

LOCATION SWANSEA

LEVEL 7

**EXAMINATION PERIOD
MAY 2015**

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LEFEL 7

**CYFNOD ARHOLIADAU
MAI 2015**

**MODULE CODE: M7X00731
Ultrasonic Methods**

TIME: 2 HOURS

ANSWER ALL QUESTIONS

Formulae and Material Properties on last two pages

ANSWER ALL QUESTIONS

Question 1. Total Marks - 20

For the following TOFD inspection configuration

- i) Determine the arrival times for the lateral, tip diffraction and back wall signals. For simplicity disregard wedge delays and use probe index points only. **(6 marks)**

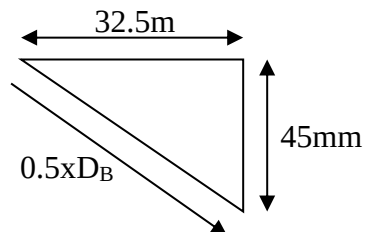
Answer:

Lateral Wave Travel Time:

Lateral Distance = 65mm at longitudinal Velocity in Mild Steel = 5960 m/s

$$t_l = \frac{d}{v_L} = \frac{65 \times 10^{-3}}{5960} = 10.91 \mu\text{s to 2 decimal places.}$$

Back wall Signal Travel Time:



With reference to the above figure, back wall travel distance can be calculated as follows:

$$D_{BW} = 2 \times \sqrt{32.5^2 + 45^2} = 111.02 \text{mm to 2 decimal place.}$$

Therefore, using the longitudinal velocity of sound, as before:

$$t_{bw} = \frac{111.02 \times 10^{-3}}{5960} = 18.62 \mu\text{s}$$

Tip Diffraction A travel time:

$$D_A = \sqrt{9^2 + 37.5^2} + \sqrt{9^2 + 27.5^2} = 67.5 \text{mm}$$
$$t_A = \frac{67.5 \times 10^{-3}}{5960} = 11.33 \mu\text{s}$$

Tip Diffraction B travel time:

$$D_B = \sqrt{40^2 + 35.5^2} + \sqrt{40^2 + 29.5^2} = 103.18 \text{mm}$$
$$t_B = \frac{103.18 \times 10^{-3}}{5960} = 17.31 \mu\text{s}$$

- ii) If the transmit pulse length is assumed to be 2 cycles at the probe centre frequency (7.5MHz), determine the system's theoretical near surface resolution limit. **(2 marks)**

Answer:

Pulse width = 2 cycles at the longitudinal wavelength (2.5MHz) in mild steel:

$$\lambda_L = \frac{v_L}{f} = \frac{5960}{7.5 \times 10^6} = 0.795mm$$

Therefore the Pulse Width:

$$PW = 2 \times 0.795mm = 1.59mm$$

This equates to a travel distance of $65 + 1.59 = 66.59mm$. Using Pythagoras theorem:

$$\begin{aligned} \text{Minimum Theoretical Depth} &= \sqrt{(0.5 \times 66.59)^2 - 32.5^2} \\ &= 7.23mm \text{ to 2 decimal places.} \end{aligned}$$

- iii) Develop and sketch a TOFD depth/arrival time correlation curve for the TOFD configuration described previously. Use the basic TOFD assumption that defect signals are assumed to originate centrally between the probe pair, and use at least 5 equally spaced depth values. Mark on the illustration the theoretical minimum depth value calculated previously, and comment on the depth resolution characteristics of the technique. **(10 marks)**

Answer:

Using depths of 0, 9, 18, 27, 36 and 45mm:

Note: We know the travel times for 0mm and 45mm from part a) of the question.

$$\begin{aligned} t_l &= 10.91\mu s \\ t_{bw} &= 18.62\mu s \end{aligned}$$

9mm Travel Time:

$$\begin{aligned} D_{9mm} &= 2 \times \sqrt{9^2 + 32.5^2} = 66.48mm \\ t_{9mm} &= \frac{66.48 \times 10^{-3}}{5960} = 11.15\mu s \end{aligned}$$

18mm Travel Time.

$$\begin{aligned} D_{18mm} &= 2 \times \sqrt{18^2 + 32.5^2} = 73.43mm \\ t_{18mm} &= \frac{73.43 \times 10^{-3}}{5960} = 12.32\mu s \end{aligned}$$

27mm Travel Time.

