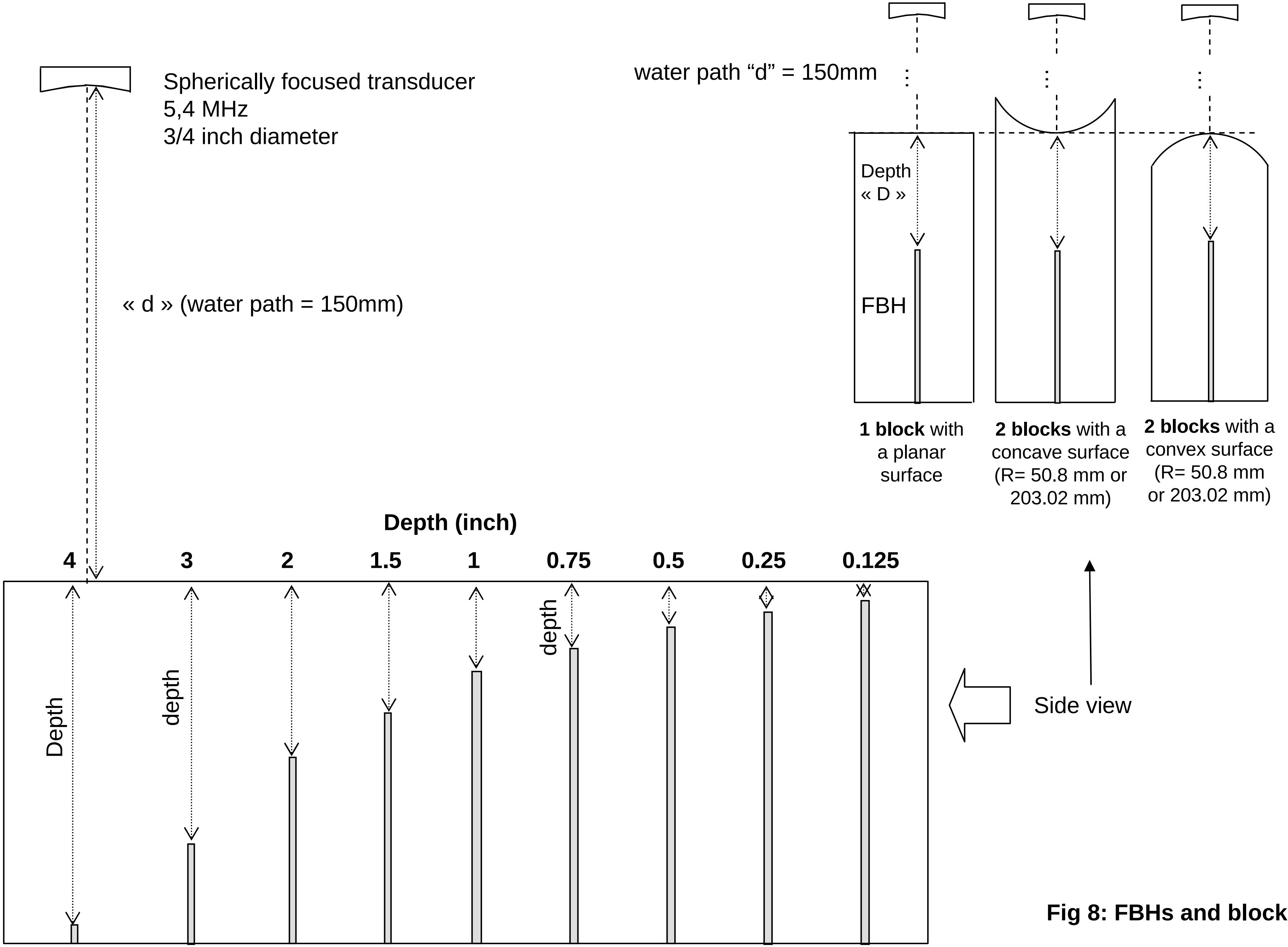
Part 2: Comparison of Models to Experiments

The blocks used for this study are five aluminum blocks with different surface curvatures (one block with a planar surface, two blocks with concave surfaces (radius 50.8 mm and 203.2 mm), and two blocks with convex surfaces (radius 50.8 mm and 203.2 mm). Each block contains nine 0.8 mm diameter flat-bottom holes (FBHs) at following depths « D »: 1/8 inch; 1/4 inch; 1/2 inch; 3/4 inch; 1 inch; 1.5 inch; 2 inch; 3 inch; 4 inch (see Fig. 8). These blocks were manufactured and the following tests conducted at CEA:

An immersion 3/4 inch diameter spherically focused transducer with a lens of radius 100 mm was used: the signal center frequency was 5.4 MHz , and the -6 dB bandwidth was 57% , wave speed (celerity) in the lens: 2929 m/sec
The water path length, « d », is 150 mm, the transducer was oriented to produce 0° refracted P waves in each block (Fig 8).

