# ESTIMATION
# OF
# THE HEIGHT OF SURFACE BREAKING CRACKS
# USING ULTRASONIC TIMING METHODS

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Approval of the Graduate School of Natural and Applied Sciences.

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## ABSTRACT


ESTIMATION OF THE HEIGHT OF SURFACE BREAKING CRACKS USING ULTRASONIC TIMING METHODS



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In this thesis, two ultrasonic timing methods are used in order to investigate the accuracy and reliability of measurements for surface breaking cracks having different orientations and heights. Also the best applicable measurement technique is searched by comparing the received test results. These methods are the Time of Flight Diffraction (TOFD) Method using diffraction of longitudinal waves and another method using the reflection of shear waves from the crack tips. In order to simulate and measure the height of surface breaking cracks three sets of test blocks from steel, and two sets of wedges from plexiglas material are manufactured. Also several probes having frequencies of 2Mhz, 4Mhz, 5Mhz and angles of 45$^o$ and 70$^o$ are used.

Some test procedures are created to make realistic comparisons between the test results and the ones found by previous studies in literature. The results are compared according to the standard deviations of errors in crack height measurements and it is found that the depth, orientation of defects and the frequency of probes have considerable affect on the results. With wider probe angles and higher frequencies of probes to some extent the errors are observed to be running low and the height of cracks could be measured closer to the original size. The amount of the errors is increased in measurements with the increasing angle of cracks. The results of both methods are found to be very satisfactory. A range of $\pm 0.5$ mm for means of error from the original vertical crack heights is determined. The results agree with the previous studies.

Keywords: Non destructive testing, NDT, Ultrasonics, Surface breaking cracks, TOFD, Ultrasonic timing methods.

# ÖZ

YÜZEY ÇATLAKLARININ
ULTRASONİK ZAMANLAMA YÖNTEMLERİ KULLANILARAK
YÜKSEKLİK DEĞERLENDİRMESİ

Öztürk, Emre
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Bu tezde, değişik yönelimde ve uzunluktaki yüzey çatlaklarının derinlik ölçümlerindeki hassaslik ve güvenilirliğin incelenmesi için iki ultrasonik zamanlama yöntemi kullanılmıştır. Ayrıca elde edilen test sonuçları karşılaştırılarak en iyi uygulanabilir ölçüm tekniği bulunmaya çalışılmıştır. Kullanılan yöntemler, boyuna dalgaların çatlak ucundan dağılımına dayanan Dağılma Uçuş Zamanı Tekniği (TOFD) ve enine dalgaların gene çatlak ucundan yansımasına dayanan başka bir yöntemdir. Çatlakların simüle edilmesi ve ölçümlerinin yapılabilmesi için çelik malzemeden üç set test bloğu ve plexiglas malzemeden iki set takoz üretilmiştir. Ayrıca 2MHz, 4MHz ve 5MHz frekanslarında, $45^o$ ve $70^o$ ses demeti açısına sahip değişik problar kullanılmıştır.

Test sonuçlarının daha gerçekçi karşılaştırılabilmesi için bazı test ölçüm prosedürleri geliştirilmiş ve sonuçlar ayrıca literatürde bulunan çalışmalar ile de karşılaştırılmıştır. Elde edilen sonuçlar, çatlak derinlik ölçümlerindeki hataların standart sapmaları göz önünde tutularak karşılaştırılmış ve çatlak derinliği, yönelimi ile prob frekanslarının sonuçlar üzerindeki etkileri açıkça görülmüştür.

Geniş açılarla ve bir dereceye kadar yüksek frekans değerlerinde yapılan ölçümlerdeki hataların azaldığı ve çatlak derinliklerinin gerçek boyutlara çok yakın ölçüldüğü gözlemlenmiştir. Artan çatlak açıları ve azalan çatlak derinlikleri ile birlikte ölçümlerdeki hata miktarının da arttığı görülmüştür. İki yöntemle yapılan ölçümler oldukça tatmin edicidir. Dikine çatlaklarda, gerçek çatlak yüksekliklerine göre $\pm 0.5$ mm ortalama hata miktarı hesaplanmıştır. Elde edilen sonuçlar önceki çalışmalarda bulunan sonuçlarla örtüşmektedir.

Anahtar kelimeler: Tahribatsız muayene, NDT, Ultrason, Yüzey çatlakları, TOFD, Ultrasonik zamanlama metodları.

To My Father

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## LIST OF SYMBOLS

SYMBOLS

| | |
|---|---|
| $f$ | Frequency [Hz] |
| $C$ | Sound velocity [m/s] |
| $V$ | Velocity of sound wave [m/s] |
| $V_C$ | Compressional Wave velocity [m/s] |
| $V_S$ | Shear Wave velocity [m/s] |
| $V_A$ | Sound wave velocity in material A [m/s] |
| $V_B$ | Sound wave velocity in material B [m/s] |
| $V_{CA}$ | Compressional Wave velocity in material A [m/s] |
| $V_{SA}$ | Shear Wave velocity in material A [m/s] |
| $V_{CB}$ | Compressional Wave velocity in material B [m/s] |
| $V_{SB}$ | Shear Wave velocity in material B [m/s] |
| $E$ | Young's Modulus [$N/m^2$] |
| $Z$ | Acoustic Impedance [$kg/m^2s$] |
| $E_T$ | The percentage of transmitted energy |
| $E_R$ | The percentage of reflected energy |
| $r_S$ | Angle of reflection for Shear Waves in material A [Degrees] |
| $r_C$ | Angle of reflection for Compressional Waves in material A [Degrees] |
| $I$ | Intensity at a distance m from initial intensity [dB] |
| $I_0$ | Initial intensity [dB] |
| $m$ | distance [m] |
| $N$ | Near field length [mm] |
| $D$ | Probe diameter [mm] |
| $a_C$ | Critical crack size [m] |
| $W$ | Work of fracture of solid [$J/m^2$] |
| $d$ | Crack height [mm] |

$t_C$ Time of flight for Compressional Waves around the crack tip [ $\mu\sec$ ]

$t_{Bw}$ Time of flight for reflecting sound waves from the backwall [ $\mu\sec$ ]

$t_0$ Time of flight for lateral wave [ $\mu\sec$ ]

S Distance between probes [mm]

H Height of test blocks [mm]

X Index length of probes [mm]

Abbreviations

| | |
|---|---|
| NDT | Non Destructive Testing |
| NDI | Non Destructive Inspection |
| NDE | Non Destructive Evaluation |
| UT | Ultrasonic Testing |
| TOFD | Time of Flight Diffraction |
| FET | Focusing Echo dynamic Time of Flight |
| ALOC | Amplitude transit-time Locus Curve |
| EFNDT | European Non Destructive Testing Federation |
| DAP | German Accreditation Council |
| BAM | German Federal Material Research and Test Institute |
| DGZfP | German Non Destructive Testing Association |
| SLV | German Welding Technology Institute |
| CAD | Computer Aide Design |
| CAM | Computer Aided Manufacturing |
| EDM | Electrical Discharge Machine |
| CNC | Computer Numerical Control |
| OSTİM | Organized Industrial Zone |
| LCD | Liquid Crystal Display |
| CRT | Cathode Ray Tube |
| ASME | American Society of Mechanical Engineers |

| | |
|---|---|
| EMA | Electromagnetic-Acoustic |
| LASER | Light Amplification by Stimulated Emission of Radiation |
| TR | Transmitter-Receiver |
| UKAEA | United Kingdom Atomic Energy Authority |
| METU | Middle East Technical University |

Greek Letters

| | |
|---|---|
| $\lambda$ | Wavelength [mm] |
| $\varphi$ | Poisson's ratio |
| $\rho$ | Density of material [g/cm$^3$] |
| $\alpha$ | Angle of incidence [Degrees] |
| $\beta$ | Angle of refraction [Degrees] |
| $\beta_S$ | Angle of refraction for Shear Waves in material B [Degrees] |
| $\beta_C$ | Angle of refraction for Compressional Waves in material B [Degrees] |
| $\delta$ | Attenuation coefficient [dB/m] |
| $\delta_T$ | True attenuation coefficient [dB/m] |
| $\delta_S$ | Scatter coefficient [dB/m] |
| $\sigma$ | Applied stress [N/m$^2$] |
| $\theta$ | Angle of incidence of probes [Degrees] |

# CHAPTER 1

# INTRODUCTION

## 1.1 THE OBJECTIVE OF THE THESIS

After the mass production started in manufacturing and as the new technologies developed, the need for improving the reliability and quality of engineering products gained more importance. Non Destructive Testing is being used for this purpose extensively in industry right now. In this thesis, ultrasonic inspection part of Non Destructive Testing is handled.

Cracks are the mostly encountered flaws during manufacturing. And ultrasonic testing is one of the best ways to detect, locate and size these kind of flaws without breaking the parts into pieces. It is mainly used for detection but it can also size the cracks very accurately. Two ultrasonic timing methods using the diffraction and reflection properties of waves are selected for the thesis study. The methods use the transit time of sound waves following various paths around the crack to measure the crack size.

In order to simulate the cracks, some test blocks are prepared from steel which include differently oriented and sized cracks. Also some wedges with various angles are produced from Plexiglas material to create the desired arrangements of probes. Every crack is tested with ultrasonic probes which produce different kind of soundwaves in various angles and frequencies. The results are compared with each other in terms of minimum error from the original crack size in measurements to find the best method and probe configuration.

## 1.2 LITERATURE SURVEY

A comprehensive introduction to the Time of Flight Diffraction measurement technique including the underlying theoretical background and basic aspects are described. Also a theoretical prediction of the amplitude of the diffracted signals, comparison with other methods, design of TOFD equipment for different type of flaws and development of the technique over the last 25 years are given. Moreover the detailed results of several trials including a project of defect detection trials with the Welding Institute organised by the UKAEA, are discussed [1].

In 2001, Balasubramanian et al presents a study where machined slits are measured with bulk wave timing methods including the diffraction of longtidunal waves and the reflection of shear waves at the crack tip. They used some steel test blocks containing vertical and inclined slits with various heights during the study. The results found to be useful in assessing the accuracy of ultrasonic timing methods in practical testing situation. While both methods were equally accurate in sizing the slits above 5 mm, only the reflection of shear wave method could be used to measure slits below 5 mm [11].

An understanding of the physical principles, capabilities and limitations of a wide range of NDT methods, including the latest developments for engineers at undergraduate and graduate levels are given. It covers concisely the major fields of NDT and indicates how they differ from each other and overlap. It also provides a balance between the relative importance of the various methods [2].

In 1982, the study of Date et al showed preliminary information on the accuracy and reliability of ultrasonic timing methods for crack height measurement. The investigation aimed to check the applicability of these methods to measurement of inclined defects and to measure the beam-path length to an accuracy of 0.01 mm. The results showed that all the methods were highly accurate but surface wave transmission method was not suitable for inclined flaws [13].

In 1975, the study of Silk et al summarised the results from a series of experiments carried out to determine the ultrasonic reflectivity of shallow slits. The measurements were only reliable when the slit depth is less than one quarter of the ultrasonic wavelength. The data suggests that the optimum ranges in the commonest testing geometries are slit depths of between one quarter and one half wavelength and of greater than four wavelengths. Also as spark eroded slits should mimic real crack surfaces more closely, it appears that data from cracks may be subject to large and unpredictable errors [16].

In 1975, the study of Lidington et al reported an investigation which was a part of a wider study of defect sizing techniques. They have examined the method of crack depth determination using scattered ultrasound developed by Böttcher et al with special reference to contact probe studies with normal grade structural steels. It is concluded that the use of amplitude of the scattered signal as a measure of crack depth suffers from some serious drawbacks, but the alternative of using the change of time delay between the transmitted and the first received signal appears to be very attractive [12].

In 1975, Silk et al presented a study of the accuracy of decibel – drop techniques with particular reference to the effects of defect shape and defect surface roughness as part of a wider reappraisal of ultrasonic defect sizing techniques. The variations found are consistent with qualitative explanations but the magnitudes of the variations may be larger than commonly expacted [17].