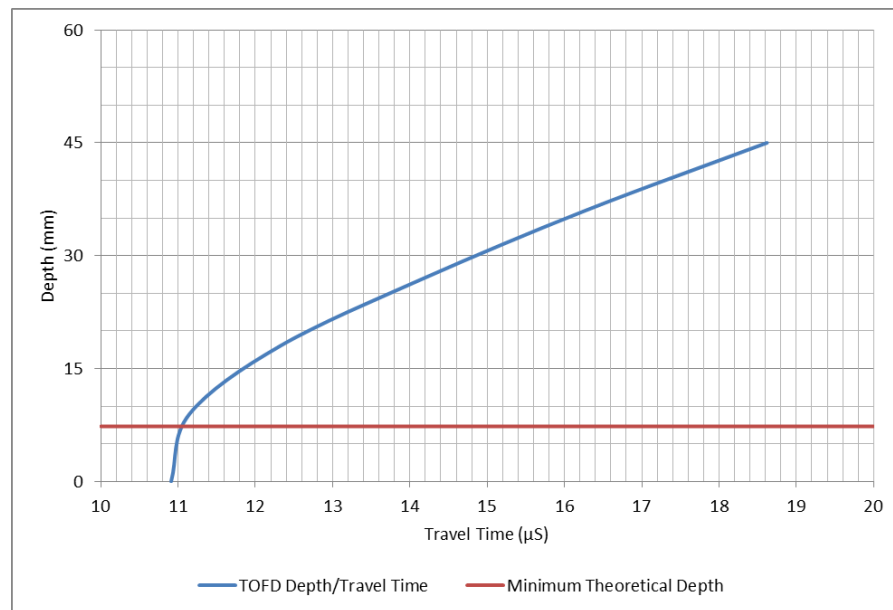
$$D_{27mm} = 2 \times \sqrt{27^2 + 32.5^2} = 84.5mm$$

$$t_{27mm} = \frac{84.5 \times 10^{-3}}{5960} = 14.18 \mu s$$

36mm Travel Time.

$$D_{36mm} = 2 \times \sqrt{36^2 + 32.5^2} = 97mm$$

$$t_{36mm} = \frac{97 \times 10^{-3}}{5960} = 16.27 \mu s$$

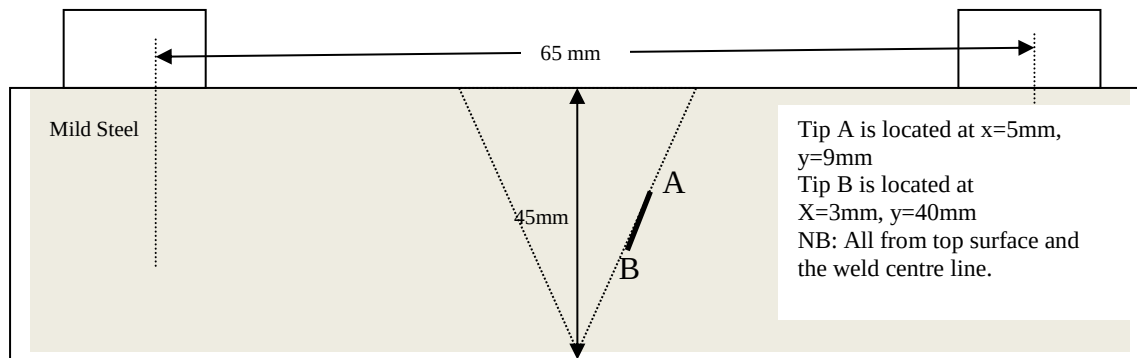


From the characteristic, it can be stated that the resolution of the technique increases with increasing depths. Also, from the parameters given, it is improbable that defects less than 7.32mm from the top surface could be determined accurately.

- iv) Briefly explain why any transmitter generated shear waves do not interfere with the general TOFD signal interpretation. **(2 marks)**

Answer:

Shear waves are generated at the transmitter wedge/material interface and is a result of wave refraction between 2 solid materials. However, for this application the generated shear wave, being approx. half of the velocity of the longitudinal velocity arrives at the receiver much later than the back wall longitudinal reflection. This is further aided by the shallower shear wave refraction angle.