The transducer was moved in two perpendicular directions over each FBH (with a step of 0.2 mm in each direction), the waveform received from the FBH was recorded at each position of the transducer and the maximum FBH amplitude of the rectified echo was stored for each FBH. The reference amplitude for all the echoes is the maximum amplitude of the corresponding rectified echo received from the 1/8 inch depth FBH under the planar surface. The ratio of the FBH amplitudes and reference amplitude were calculated (in dB), taking into account any differences in gain settings and the results placed in a table (see Table 1)

For this curvature study, use appropriate beam models and flaw scattering models to determine the corresponding amplitude ratios (in dB) given in Table 1. Also, generate a table of the same cases showing the difference in dB from the model predictions and the experimental results.



Spherically focused transducer
5,4 MHz
3/4 inch diameter

« d » (water path = 150mm)

water path “d” = 150mm

Depth
« D »

FBH

1 block with a planar surface

2 blocks with a concave surface (R= 50.8 mm or 203.02 mm)

2 blocks with a convex surface (R= 50.8 mm or 203.02 mm)

Depth (inch)

4	3	2	1.5	1	0.75	0.5	0.25	0.125

Depth

depth

depth

Side view

Fig 8: FBHs and blocks

	Density	c_L	c_T
water	1g/cm^3	1486 m/sec	-
Aluminium	2.7g/cm^3	6381.2 m/sec	3000 m/sec

Acoustical properties of the block and water

Waves	Shape	Dimension (diameter)	Central frequency	c in the lens
P-waves	circular	19.05 mm	5.4 MHz	2929 m/sec

Transducer characteristics

Defects	Diameter:	Distances from the surface (mm):	Orientation
9 Flat Bottom Holes	0.8 mm	3.2 to 101.6 (see figure)	Normal axis of the FBH perpendicular to the surface

Flaw characteristics

depth of the FBH (mm) block	**3.2**	**6.35**	**12.7**	**19.05**	**25.4**	**38.1**	**50.8**	**76.2**	**101.6**
Planar surface	**0**	- 0.4	- 2	-4.1	-7.8	-14.4	-19.1	-26.1	-29.8
R = 50.8 mm, concave surface	1.6	3.6	-0.9	-9.1	-11.6	-19.8	-28.5	-33.5	-39.5
R = 50.8 mm, convex surface	-2.1	-2.7	-5.8	-9.3	-12.3	-18.2	-22.5	-28.8	-35.9
R = 203 mm concave surface	0	-1.6	-3.2	-5.8	-6.1	-13.7	-19.6	-27.1	-34
R = 203 mm, convex surface	-0.7	-0.9	-3.4	-5.6	-8	-13.1	-16.2	-22.8	-29.8

Table 1: Relative amplitudes in dB of the P-wave direct echo of the FBH

The amplitude of reference A_{REF} = amplitude maximum of the echo of the FBH at ¾ inch depth under the planar surface.

The relative amplitude A_R of the FBH printed in table 1 is in dB: $A_R = 20\log(A_{FBH} / A_{REF})-(G_{FBH}-G_{REF})$
where G_{FBH} and G_{REF} are the gains present in dB for the FBH and reference cases, respectively.

PARTICIPATION IN THE STUDY

The data files for this benchmark study have been placed on the web at ftp://cnde:Bruce@ftp.cnde.iastate.edu
The results of these benchmark studies will be presented the Review of Progress in Quantitative Nondestructive Evaluation meeting to be held in Golden, Colorado by May 4, 2007. However, feel free to work on these problems even if you are not presenting at that meeting. For any questions, please e-mail Prof. Schmerr at lschmerr@cnde.iastate.edu

Les Schmerr
Permanent Secretary, World Federation of NDE Centers
May, 2007