In 1977, the study of Silk et al showed a method for sizing crack-like defects in steel, using a single probe ultrasonic technique. The results of size measurements on T-butt welds were reported and a preliminary theoretical analysis of the method was given. The possibility of extending the method to the use of shear waves was also mentioned [18].

In 1974, the study of Lidington et al described a second statistical analysis of the variations in the properties of ultrasonic probes. It appears that the probability of a probe giving a malfunction is 53% for lower frequency probes compared with 76% for higher frequency probes. These figures compared with earlier estimates, based on the same limits of acceptability, of 45% and 81% respectively [21].

## 1.3 OUTLINE OF THE THESIS

The following chapter overviews Non Destructive Testing methods and Ultrasonic Testing. Main emphasis is given to the ultrasonic method and its basics; to better understand the calculations, important points and arrangements done during tests.

The third chapter includes Time of Flight Diffraction method which is one of the two methods used during tests. A general information about the technique, how it is applied and the factors affecting the measurements during tests are described in detail.

The fourth chapter is devoted to the description of experimental work. The instruments, test blocks and wedges used during tests and inspection methods are described. The test results are given at the end of this chapter.

The fifth chapter includes discussions and conclusions about some important points encountered during the measurements. These include the reasons for the selection of the type of cracks and methods being used during the tests, parameters used in the simulation of cracks, test accuracies, and the selection of wedge materials. Some recommendations for future studies are included at the end of this chapter, too.

# CHAPTER 2

# NON-DESTRUCTIVE TESTING

## 2.1 INTRODUCTION

Much of the destructive testing as we know it today originated as recently as the middle of the last century. Non-destructive testing is a natural outgrowth from destructive testing and some of its widespread used forms has been recognised and practiced for a very long time. The age-old practice of ringing pots against one another in order to detect the presence of cracks, the charring of the outer layers of a log to check its soundness for use could be some examples.

During the World War II, United States brought a radically new approach to shipbuilding using the techniques of mass production which is heavyly related to welding instead of riveting. But most of the ships build with this technique exhibited a tendency to crack and failed in service just like the one seen on Figure 2.1. So modern developments in the use of atomic energy, guided missiles, and the attainment of flight by manned aircraft at supersonic speeds especially after the World War II provided further reasons for improving the quality and reliability of engineered products. All these developments made non-destructive testing more important and it is moving rapidly from the era of wheel-taping to the atomic age.

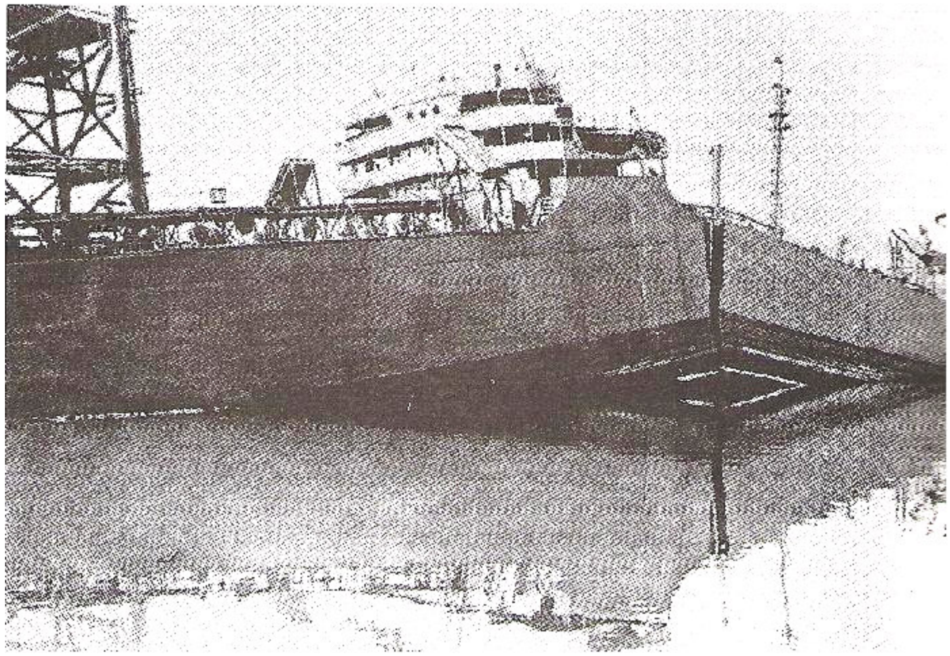

**Figure 2.1** Failure of a Liberty ship at dockside [10]

Non-destructive testing is defined by Hinsley as 'the science of examining materials or manufactured articles in order to determine their fitness for certain purposes without impairing the desirable properties of such materials or articles'. Even tough, we assume a non-destructive test will not damage the material being examined without destroying its capability for the purpose which it was originally intended; most of the tests involve some degree of damage [4].

The terms 'non-destructive testing' or abbreviated as 'NDT', and 'non-destructive inspection' could be used interchangeably but a newer term 'non-destructive evaluation' is coming into use nowadays. In NDT, after flaw-detection applications from the end product which is a description of the flaws like its nature, size or location; a decision is made on the acceptance-rejection of the material by the designer. In NDE tough, this decision is a part of the testing process. So although many NDT methods reached a stage of development that they can be used by semi-skilled operators, they still need to know the scientific understanding of the fundamental physics involved in the tests [2].

Most NDT techniques have a wide range of applications and continually growing. Most important ones are the examination of welded joints, nozzles, surfaces in pressure vessels [22, 23], containers for industrial liquids and gases, oilrigs like the one seen on Figure 2.2 which dwarfs the famous Big Ben in London, pipelines, the aero-space and railroad industries where measurement and working conditions are harsh and no failures are tolerated [19, 20].

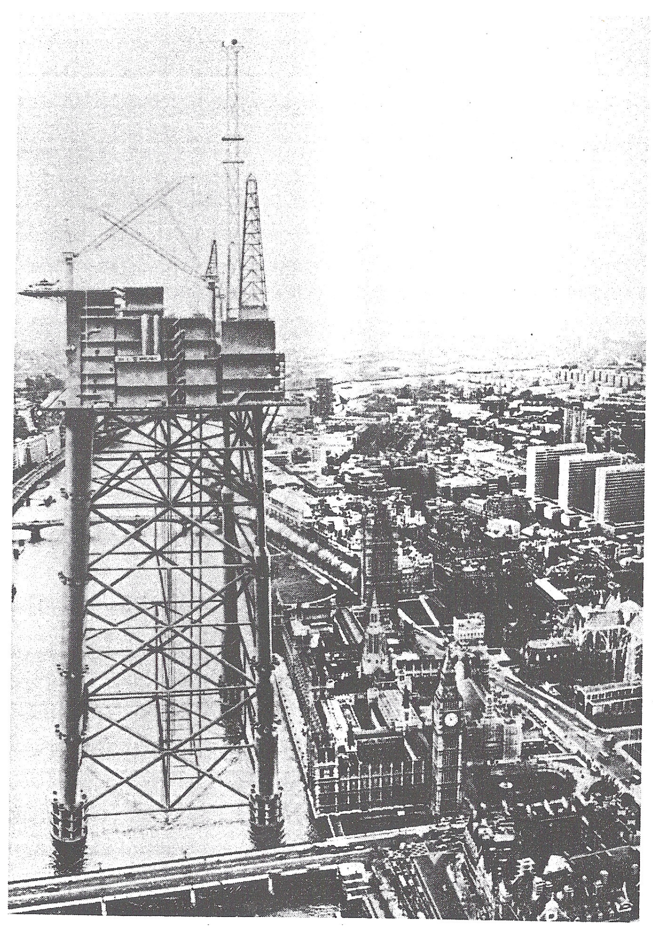

**Figure 2.2** Size scale of an oilrig [3]

The degree of examination employed and the standard of quality demanded should all times be compatible with service requirements too [4]. By this means, besides the type of defects searched, the accuracy and precision in measurement; economics also plays a considerable part in the selection of suitable NDT methods.

Although a great deal of NDT is carried out for flaw detection in materials like the weld defects, lack of bond or fatigue cracks; it has also important applications in the examination of assemblies like the detection of mis-assembled components, missing or displaced parts, measurement of spacing, stresses in metals [2]. A broad overview of the size scales of cracks and the possibilities for measurements are given in Fig 2.3. Here the increasing strength of the arrow labelled 'practical NDT', indicates an increasing likelihood of crack detection and measurement by conventional non-destructive testing techniques. A crack of 1 mm may possibly be seen by naked eye, of course if the location of crack and the surface conditions are known. The cracks smaller than this value should be monitored with laboratory based techniques [3].

The NDT methods can be divided into nine main groups:

1. Radiological methods;
2. Elastic methods;
3. Electrical and magnetic methods;
4. Optical methods;
5. Thermal methods;
6. Mechanical methods;
7. Atomic and nuclear methods;
8. Chemical methods;
9. Penetrant methods.

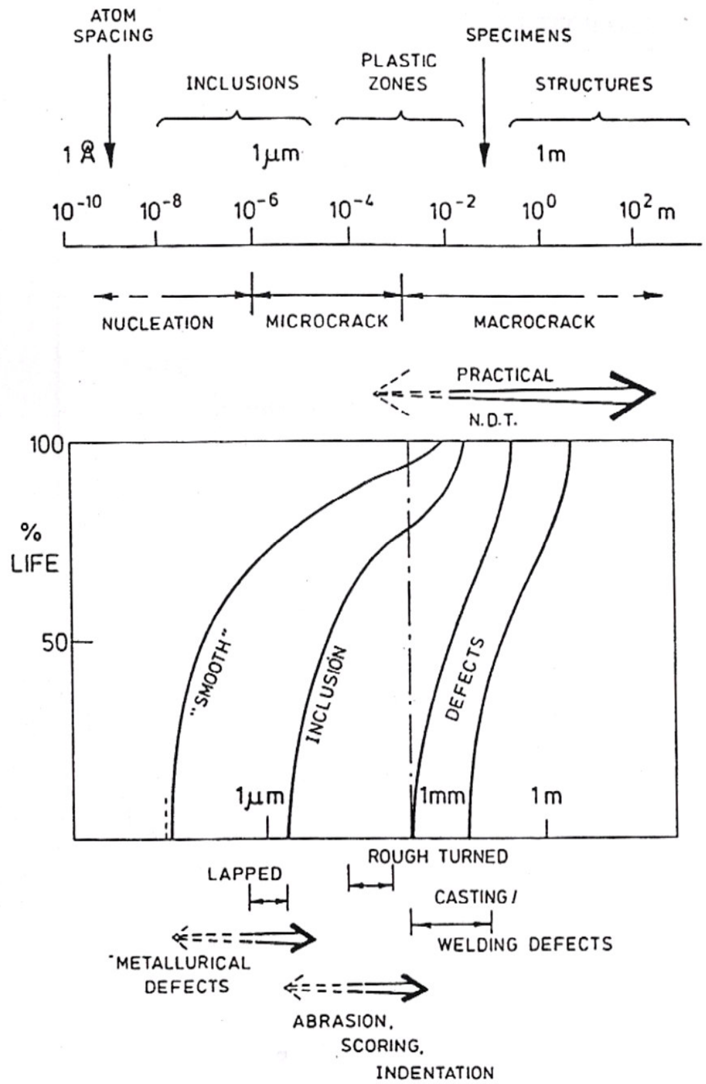


**Figure 2.3** Size scales associated with fatigue [3]

The major NDT techniques used in industry are Radiography (Radiological methods), Ultrasonic (Elastic methods), Magnetic, Electrical (Electrical and Magnetic methods), and Penetrant testing [6]. There are many more techniques besides the given ones above in NDT and it is almost impossible to mention every one of them in detail even in a book. In the next part, basicly ultrasonic and its testing which is used during the thesis study will be explained in detail.