Question 2. Total Marks - 20

- i) What do we mean by the term 'Q' factor and how is it used with regards an ultrasonic probe specification. **(6 marks)**

Answer:

In practice the transducer does not generate a single pure frequency sound wave and will contain a band of frequencies. These are effected by:

the thickness of the crystal, its diameter or length and width,
 the effects of the damping medium, and
 the electrical characteristics of the transducer and associated circuits.

We refer to this spectrum as the '**Bandwidth**' of the probe.

In a well-designed probe, the centre of this band should be the desired probe frequency and the lower and upper limits are usually defined as the frequencies at which the amplitude is reduced by a given factor. The upper and lower limits constitute the bandwidth of the probe , and can be based on 30% (-3 dB) and 50% (-6 dB) amplitudes.

One way of expressing bandwidth that is also common in other branches of electronics is the 'Quality factor' or 'Q' of the probe and is defined by the formula:

$$Q = \frac{f_c}{f_2 - f_1}$$

Where f_c = the centre frequency

f_1 = the upper -6dB frequency

F_2 = the lower -6dB frequency

- ii) For an 8mm diameter PZT crystal of thickness 1mm, and given that the compression wave velocity for PZT is 3000m/s, determine the crystals near field distance when transmitting into Perspex. **(2 marks)**

Answer:

PZT Crystal: thickness = 1mm,
Velocity = 3000m/s,
Diameter = 8mm

To determine the near field distance in Perspex, we need the crystals resonant frequency:

$$f = \frac{v}{2 \times t} = \frac{3000 \times 10^3}{2 \times 1} = 1.5MHz$$

Using Longitudinal Velocity in Perspex = 2680m/s:

$$NF = \frac{D^2}{4\lambda} = \frac{8^2}{4\lambda}$$

Wavelength in Perspex at 1.5MHz:

$$\lambda = \frac{v}{f} = \frac{2680 \times 10^3}{1.5 \times 10^6} = 1.787mm$$

Substituting this into the Near Field Distance Equation:

$$NF = \frac{64}{4 \times 1.787} = 8.954mm \text{ to 3 decimal place.}$$

- iii) If the crystal is in direct contact with a mild steel surface, calculate the theoretical -6dB ultrasonic beam width for the crystal at a thickness in mild steel of 60mm. **(2 marks)**

Answer:

Using:

$$\sin \frac{\theta}{2} = \frac{0.56\lambda}{D}$$

Need to determine λ in mild steel.

$$\lambda = \frac{5960 \times 10^3}{1.5 \times 10^6} = 3.973mm$$

Therefore:

$$\frac{\theta}{2} = \sin^{-1} \left[\frac{0.56 \times 3.973}{8} \right] = 16.15^\circ$$

Substituting into:

$$\tan \frac{\theta}{2} = \frac{0.5 \times BW}{60}$$

$$BW = 2 \times 60 \times \tan 16.15 = 34.7mm \text{ to 1 decimal place.}$$

- iv) If a suitable Perspex delay line were to be used determine the change in -6dB half beam spread angle at a Perspex/mild steel interface. **(2 marks)**

Answer:

Determine the half spread angle for -6dB in Perspex.

$$\sin \frac{\theta}{2} = \left[\frac{0.56\lambda}{D} \right]$$

λ in Perspex: 1.787mm determined earlier.

$$\frac{\theta}{2} = \sin^{-1} \left[\frac{0.56 \times 1.787}{8} \right] = 7.186^\circ$$

Then use Snell's law:

$$\frac{\sin 7.186}{2680} = \frac{\sin i_r}{5960}$$

$$i_r = \sin^{-1} \left[\frac{5960}{2680} \times \sin 7.186 \right] = 16.152^\circ$$

Therefore:

$$\Delta \text{Beam Angle} = 16.152 - 7.186 = 8.97^\circ \text{ increase.}$$

- v) For an ultrasonic probe with a 'Q' factor of 1.6 and wavelength of 1.192mm in steel, estimate its centre frequency and spectral bandwidth. State the upper and lower frequency values that would have been used in its initial determination. How does this relate to minimum detectable defect size? **(4 marks)**

Answer:

Q = 1.6, $\lambda_{\text{steel}} = 1.192\text{mm}$.