## 2.2 ULTRASONICS

### 2.2.1 Basics

During this NDT technique, mechanical vibrations are being used. These vibrations can propagate in solids, liquids, gases and have a frequency measured in hertz unit ('Hz') which equals to the number of cycles of motion per second. The sound that we can hear approximately ranges between 10 – 20.000 Hz, and above this value the sound waves are referred to as 'Ultrasonic'.

As the ultrasonic waves are not electromagnetic radiation, they have different wavelengths in different materials. The velocities of different form of ultrasonic waves in different materials are given in Table 2.1. If the particle vibration is sinusoidal, the waves can be assigned a single wavelength ($\lambda$) and the wave velocities can be calculated from the elastic constants of the material with equations (2.2) and (2.3).

$$f = \frac{c}{\lambda} \tag{2.1}$$

$$V_C = \left[ \frac{E(1-\sigma)}{\rho(1+\varphi)(1-2\varphi)} \right]^{1/2} \tag{2.2}$$

$$V_S = \left[ \frac{E}{2\rho(1+\varphi)} \right]^{1/2} \tag{2.3}$$

**Table 2.1** Ultrasonic wave velocities [7]

| Material | Density (g/cm$^3$) | Velocity (m/s) | |
|---|---|---|---|
| | | Compressional | Shear |
| Aluminium | 2.70 | 6300 | 3130 |
| Berilium | 1.85 | 12400 | 8650 |
| Lead | 11.4 | 2160 | 700 |
| Mild Steel | 7.7 | 5900 | 3230 |
| Magnesium | 1.74 | 5740 | 3080 |
| Nickel | 8.8 | 5630 | 2960 |
| Copper | 8.90 | 4700 | 2260 |
| Titanium | 4.51 | 6000 | 3000 |
| Tungsten | 19 | 5460 | 2620 |
| Polythene | 1.20 | 2000 | 540 |
| Perspex (Lucite) | 1.18 | 2700 | 1300 |
| Water | 1.00 | 1490 | - |
| Air | - | 344 | - |

### 2.2.2 Types of Waves

Some types of waves used in ultrasonics are the Lamb (Plate), Stoneley, Flexural, Rayleigh, Love, Shear and Compressional waves. But by far the most important types of waves for industrial ultrasonic applications are the compressional and shear waves. The other ones are used generally for special applications.

If the particle motion in a wave is along the line of the travel direction of the wave, it is called a compressional, longitudinal or primary wave (P-wave). These waves can propagate in every medium.

If the particle motion in a wave is at right angles to the travel direction of the wave, it is called a shear or transverse wave. These waves usually have a velocity approximately half of the compressional waves in the same medium and can not propagate in liquids or gases [2]. They can also be polarised because of the shear displacement which can occur in any direction [3].

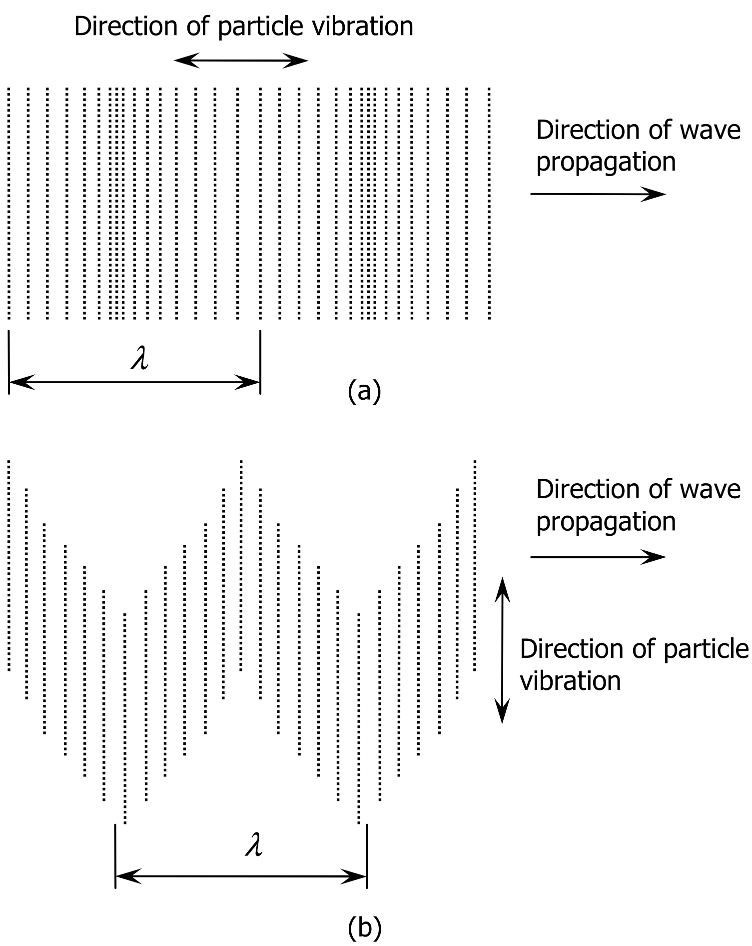


**Figure 2.4** (a) Compressional wave, (b) Shear wave [7]

### 2.2.3 Acoustic Impedance

When an ultrasonic wave hits a boundary surface between two different medium, some of the energy is transmitted and some is reflected depending on the acoustic impedance values of medium materials. This value for each material is found as;

$$Z = \rho.V \quad (2.4)$$

For two materials having the acoustic impredances of $Z_1$ and $Z_2$, the percentage of energy transmitted and reflected can be calculated from equations (2.5) and (2.6). For the amplitude values of waves transmitted and reflected, the square roots should be taken [2]. Some typical acoustic impedances for materials are given in Table 2.2.

$$E_T = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2}.100 \quad (2.5)$$

$$E_R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2.100 \quad (2.6)$$

**Table 2.2** Typical acoustic impedances for engineering materials [26]

| **Material** | **$z.10^6$ kg/m$^2$s** |
|---|---|
| Steel | 45 |
| Copper | 42 |
| Plexiglas | 3.2 |
| Quartz | 15.2 |
| BaTi (Barium titanate) | 31.2 |
| PZT (Lead zirconate titanate) | 33.0 |
| Water | 1.5 |
| (Mounting and backing materials for transducers) | |
| Araldit casting resin | 2.8 – 3.7 |
| Casting resin | 5.2 |
| Tungsten / epoxy (200:100) | 9.4 |

For example the acoustic impedance value of steel is so high with respect to air that, in a steel-air interface almost all the energy is reflected back into the steel. But in some situations including very tight cracks having a length less than 1 $\mu m$, nearly 30% of the energy can be transferred to the other side of the crack which causes practical problems in crack detection [2]. Besides even for liquid or solid filled cracks, ultrasonics is a very good technique for detecting flaws compared to radiography.

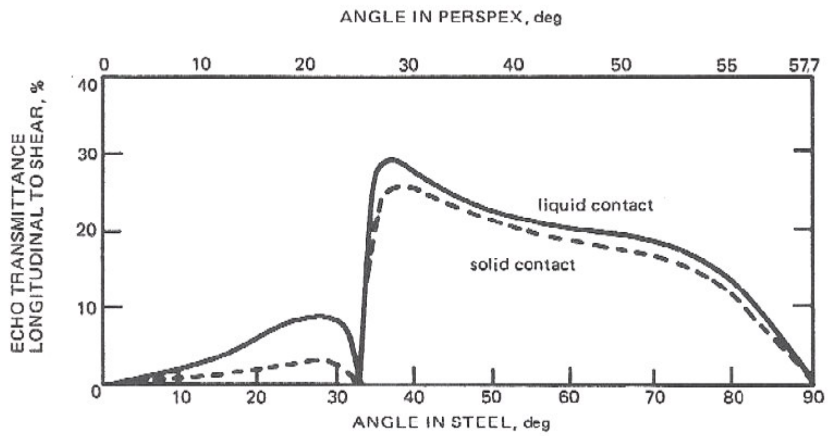


**Figure 2.5** Transmission of ultrasound across a perspex-steel boundary [3]

### 2.2.4 Oblique Incidence

As mentioned in the previous part, some part of an ultrasonic wave is reflected and some is refracted when it is incident at an interface between two different materials with an angle to the normal. The angle of refraction of the transmitted wave can be calculated with a simple relationship called *Snell's Law*.

$$\frac{Sin\alpha}{Sin\beta} = \frac{V_A}{V_B} \tag{2.7}$$

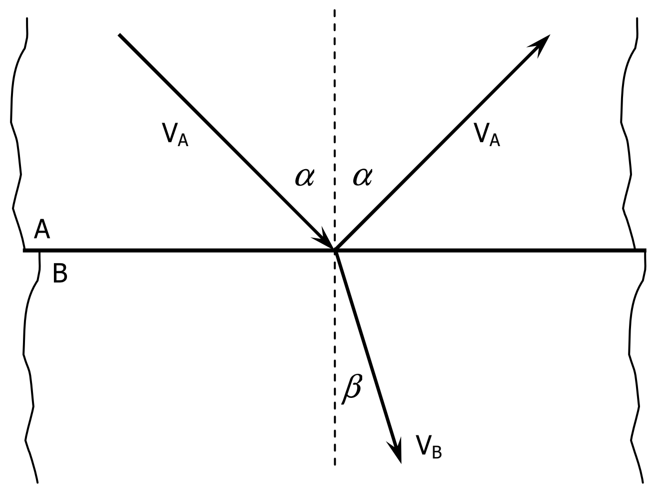


**Figure 2.6** Ultrasonic wave at an interface between two material, $V_A > V_B$ [2]

The angle of incidence is equal to the angle of reflection for both the compressional and shear waves. But depending on the wave velocities, with a suitable arrangement of the angle of incidence, the angle of refraction can get a value of 90°. In this situation the angle of incidence is called 'the critical angle', and for the angles greater than this value the ultrasonic wave is totally reflected with no energy transmitted to the second medium.

At an interface between two solid medium, there are two critical angles. After the first critical angle, the compressional transmitted waves; and after the second critical angle, the shear transmitted waves disappear. The general cases of an incident compressional and shear wave have the Snell's law as shown in equations (2.8) and (2.9).

$$\frac{Sin\alpha}{V_{CA}} = \frac{Sinr_S}{V_{SA}} = \frac{Sinr_C}{V_{CA}} = \frac{Sin\beta_S}{V_{SB}} = \frac{Sin\beta_C}{V_{CB}} \quad (2.8)$$

$$\frac{Sin\alpha}{V_{SA}} = \frac{Sinr_C}{V_{CA}} = \frac{Sin\beta_S}{V_{SB}} = \frac{Sin\beta_C}{V_{CB}} \quad (2.9)$$

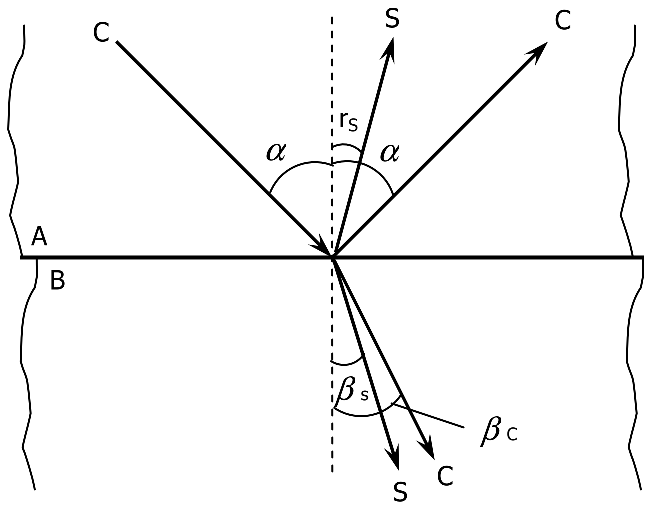


**Figure 2.7** Compressional wave at an angle onto an interface between two materials, $V_A > V_B$ [2]

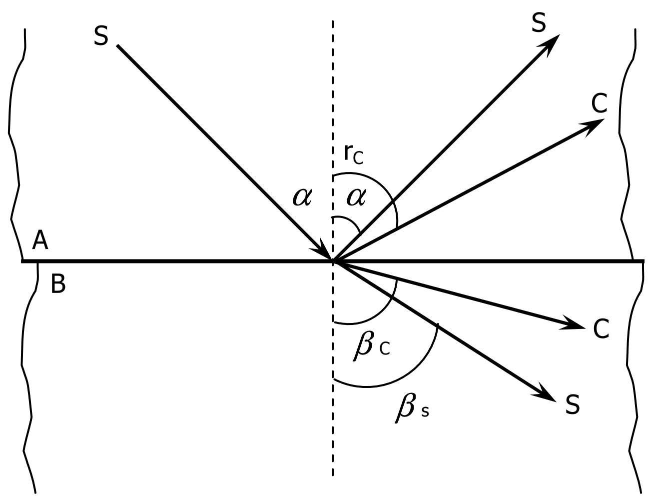


**Figure 2.8** Shear wave at an angle onto an interface between two materials, $V_B > V_A$ [2]

There are two more important feature about incident ultrasonic waves at an interface. First, the incident angles up to 30° it is better to operate with compressional waves, but above 35° shear waves become more favourable. And second, plane of oscillation of shear waves has a huge role in mode conversion. If the plane of oscillation is at right angles to the plane of incidence, the shear wave will be totally reflected at all angles and will not be mode converted. On the other hand the mode converted shear waves have the plane of oscillation in the plane of incidence. The relative amplitudes of mode converted shear and compressional waves with different incident angles of compressional and shear waves can be seen in Figures 2.9 and 2.10.

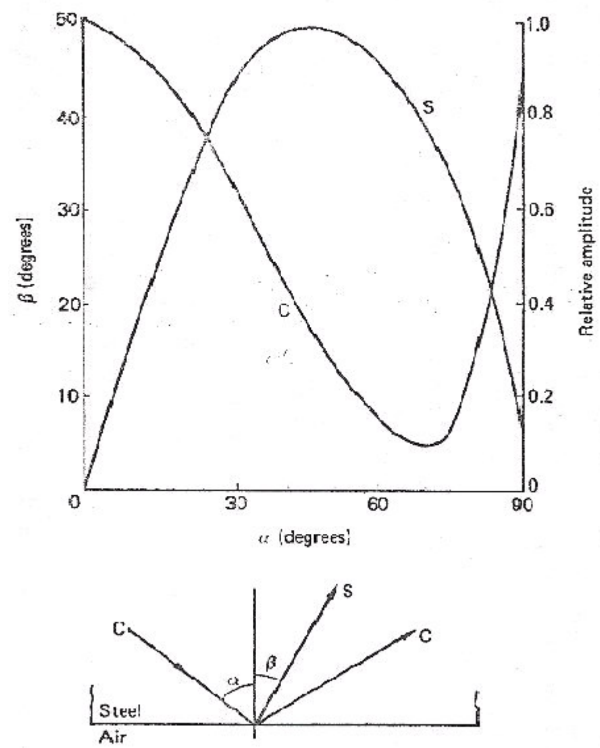


**Figure 2.9** Relative amplitudes for waves at a Steel/Air interface for an incident Compressional wave [2]

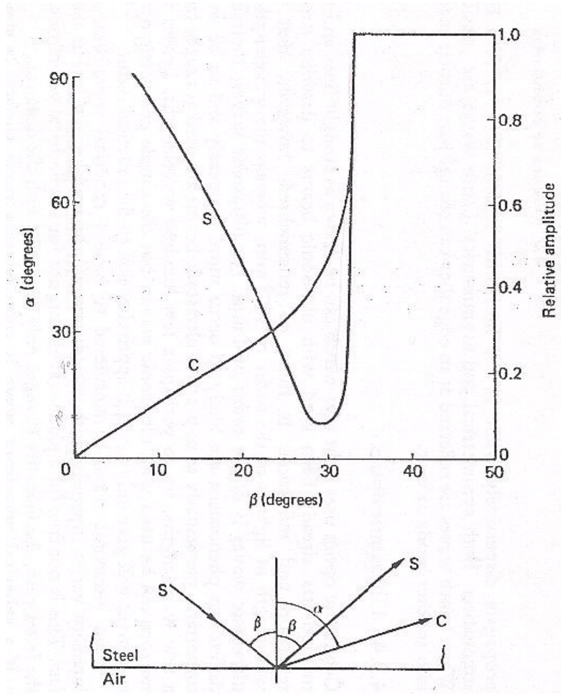


**Figure 2.10** Relative amplitudes for waves at a Steel/Air interface for an incident Shear wave [2]

### 2.2.5 Attenuation

Ultrasonic waves lose their energy as they propagate into most of the materials. Beam spreading, absorption and scatterring are three basic processes that result in the loss of pulse energy due to some reasons like grain size, grain orientation and ultrasonic frequency.

Beam spreading is a geometric function where the intensity is decreasing with the square of the distance traveled. As the wave front advances, the initial pulse energy is distributed over a large spherical area because of beam spreading.

Absorption term is used for the mechanical energy converted to heat energy as the wave front passes. The absorbtion varies with the ultrasonic beam direction, and most of the materials behave as they are anisotropic.

Scattering occurs at grain boundaries, small cracks or other discontinuities because of reflections. It causes serious energy loses which can make a specimen uninspectable. But it is useful in measuring grain size in metals nondestructively [26].

Attenuation can be formulised in terms of attenuation coefficients as follows and some typical ones for engineering materials are given in Table 2.3.

$$\delta = \delta_T + \delta_S \tag{2.10}$$

$$I = I_0 \exp(-\delta m) \tag{2.11}$$

**Table 2.3** Typical attenuation coefficients for engineering materials [26]

| Material | Frequency (MHz) | Mode | $\delta$ (dB/m) |
|---|---|---|---|
| Pearlitic steel | 5 | Compressional | 6.1 |
| Pearlitic steel | 2.25 | Shear | 8.8 |
| Stainless steel | 2.25 | Compressional | 110 |
| Aluminum | 2.25 | Compressional | 90 |
| Plastic (clear acrylic) | 2.25 | Compressional | 380 |

The changes in intensity or amplification is measured in units of decibel (dB). A decibel is 1/10th of a bel, which is a unit based on logarithms to base 10 [2]. As the decibel unit is based on a logarithmic scale, it is convenient to use this unit when the measured parameters vary over a very large scale. So if the difference between two amplitudes is known as n decibels, it can be shown as;

$$n = 20\log_{10}\left(\frac{A_1}{A_2}\right) \text{ decibels} \qquad (2.12)$$

If the amplitude ratio between two ultrasonic waves is 2:1, then the difference between them can be calculated to be 6 dB. Even though the decibels values can be added or subtracted arithmetically; amplitudes must be multiplied. Table 2.4 shows how amplitudes changes with respect to decibel values.

**Table 2.4** Decibel values vs. Amplitudes [2]

| Decibel Value | Amplitude ratio |
|---|---|
| 3 | 1.41 |
| 6 | 2.00 |
| 10 | 3.16 |
| 20 | 10.00 |
| 30 | 31.60 |
| 80 | 10000.00 |

## 2.3 ULTRASONIC TESTING

During ultrasonic testing of materials some equipments like transducers or probes, amplifiers, signal converters and oscilloscope screens are needed. The probes are used to generate ultrasound and receive the reflected pulses coming from the flaws, edges or other surfaces of the specimen. These pulses are converted to electrical signals by probes again, then amplified and displayed in a scan on a timebase on an oscilloscope screen. The time interval between the transmitted and reflected pulses observed on the screen is a measure of the distance of the discontinuity from the surface, and size of the return pulse can be a measure of the size of the flaw. This is the simple principle of the ultrasonic flaw detector [2]. The ultrasonic sound waves penetrate many of the materials used in industry very easily and there is no significant radiation hazard requiring any precautions. Also nearly 90% of ultrasonic testing is still carried out manuelly.

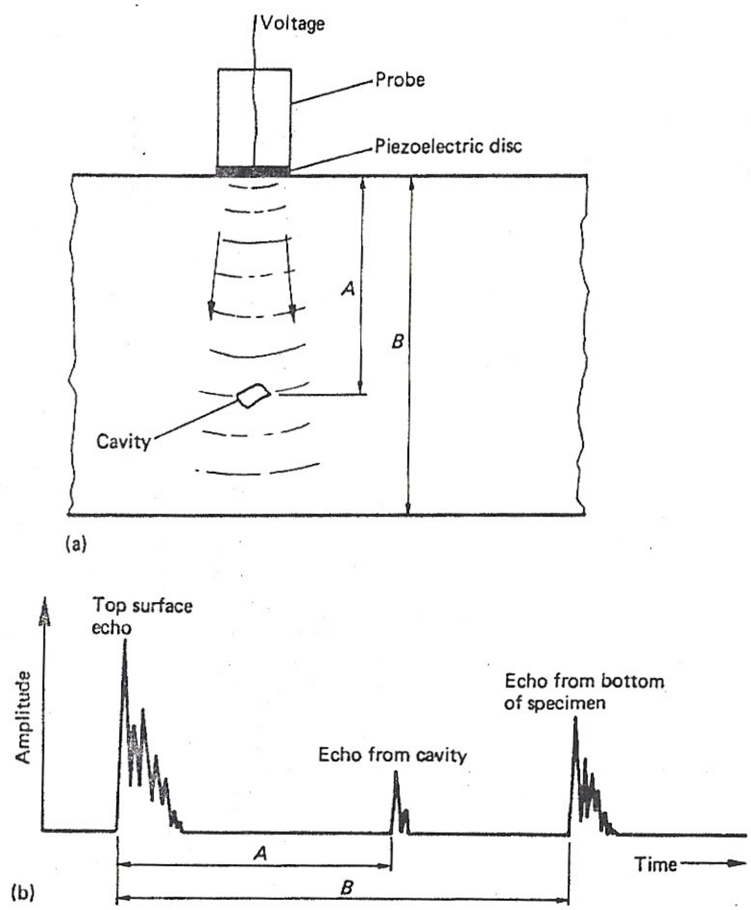


**Figure 2.11** Simple principle of ultrasonic flaw detector [2]

Even though ultrasonics is used to size slits in this study, its use in finding flaws should not be thought of separate. The precision of the technique is important in its success in flaw detection [3]. This precision is required in the location of the flaws or other inhomogeneities both laterally and in depth. To obtain the precision in measurements of the distance of a flaw and its direction with respect to the source, the sound waves being used must be relatively narrow [4]. This kind of sound waves can be generated by large diameter probes having a longer near field length which will be discussed in the next sections. So before getting into the structure of the probes and calibration blocks, the author thinks it is necessary to know how the ultrasonic waves are generated.

### 2.3.1 Generation of Ultrasonic Waves

As mentioned before ultrasonic waves are mechanical vibrations having a frequency over 20 kHz. In order to create a vibration like this, some materials having different characteristic properties and different methods are being used. Some of these methods are:

- Magnetostriction effect: Materials having this property change their original shape when a magnetic field is applied. One of the most useful material in this class is nickel. Transducers using this method to generate ultrasound has very low frequencies smaller than 200kHz. For this reason they are used generally to examine concrete like materials.

- Electromagnetic-Acoustic (EMA) effect: Ultrasonic waves can be generated by direct coupling between an external coil and the electronic currents generated in the surface layer of the material. This method is finding a larger area of application in flaw detection from day to day.

- LASERs: A point on the surface of a speciman is hit with laser pulses. The electromagnetic radiation created by the LASER, is partly absorbed and it causes sudden temperature rises, thermal expansions and a pulse of elastic compressive waves parallel to the surface.