Need to calculate centre frequency:

$$\lambda_{\text{steel}} = \frac{v_{\text{steel}}}{f};$$

$$f = \frac{5960}{1.192 \times 10^{-3}} = 5\text{MHz}$$

Using:

$$Q = \frac{f_c}{f_2 - f_1};$$

$$f_2 - f_1 = 3.125$$

Therefore, Bandwidth of Probe = 3.125MHz, with $f_2 = 6.5625\text{MHz}$ and $f_1 = 3.4375\text{MHz}$.

To determine defect sensitivity in mild steel, the rule of thumb is $>0.5 \times \lambda$.

We could use the probes centre frequency thus:

$$\lambda = \frac{5960}{5 \times 10^6} = 1.192\text{mm}$$

Which indicates that defects >0.596mm are likely to be detectable. However, using the upper frequency, $f_2 = 6.6\text{MHz}$ from the probes spectral response, this would indicate:

$$\lambda = \frac{5960}{6.6 \times 10^6} = 0.903\text{mm}$$

Which would indicate that defects >0.903mm are also likely to be detectable. This highlights the importance of knowing the spectral resolution of the probe to be used, and also requires consideration of material grain boundaries.

- vi) A 5MHz 45° single crystal shear wave mild steel probe with a Perspex wedge is used to inspect an aluminium component of nominal wall thickness of 150mm. Determine the full surface skip distance in the component. Estimate the error that would occur in this value if the incorrect angle was used. **(4 marks)**

Answer:

Since the Probe angle is quoted for mild steel, we need to determine the probes incident angle in the wedge.

$$i = \sin^{-1} \left[\frac{2680}{3240} \times \sin 45 \right] = 35.8^\circ$$

Next determine the refracted angle in aluminium.

$$\theta = \sin^{-1} \left[\frac{3130}{2680} \times \sin 35.8 \right] = 43.1^\circ$$

To calculate the true full skip distance:

$$\text{True Full Skip Surface Distance} = 150 \times \tan 43.1 = 140.4\text{mm}.$$

If 45 degrees had been used then:

$$\text{Incorrect Full Skip Surface Distance} = 150 \times \tan 45 = 150\text{mm}.$$

In other words a surface distance error of +9.6mm would result.

Question 3. Total Marks – 20

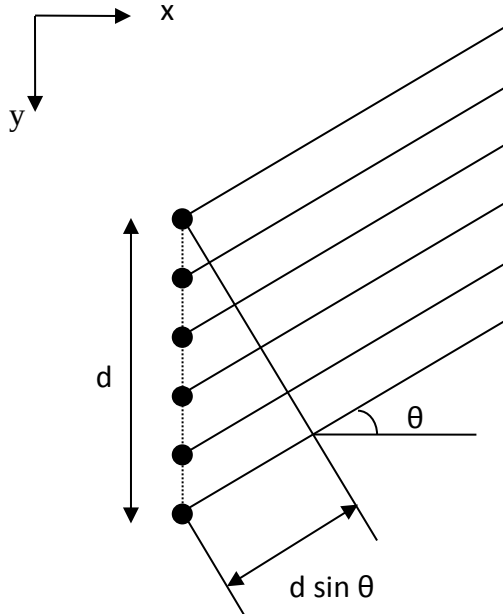
- i) For a single element rectangular ultrasonic crystal, show that the field distribution in the far field can be given as:

$$A(\theta) = a_o d \frac{\sin(\alpha)}{\alpha}$$

Where a_0 is the ray amplitude, $\alpha = k \frac{d}{2} \sin(\theta)$ where k is the wave number ($2\pi/\lambda$) and d is the aperture width. **(8 marks)**

Answer:

Fraunhofer (far field) approximation



Assume all rays are parallel to a point far away. Probe is represented by N point sources. Extra path length as y increases – $y \cdot \sin(\theta)$

$$a(y) = a_0 e^{-jky \sin \theta}$$

For each point source a_0 is the same amplitude. Note: this form is only looking at a fixed angle from the centre of the probe to a point far away.
Now create the sum for all point sources (integrate over y)

$$\begin{aligned} a(\theta) &= \int_{-d/2}^{d/2} a_0 e^{-jky \sin \theta} dy \\ a(\theta) &= \left[\frac{a_0 e^{-jky \sin \theta}}{-jk \sin \theta} \right]_{-d/2}^{d/2} \\ a(\theta) &= \frac{a_0}{-jk \sin \theta} \left[e^{-jk \frac{d}{2} \sin \theta} - e^{jk \frac{d}{2} \sin \theta} \right] \\ e^{-jk \frac{d}{2} \sin \theta} &= \cos \left(k \frac{d}{2} \sin \theta \right) - j \sin \left(k \frac{d}{2} \sin \theta \right) \\ e^{jk \frac{d}{2} \sin \theta} &= \cos \left(k \frac{d}{2} \sin \theta \right) + j \sin \left(k \frac{d}{2} \sin \theta \right) \end{aligned}$$

Subtracting the exponential terms leaves:

$$a(\theta) = \frac{a_0}{-jk \sin \theta} \left(-2j \sin \left(k \frac{d}{2} \sin \theta \right) \right)$$

$$a(\theta) = a_0 2 \frac{\sin(k \frac{d}{2} \sin \theta)}{k \sin \theta}$$

Multiplying top and bottom by $\frac{d}{2}$

$$a(\theta) = a_0 d \frac{\sin(k \frac{d}{2} \sin \theta)}{k \frac{d}{2} \sin \theta}$$

Let $\alpha = k \frac{d}{2} \sin \theta$

$$a(\theta) = a_0 d \frac{\sin \alpha}{\alpha}$$

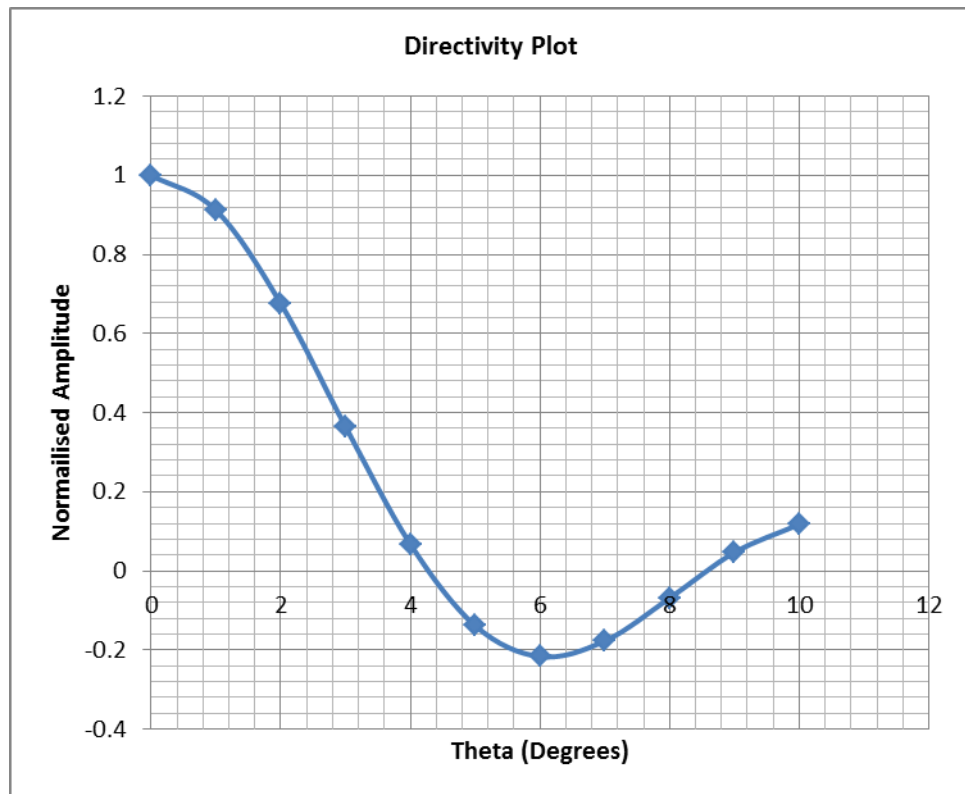
$$a(\theta) = a_0 d \text{sinc } \alpha$$

- ii) A direct contact 64 element 10MHz array probe with an element pitch of 0.5mm is used to inspect a mild steel component. An aperture size of 16 elements is used to perform a linear B-scan. Using the fraunhofer 'far-field' approximation, produce a normalised directivity graph for the specified aperture size. Hint: Use angles from 0 to 10° with 1° increments.