- Piezoelectric effect: A piezoelectric material produces electric charges on its surface if it is deformed by an external pressure. This works the other way around, too. If an electric potential is applied to the material, it changes its shape and this is called the 'inverse piezoelectric effect'. So by altering the potential, a mechanical oscillation can be produced. In NDT, most of the transducers use this inverse piezoelectric effect to generate ultrasound. Some natural crystals like quartz and lithium sulphate, Rochelle salt and fabricated polycrystalline ceramics like barium titanate are examples of materials having this effect. These various piezoelectric materials differ according to piezoelectric modulus, heat resistance, mechanical strength, and ease of processing. Some properties of these materials are given in Table 2.5. Some of these properties of materials can be improved by additives and special production processes [8]. But most piezoelectric materials have a high acoustic impedance values, and are not prefered either in immersion techniques or with liquid couplants.

**Table 2.5** Properties of some Piezoelectric materials [26]

| **Material** | **Piezoelectric modulus $10^{-12}$.(m/v)** | **Density g/cm$^3$** | **Maximum permissible stress, MN/m$^2$** | **Maximum permissible temperature, °C** |
|---|---|---|---|---|
| Quartz | 2.3 | 2.65 | 100 | 550 |
| Rochelle salt | 150 | 1.77 | 15 | 45 |
| Ammonium dihydrophosphate | 8.7 | 1.80 | 20 | 125 |
| Barium-titanate ceramics | 190 | 5.7 | 80 | 120 |

### 2.3.2 UT Probes

The most important equipments used in NDT are definitely the probes. Ultrasonic waves are produced with the piezoelectric materials found in these probes. They are usually circular in shape, and typical diameters are 6 – 30 mm, with a frequncy range of 1 – 15 MHz [2]. This range of frequency is used usually for structural materials such as steel. But sometimes when very small flaws are searched, the frequency value may jump up to 50MHz [3].

The piezoelectric crystal is found on the bottom side where the probe touches the specimen. But the crystal faces are metallised, either by coating electro conductive ink or vacuum deposition of nickel with an over-coating of alumininum produced by ionic bombardment for wear protection. The crystal is backed also with a damping material which has a similar acoustic impedance with the crystal, to prevent the created sound waves reflect back to the crystal again from the probe's inner surfaces. For this reason damping material must be highly absorbent, and bonded to the crystal very well.

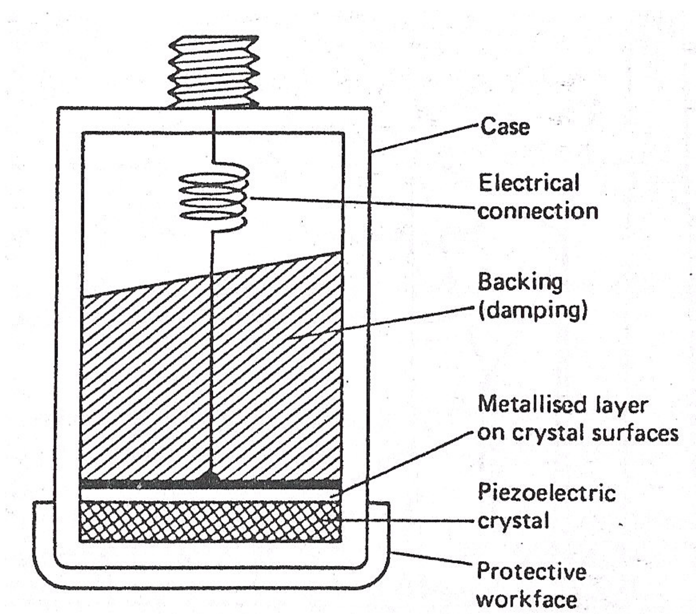


**Figure 2.12** Cross section of an ultrasonic probe [2]

Different kinds of probes can be produced with different arrangements of piezoelectric crystals. There are mainly 5 types of probes being used currently in industry:

- Straight beam probes
- Angle beam probes
- TR probes
- Focussing probes
- Phased Array Probes

Actually in every probe compressional sound waves are generated, but with the help of some wedges or shoes they are mode converted to the desired type of sound waves. In angle beam probes, only shear waves propagate into the specimen because the associated compressional wave is totally reflected back into the probe at the interface. Also angle compressional wave probes can be produced with an accompanying shear wave but they are generally used in special studies with high angle beams for the detection of surface breaking cracks.

When compressional waves are being used tough, they are usually send into the specimen with a direct transmission because it is easy to achieve and shear waves are not generated by mode conversion at normal incidence. But it should not be misunderstood that all the shear wave beams are angled and compressional wave beams are normal [3].

The shape of a typical main lobe of a sound beam created by a circular probe is given in Figure 2.13. The lobe is a constant pressure plot of the emitted energy but there are erratic pressure fluctuations in the 'near field' (N) adjacent to the probe. Beyond the near field, the pressure decays smoothly as a function of the distance from the probe and it is called the 'far field'. The final maximum value of the pressure fluctuations occur at the near field length and it can be calculated by equation (2.13). In order to have reliable measurements with a probe, the flaws searched should be in the far field to eliminate any errors caused by the fluctuations in the near field.

$$N = \frac{D^2}{4\lambda} \tag{2.13}$$

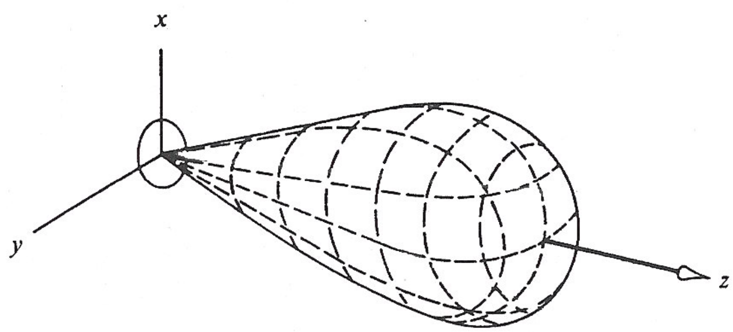


**Figure 2.13** Pressure pattern of the major lobe for a piston source [26]

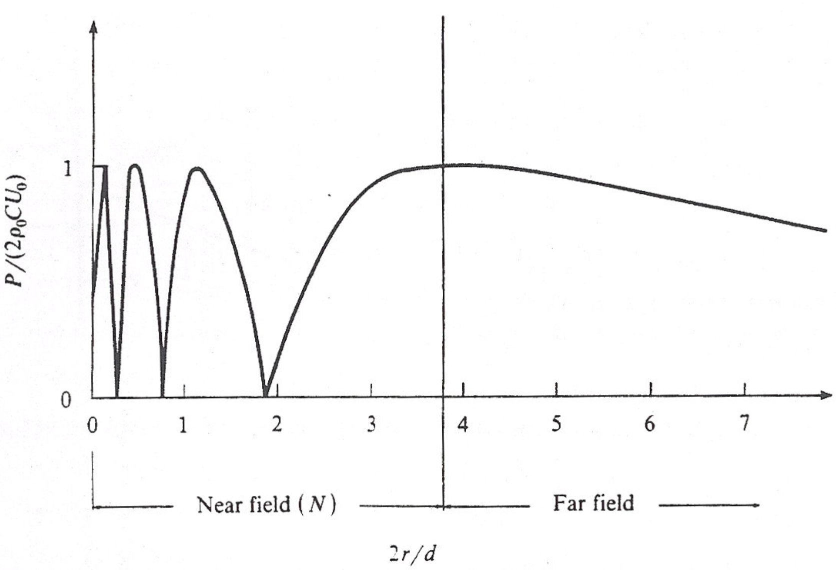


**Figure 2.14** Pressure fluctuations along the axis of sound beam, $d/\lambda = 8$ [26]

One important feature of probes is that in many applications they need a couplant between the crystal and specimen surfaces in order to maintain ultrasonic contact. The couplant should have as high acoustic impedance as possible, and must be non-corrosive, non-toxic, high viscosity and inexpensive. Oils, with different viscosity values are the most common couplants. Even tough the couplant layers reduce the sensitivity of test results and prevents shear waves to penetrate into the specimen, they are indispensable in UT.

The angle of the sound beams being generated, and the probe index points are also very important characteristic of any probe and they need to be determined for each individual probe with the help of calibration blocks.

### 2.3.3 Calibration Blocks

In order to obtain reliable test results, the probes have to be calibrated before each test with the calibration blocks. These blocks are designed only for use with contact probes and should be made of the same material with the test specimen. In industry two blocks called the K1 and K2 are being used for this purpose.

As mentioned before ‘probe index’ and ‘probe angle’ are two important parameters of probes, and these can also be measured by the calibration blocks. The true probe index can easily be calculated at the engraved mark on the K1 calibration block where the maximum signal amplitude is obtained from the quadrant surface. The mark is also the center of the curvature of the quadrant.

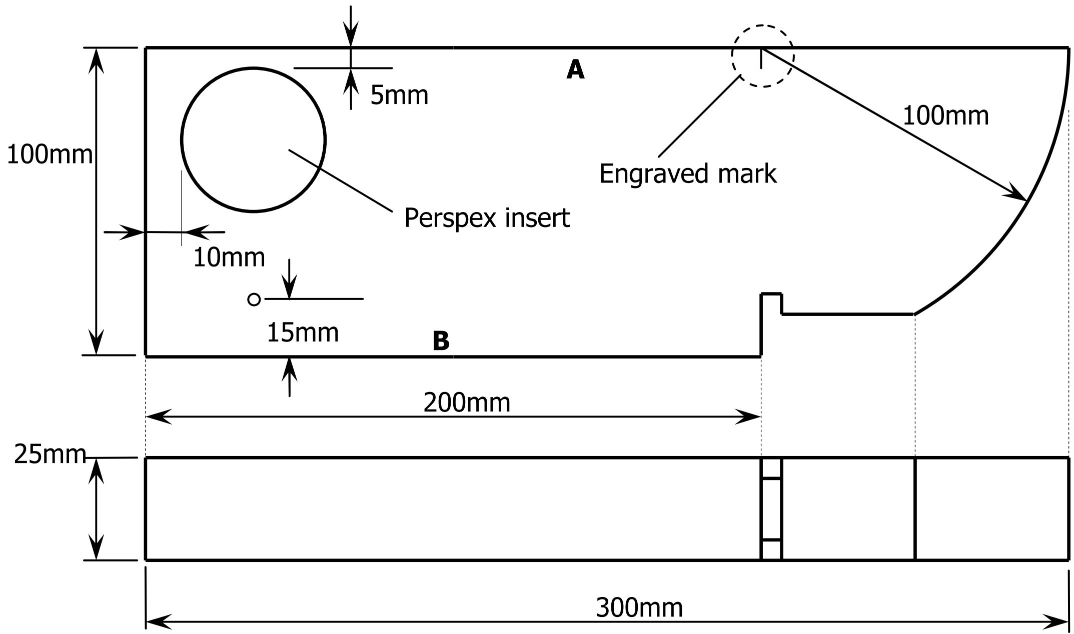


**Figure 2.15** K1 Calibration block [6]

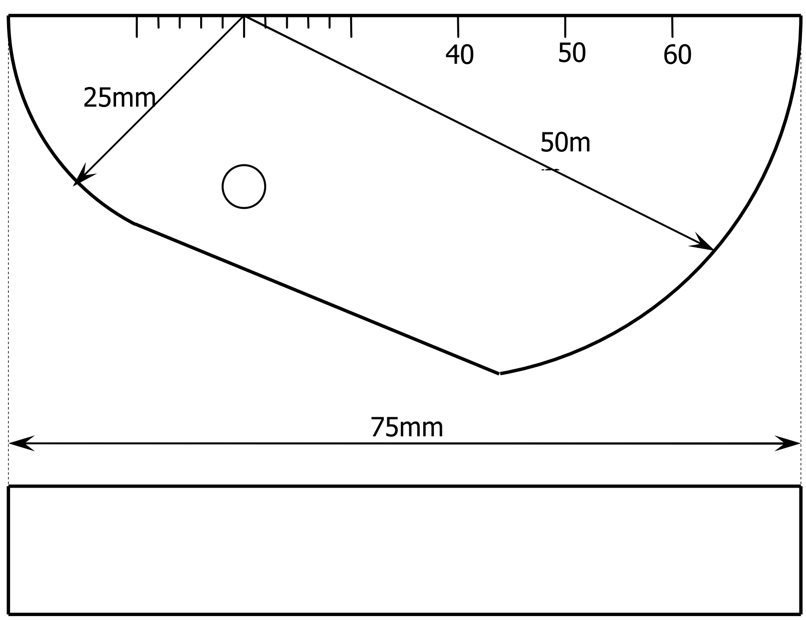


**Figure 2.16** K2 Calibration block [6]

With the probe index determined, the probe angle is found by directing the ultrasound beam at the 50 mm hole from surface B. The angle value is then read from the marking corresponding to the probe index when the echo height is maximized. K2 calibration blocks can also be used for probe angle determination. They are miniature blocks for easy usage on site.

# CHAPTER 3

# TIME OF FLIGHT DIFFRACTION

## 3.1 INTRODUCTION

Ultrasonic testing is used firstly to detect and then size internal flaws in areas and structures like water or gas-cooled nuclear pressure vessels and nozzles, other nuclear components, turbine and generator components, offshore structures, weld inspections, monitoring defect growths, and inspection of steel bridges where catastrophic failures can occur. As the most serious defect in a stressed component is a crack perpendicularly oriented to the principle stress, measuring the height of crack like defects as precisely as possible is very important.

The critical crack size for different materials can be calculated from equation (3.1). These values are 27 $\mu$m for glass, 1.3m for steel in infinitely wide and thick plates, and they are further reduced for realistic sized structures [1].

$$a_C = \frac{2WE}{\pi\sigma^2} \tag{3.1}$$

For this purpose different measurement techniques have been used like 'pulse-echo' and 'through-transmission' which are the most widely used ones in ultrasonic testing.

In pulse-echo technique one probe is used to send and receive pulses from one side of the specimen while two probes are used on opposite surfaces of the specimen in through-transmission technique. In both of these techniques, the size and position of the flaw is estimated by the reduction of the intensity of the transmitted ultrasonic energy as it travels between the probes and the other surfaces, which can be observed from the received signals on the CRT screen of oscillators. In order to use the amplitude of signals as a quantitative estimator for crack heights, the defect dimensions should be smaller than 1-2 $\lambda$ and they are affected by some factors like coupling layers, reflectivity, the angle and type of the defects [13,15]. So even though the defects could be located, there was very little precision in sizing them.

In order to overcome the affect of these factors and increase the accuracy and precision in measuring the through-wall size of crack like defects, another way of measurement is found which is mostly based on the diffraction process of soundwaves.

## 3.2 TIME OF FLIGHT DIFFRACTION (TOFD):

### 3.2.1 Diffraction

Just like a light beam bending into the shadow zone behind an obstacle on its path, ultrasonic sound waves also diffracts from the ends of cracks in a material. And because of their larger wavelengths in the order of a few millimeters in comparison to light, the diffraction effect can be observed much more easily in sound waves. Also specular reflections used in pulse-echo techniques can only occur for a limited range of orientations of defects and when these reflections are absent, the returning signals are the ones created by scattering from the surfaces of the crack and by diffraction from the edges of the crack. As the diffracted signals are associated with the extremities of the defect and travel in all directions from the edges, they may be used in estimating the size of the defects. The angular distribution of these diffracted waves does not depend on the frequency.

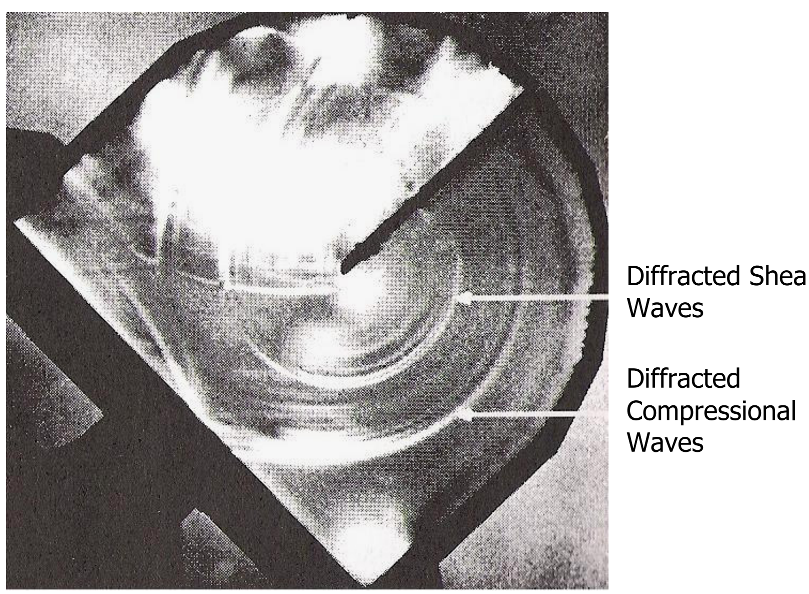


**Figure 3.1** Ultrasonic diffraction at the tip of a slot [1]

### 3.2.2 The Technique

Although Dr.Miller was the first person to detect diffracted signals from crack tips in 1970, he missed the opportunity of inventing the Time of Flight Diffraction (TOFD) technique by not recognising where the signals were coming from. So the technique has been invented by Dr. Maurice Silk at the Harwell Laboratory in National NDT Center in England, over a period of 10 years starting in the early 1970s. The thought behind the technique can be summarised as follows:

" If pulse-echo inspection, while usually based on a search for specular reflections, is actually relying in some cases of diffracted waves for accurate sizing, would it not be advantageous to design a technique which is aimed directly at those diffracted waves and which deliberately avoids the specular reflections which may mask them? In addition, timing measurements may be made to high accuracy and if this can be used to size defects, the defect size should be measured accurately." [1]

The technique has been called "the Time of Flight Diffraction" because the only significant information is in the signal timing and it is regarded as a very accurate sizing method for cracks. But even though the amplitude of signals are not used for sizing defects in TOFD, there are still some situations where they are employed in TOFD measurements.

- Where the searched pulses of flaws can be resolved against the local backgound noise.

- Where the diffracted pulses from the extremities of flaws may provide important information about the flaw itself.

- Where an artificial flaw pulse is being used for calibration purposes. [14]

Generally the method is used with two probes, one transmitting and the other receiving compressional waves. But it can also be conducted with a single transducer using shear waves which can be regarded as a special case of TOFD where the reflection of shear waves are taken into account [13]. For efficient usage of the technique at least two probes are needed because the calculated height is more affected with separation errors and the angle of received signals need to be known accurately for a single probe test.

As the wave velocity of shear waves is only about half that of compression waves, they are not preferred in TOFD measurements. So the primary diffracted signals are compressional waves and arrive the receiver transducer before any other signals travelling in the specimen.

As discussed in the previous chapter the mode conversion property of ultrasonic waves at boundaries between two different media and at the free surfaces, makes this technique complicated than it is thought. In order to use compressional waves with appropriate angles you need to use some wedges too. Accompanying shear waves are created by mode conversion because of these wedges. They increase the number of received signals to great numbers which makes it very hard to separate the desired signals from the other ones.

The mode converted waves are not the only factors effecting the technique though. There is also another wave motion occuring at stress-free boundaries which is called the Rayleigh wave. As this type of creeping waves expand in two dimensions only, they carry their energy further from the source creating large signals which can be confused with bulk wave signals. As a further information

Rayleigh waves are the type of waves which creates most destruction in earthquakes.

Beside the factors mentioned above there found to be also four possible disadvantages in the use of this technique.

1. The technique can not be expected to size very small cracks with a lower limit of 3-4 mm because of the width of the probe beam and the physical size of transducers; and to eliminate Rayleigh waves during measurements.
2. It is very difficult to achieve a constant coupling factor and differences of 2-3 dB are not uncommon.
3. The angle of the crack might have a great effect on the magnitude of received signals.
4. In many steels the most obvious causes of scattered ultrasonic waves are the inclusions. Therefore the affect of inclusions introduces an amplitude variation which might affect the reliability and sensitivity of the technique [12].

The schematic representation of TOFD technique is given in Figure 3.2. In the technique two probes are being used as transmitter and receiver. When a surface breaking crack in an isotropic homogeneous material is investigated, the energy incident on the surface of the crack is reflected just like a mirror if the crack face is smooth and the reflected energy is directed away from the transducers. Even though most of the energy is not transmitted to the transducers in this way, some fraction of the energy is scattered from the edges of the crack and reaches the receiving transducer with the backwall echo. These signals may appear on the CRT screen as shown in Figure 3.3.

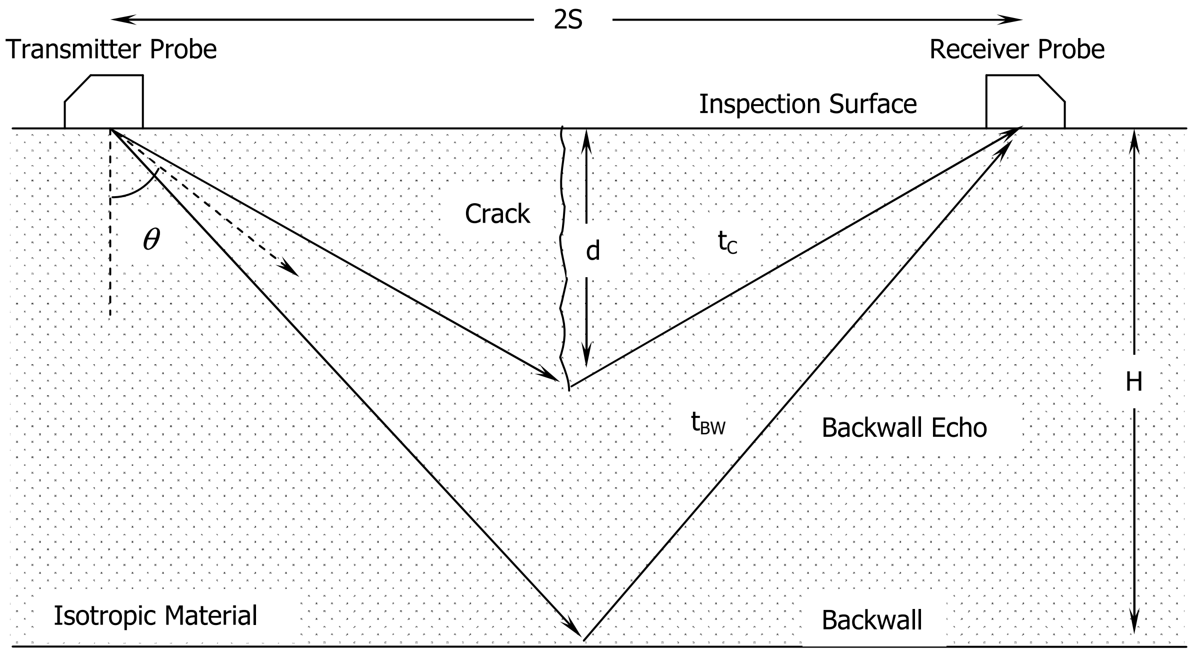


**Figure 3.2** The two probe basis of the Time of Flight Diffraction technique for surface breaking cracks.

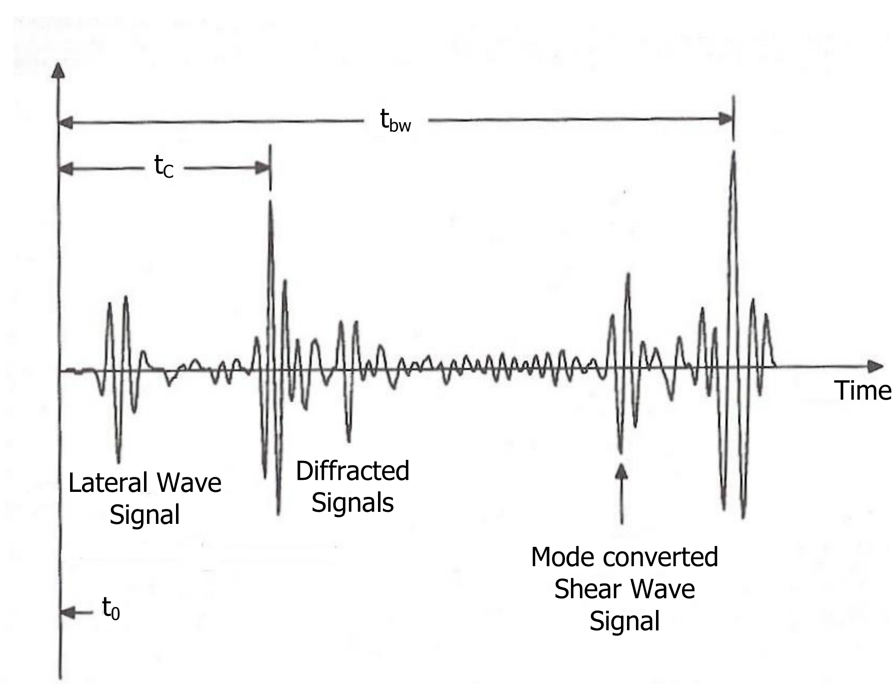


**Figure 3.3** Some expected signals for an internal crack [9]

There are two conditions which are very important and need to be fulfilled in order to assume that the ultrasonic wavefront is coming from a point source regarding the crack edge and converging on a point detector.