(4 marks)

Answer:

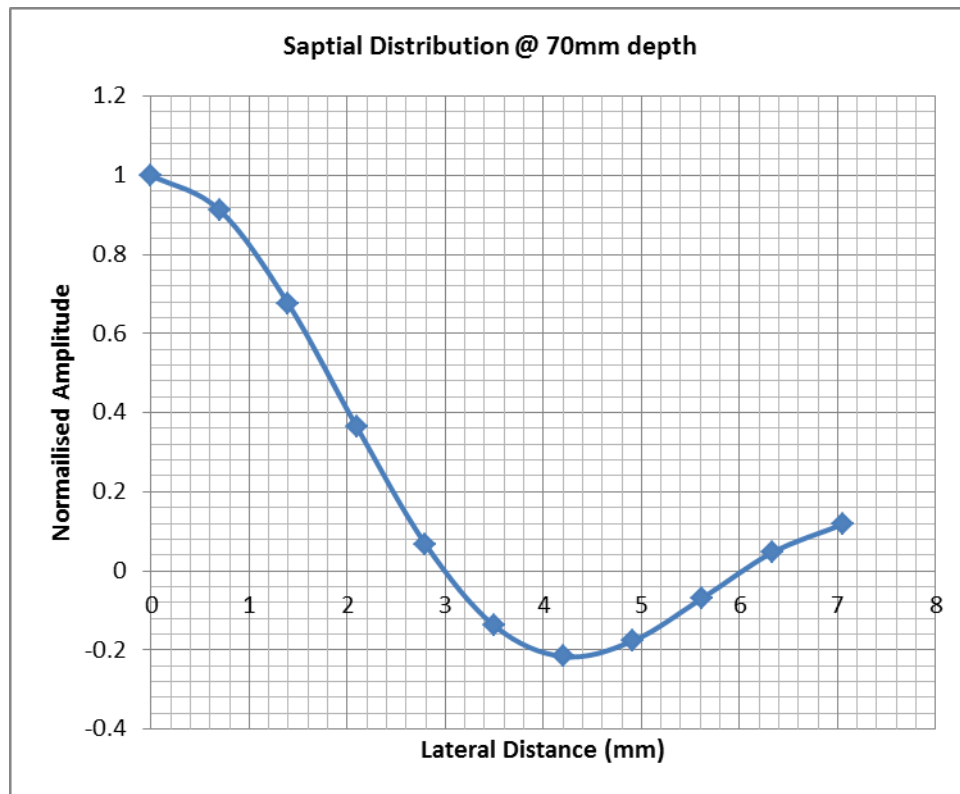
Theta	alpha	sinc
0	0	1
1	0.735951	0.912143
2	1.471678	0.676161
3	2.206956	0.364476
4	2.941563	0.067549
5	3.675273	-0.13841
6	4.407864	-0.21643
7	5.139112	-0.17714
8	5.868795	-0.06861
9	6.596689	0.04675
10	7.322575	0.117731



iii) Using your directivity derived values determine and plot the spatial intensity distribution at a depth of 70mm. **(4 marks)**

Answer:

Theta	alpha	sinc	x
0	0	1	0
1	0.735951	0.912143	0.698203
2	1.471678	0.676161	1.396831
3	2.206956	0.364476	2.096311
4	2.941563	0.067549	2.797072
5	3.675273	-0.13841	3.499547
6	4.407864	-0.21643	4.204169
7	5.139112	-0.17714	4.911382
8	5.868795	-0.06861	5.621633
9	6.596689	0.04675	6.335378
10	7.322575	0.117731	7.053079



- iv) Estimate from the plots the -6dB and absolute beam widths at this depth and compare to those that would be obtained using the half angle approximations given. **(4 marks)**