- First condition: The crack edges creating the diffracted signals have to be in the Far Field of the transmitter and receiver probes.

- Second condition: The diffracted source should lie on or very close to the beam axes of the transmitter and receiver probes.

After these two conditions are met, the assumption will be sufficiently accurate. And Pythagoras's theorem can be used to calculate the crack height from the inspection surface. The time travel of sound waves in the test material and the crack height in Figure 3.2 are found from the equations below.

$$t_C = \frac{2\sqrt{S^2 + d^2}}{C} \tag{3.2}$$

$$t_{bw} = \frac{2\sqrt{S^2 + H^2}}{C} \tag{3.3}$$

$$d = \frac{1}{2}\sqrt{C^2 {t_C}^2 - 4S^2} \tag{3.4}$$

As mentioned before the shear waves are not preferred in this technique because of its difficulty in interpretation. So in order to eliminate the shear wave signals from the area which is important in our measurements, an appropriate probe separation can be chosen. So that any shear wave signals arrive at the receiver probe after the compressional wave backwall echo. It may also optimize insonification of the area of interest, ensure adequate diffracted energy from crack tips, and maintain acceptable resolution of signals [14]. This probe separation is calculated from the equations (3.5) and (3.6). The first parameter in the equation is representing the shortest travel time of shear waves which is the direct way from the transmitter to the receiver transducer and the second parameter is representing the travel time of compressional waves reflecting from the backwall of the specimen. So the favorable probe separation found to be larger than $2H/\sqrt{3}$. It may be small enough for resolving or large enough for insonification purposes [1,14].

$$t_{Surface}(shear) \rangle t_{bw}(compression) \tag{3.5}$$

$$\frac{2S}{V_S} \rangle \frac{2\sqrt{S^2 + H^2}}{V_C} \quad (V_C \cong 2V_S) \tag{3.6}$$

The probe positions are assumed to be symmetric around the crack during measurements. But this is not the case mostly and the crack's position changes between the probes, not necessarily at the midway point as shown in Figure 3.4. The possible distribution of crack tips form an ellipse shape in the material where the time travel of diffracted signals are constant by placing the probes at the foci of this ellipse. In this type of measurements, there are some ambiguity which decays as the points gets closer to the midway position. In order to eliminate this ambiguity in measurements the crack may tried to be fixed at the midway point between probes or the number of probes can be increased to three.

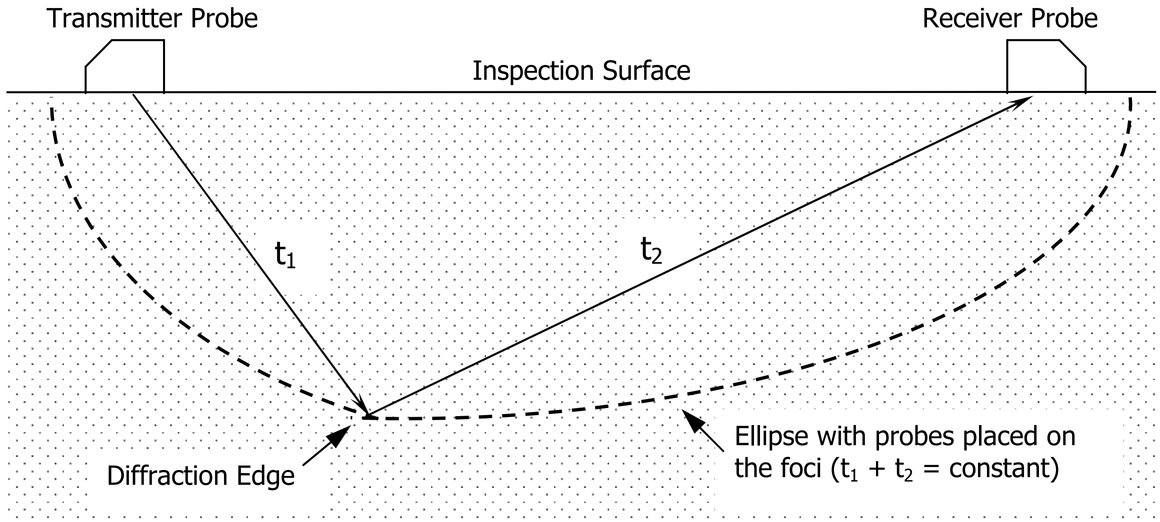


**Figure 3.4** Elliptical locus of points with constant travel time from transmitter probe to receiver probe [1]

During measurements when the probes are scanned over the inspection surface together parallel to the plane defined by the beam axes, the diffraction signal received from the crack tip has a general hyperbolic shape on the screen. The shape of this signal flattens near the minimum as the crack tip gets closer to the inspection surface. As the amplitude of diffracted signals are smaller compared to specular reflection signals and affected by some factors like compressive forces on the crack face, crack orientation with respect to the probes, the nature of the crack tip; higher gain values during measurements are needed.

Mostly different angle beam probes are being used in inspections because of the range of angles where the defects may occur is not known. So according to ASME the inspections require 0°, 45°, 60° and 70° angle beam probes and generally the peak of a diffracted signal from a crack tip with a good resolution is received with probes having beam angles between 60° - 75°. However a knowledge of the precise beam angle is not necessary for TOFD inspection and a variation of $\pm 5°$ from nominal do not affect the quality of inspection [14].

### 3.2.3 Factors Effecting the Measurements

The sensitivity and accuracy of measurements done in TOFD technique is better than the other ultrasonic testing techniques. But besides this advantages of TOFD, there are still some parameters which effects the measurements to some extend. These parameters can be listed and summarised as follows:

- Probe shoe: In order to use angled longtidunal sound waves in contact type testing, wedge-shaped shoes are needed. The usage of shoes increase the travel distance and consequently the travel time of sound waves. This extra travel time can be added to the transit time of all the signals as a constant probe delay which can be calculated during the calibration process and used in all the tests by setting up the ultrasonic testing device.

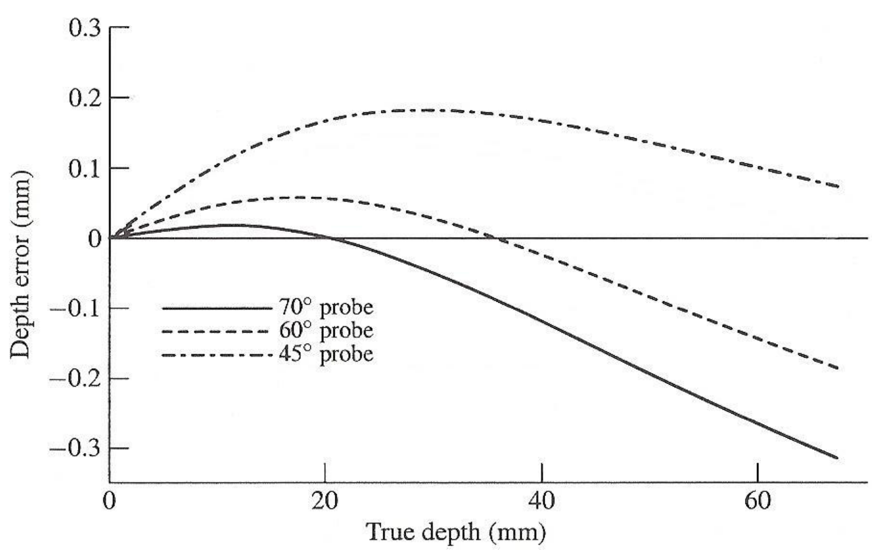


**Figure 3.5** The effect of probe shoe on height estimation [1]

- Coupling thickness: Normally the thickness of coupling material used between the probes and the test surface is so small that its influence on the timing of ultrasonic signals is negligible. This thickness may change up to a value of 0.5 mm above which is unusual.

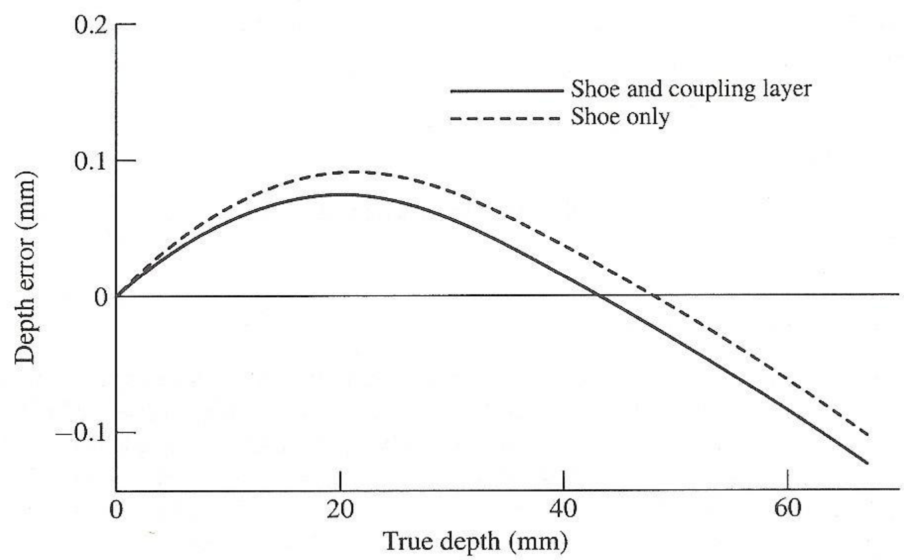


**Figure 3.6** The effect of 0.5mm coupling layer on height estimation [1]

- Velocity variation: The material tested should be homogeneous and isotropic in order to prevent significant errors in measurements. To check if there are any variations in the velocity of ultrasonic signals in the material, the timing of backwall echoes can be monitored. The probe delay must be known in this process.

- Inspection surface: It should be a smooth flat plane like machined, as-rolled or lightly corroded surfaces. Any departures in flatness may cause misalignment between transmitter and receiver probes and degrades the accuracy of measurements. The roughness of the surface condition may also affect the height estimation up to 3.5mm. The greater scattering ability of rough defects causes an overestimation of defect size [17].

- Misorientation: Even a few degrees of difference from the specular orientation of a circular defect, the amplitude at the probe decreases very rapidly as the misorientation increases. About a 15° difference reduces the signal strength by 6 db from the perfect orientation. But this is not the case when the defect is a crack which is perpendicularly oriented to the inspection surface and the line joining the probe index points. The signal amplitude decreases very smoothly as the skew angle between the line joining the probe index points and the crack mouth increases.