Answer:

Estimated from Plots:

-6dB Half Angle: 2.5°

Absolute Half Angle: 4.25°

-6dB Beam Width @ 70mm depth: 3.6mm

Absolute Beam Width @ 70mm: 6mm

Using Half Angle Calculations:

-6dB Half Angle: 2.39°

Absolute Half Angle: 5.21°

-6dB Beam Width @ 70mm depth: 5.84mm

Absolute Beam Width @ 70mm: 12.76mm

The differences relate to initial assumptions in the fraunhofer approximation, ie. far field only, all rays are assumed parallel and that the passive plane of the transducer elements are greater than the active aperture width, compared with the half angle analytical approximations being valid for circular transducers.

Material Properties.

Material Units	Velocity (C) m/s x 10 ³	Velocity (S) m/s x 10 ³	Density kg/m ³	Acoustic Impedance
Air	0.33	-	1.2	0.0004
Aluminium	6.40	3.13	2700	17.3
Barium Titanate A	5.26	-	5700	30.0
Barium Titanate B	5.53		5700	31.5
Beryllium	12.89	8.88	1800	23.2
Brass	4.37	2.10	8450	37.0
Cast Iron	3.5 to 5.6	2.2 to 3.2	7200	25 to 40
Copper	4.76	2.33	8930	42.5
Glass (Crown)	5.66	3.42	3000	17.4
Gold	3.24	1.20	19300	63.0
Iron	5.96	3.22	7850	46.8
Lead	2.40	0.79	11300	27.2
Lead Niobate	2.76	-	5800	16.0
Lead Zirconate Titanate A	3.00	-	7600	22.8
Lead Zirconate Titanate B	3.00	-	7500	22.5
Lithium Sulphate	5.45	-	2060	11.2
Magnesium	5.74	3.08	1720	9.90
Mercury	1.45	-	13550	19.6
Molybdenum	6.25	3.35	10200	63.7
Nickel	5.48	2.99	8850	48.5
Oil	1.44	-	900	1.3
Perspex	2.68	1.32	1200	3.2
Platinum	3.96	1.67	21400	85.0
Polystyrene	2.35	1.12	1060	2.5
Steel (Mild)	5.96	3.24	7850	46.7
Steel (Stainless)	5.74	3.13	7800	44.8
Silver	3.70	1.70	10500	36.9
Tin	3.38	1.61	7300	24.7
Titanium	5.99	3.12	4500	27.0
Tungsten	5.17	2.88	19300	100.0
Tungsten-Araldite	2.06	-	10500	21.65
Tungsten-Carbide	6.65	3.98	10000 to 15000	66.5 to 98.5
Uranium	3.37	2.02	18700	63
Water	1.48	-	1000	1.48
Zinc	4.17	2.48	7100	29.6
Zirconium	4.65	2.30	6400	29.8

Formulae

Snell's Law: $\frac{\sin i}{V_1} = \frac{\sin r}{V_1} = \frac{\sin R}{V_2}$	Reflected Energy Equation: $RE = \frac{Z_1 - Z_2}{Z_1 + Z_2} \times 100\%$
Ultrasonic Beam Formulae: $NF = \frac{d^2}{4\lambda}$ Where: NF = Near Field Distance d = Crystal diameter or aperture width λ = wavelength	Far Field Approximation: $A(\theta) = \frac{\sin(\alpha)}{\alpha}$ Where $\alpha = k \frac{d}{2} \sin(\theta)$ K is the wave number ($2\pi/\lambda$) and d is the aperture width.
$\sin \frac{\theta}{2} = \frac{1.22\lambda}{D}$ Defines the absolute edge $\sin \frac{\theta}{2} = \frac{0.56\lambda}{D}$ Defines the 6 dB edge	$\sin \frac{\theta}{2} = \frac{1.08\lambda}{D}$ Defines the 20 dB edge
Q Factor $Q = \frac{f_0}{f_2 - f_1}$ Where: f₀ = the centre frequency f₂ = the upper -6dB frequency f₁ = the lower -6dB frequency	
Frequency thickness crystal constant: $f \times t = V/2$ Where, • f = desired frequency • t = crystal thickness, and • V = compression wave velocity in the crystal material	