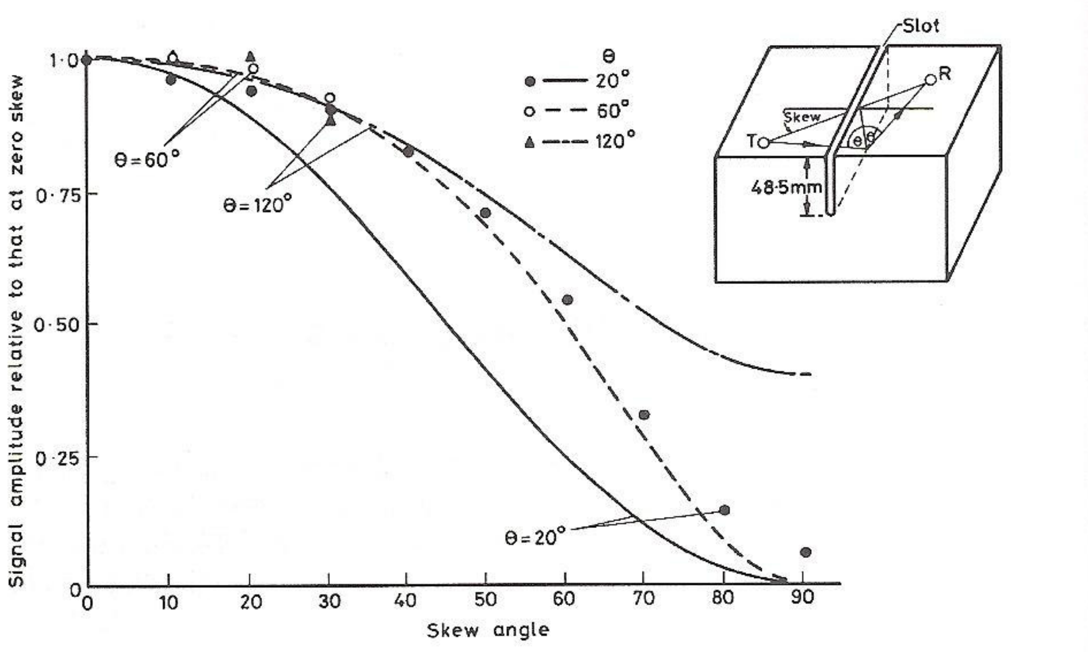


**Figure 3.7** The effect of crack skew on TOFD Signals [1]

- Influence of Stresses: It has been shown that the signals received from fatigue cracks are reduced with decreasing acoustic reflectivity of crack tips at the same time when compressional loads are applied to the crack. Without any load, the crack tips can be determined more clearly from other indications on oscillator screens [31].

In addition to the above parameters which need to be controlled carefully, there are also some important points in the application of TOFD technique. One of them is the preferred usage of smaller probes because of their wider sound beam output which are less distorted. In materials having high attenuation, the pulse shapes change a lot and as the attenuation increases with frequency, probes having lower frequency values are preferred in these measurements.

# CHAPTER 4

# EXPERIMENTAL WORK

## 4.1 TEST EQUIPMENT

During the experiments a digital oscillator, 7 probes having different angles and frequencies, two sets of Plexiglas wedges to work with longitudinal wave probes in an angled arrangement, and three sets of test blocks for crack simulation are used.

### 4.1.1 Test Blocks

The material of the test blocks is hot rolled St 60 steel and they are purchased from Ankara Celik Boru Company having a square cross section of 50x50 mm. Then the material is cut and milled according to the dimensions given in the technical drawing of test blocks in Appendix C. The inspection surfaces of test blocks are also ground for better sound wave transmission and to reduce the wide spread distribution of the amplitude values [25]. All these processes took place in the workshop of mechanical engineering department. After having the desired outer dimensions, the blocks are taken to the METU CAD/CAM Center and the slits are opened with the EDM.

The travel time of each sound wave type across the blocks are measured by 3.5 MHz Panametrix straight beam longitudinal wave and 2.25 MHz Panametrix straight beam shear wave probes from every surface. They are found to be 13.6 $\mu \sec$ for longitudinal and 24.8 $\mu \sec$ for shear waves from inspection surfaces. So the velocities of sound waves in the test blocks are calculated as 5882.35 m/s for longitudinal and 3225.8 m/s for shear waves according to the height of test blocks. Also any anisotropy and defect is searched with ultrasonic and radiographic methods. The test blocks are found to be isotropic without any change in sound velocity values with respect to directions and include no defect.

### 4.1.2 The Plexiglas Wedges

Angled longitudinal sound waves are used during the inspections with the Time of Flight Diffraction method. As there are only straight beam longitudinal wave probes found in the laboratory, some wedges were needed to make this probes behave as angled beam probes. For this reason two wedge pairs from Plexiglas material are designed in order to send the longitudinal sound waves into the test blocks with angles of 45° and 70°. The angles are selected as the previous studies about this topic are considered and because of their general usage in industry. In addition to this, 60° angled beams are not used in this study because of the full mode conversion problem during their usage.

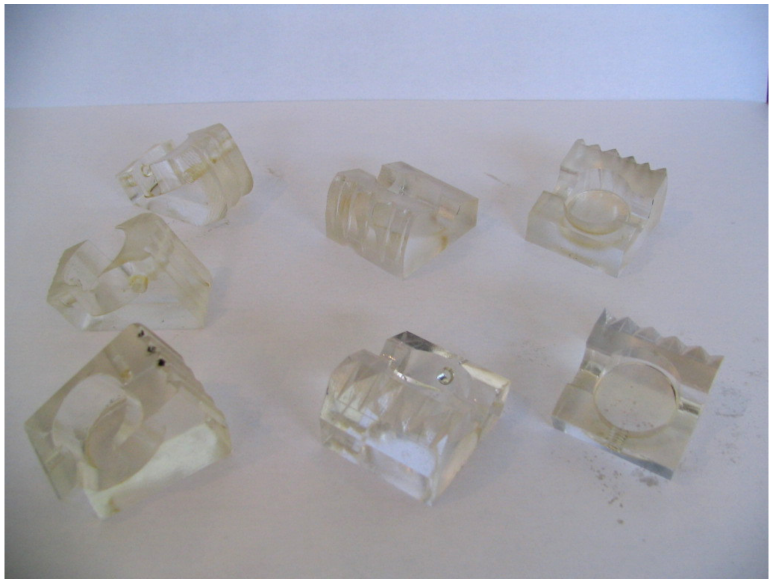

**Figure 4.1** The Plexiglas Wedges

Many wedges are manufactured for the thesis study but most of them did not work correctly. The problems occurred because of the tandem usage of two probes during the tests in TOFD method. The wedges needed to be almost identical to receive the optimum sound waves when they faced each other. The first trials are done in the workshop of mechanical engineering department but because of insufficient accuracy of the old machines and separate production, it is understood during calibration that they would fail in tests. The received signals during calibration should have their highest values when the wedge is perfectly parallel to the side edges of the calibration block K1 which was not the case for the first trials of wedges. Three of these obsolete wedges are shown on the left hand side of Figure 4.1.

After these failures, the author decided to manufacture the wedges in CNC machines in TeknoTes Company in OSTİM. The wedge pairs are manufactured at the same time in order to make the dimensions as identical as possible. These wedges are shown on the right hand side of Figure 4.1 as two pairs and worked properly. The wedges on the lower part are used to create 70°, and the others above are used to create 45° longitudinal sound waves in the test blocks.

The technical drawings of the wedges are given in Appendix D. But the notched parts seen in Figure 4.1 are not shown in these drawings. They are created with a file by the author in order to save time during production. Their aim is to scatter the reflected sound waves in the wedges as much as possible and minimize the amount of waves returning to the probe itself.

As the CNC machines had only 3 axes, the desired angles are adjusted manually which created an inaccuracy. So in order to make as little error as possible the angles of bottom faces of drilled holes where the probes are placed, are chosen as 20° and 26° corresponding to almost 45° and 67° in test block material. They are calculated with the help of Snell's law discussed in Chapter 2.

The angles of each wedge pair is controlled by a mechanism shown below in Figure 4.2. The mechanism consists of a circular steel part with a flat surface on the top where the probe wedge pairs are placed and fixed. Two sensors for both longitudinal and shear sound waves which can move across the circular part, are used to catch the ultrasonic waves at proper angles. Both the sensors and the probe wedge pairs are connected to the digital oscillator. When the produced sound waves by the probe, meets the sensor after through transmission a signal is spotted on the screen and the angle can be read at the same time. After the control of each wedge probe pair, it is observed that the wedges produce sound waves at the desired angles.

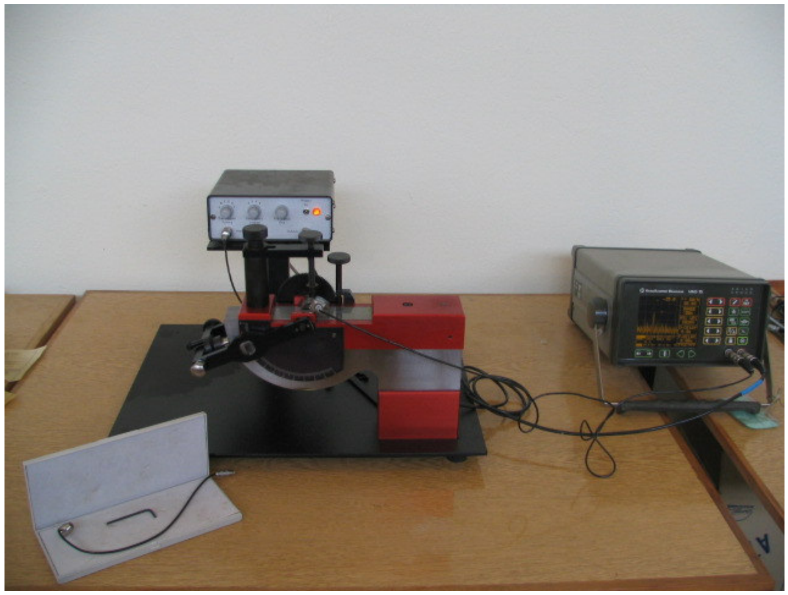

**Figure 4.2** Angle control mechanism

**Figure 4.3** Close up view of angle control mechanism

### 4.1.3 The Probes

During the tests 4 MHz and 5 MHz straight beam longitudinal and 4 MHz 70°, 4 MHz 45° and 2 MHz 45° angled shear wave probes are used. The shear wave probes are shown on the left hand side and longitudinal wave probe pairs used in TOFD method are shown on the right hand side of Figure 4.4.


**Figure 4.4** The probes used during tests

### 4.1.4 Digital Oscillator

Krautkramer Branson USD 15 digital oscillator is used during the tests. The advantages of using a digital oscillator rather than an analog one is obvious. Its user interface is easy to understand and makes it operational during tests. The clear LCD screen makes the signals more visible and with the help of its memory, it is not needed to calibrate the probes before every measurement. Even though it is turned off, it keeps the last settings like measurement range, gain value, sound velocity, probe delay time, display delay length, etc. in its memory; and the tests can be continued wherever it stopped. It also has a straight forward user manual which helps a new user to start any measurement in a very short time. But it can only measure the sound beam paths to an accuracy of 0.1 mm.


**Figure 4.5** Krautkramer Branson USD 15 digital oscillator

## 4.2 TEST METHODS

### 4.2.1 Time of Flight Diffraction Method

The method is discussed in the previous chapter in detail. In this method two wedge probe pairs are used as tandem arrangement. The transit time of diffracted longitudinal waves from various slit tips are measured and from these measurements the heights are calculated from a triangle of diffraction according to equation (4.1). The main picture of TOFD is also given in Figure 4.6. As the TOFD method is based on the transit time of sound waves rather than on reflected pulse amplitudes, the author did not have to think about the serious limitations like flaw angle, flaw surface roughness, flaw transparency, flaw shape, material attenuation, coupling efficiency, reflectivity, the orientation and type of defects, etc [11].

$$d = \sqrt{(h_c)^2 - (S+x)^2} \qquad (h_c = t_c \cdot V_C) \qquad (4.1)$$

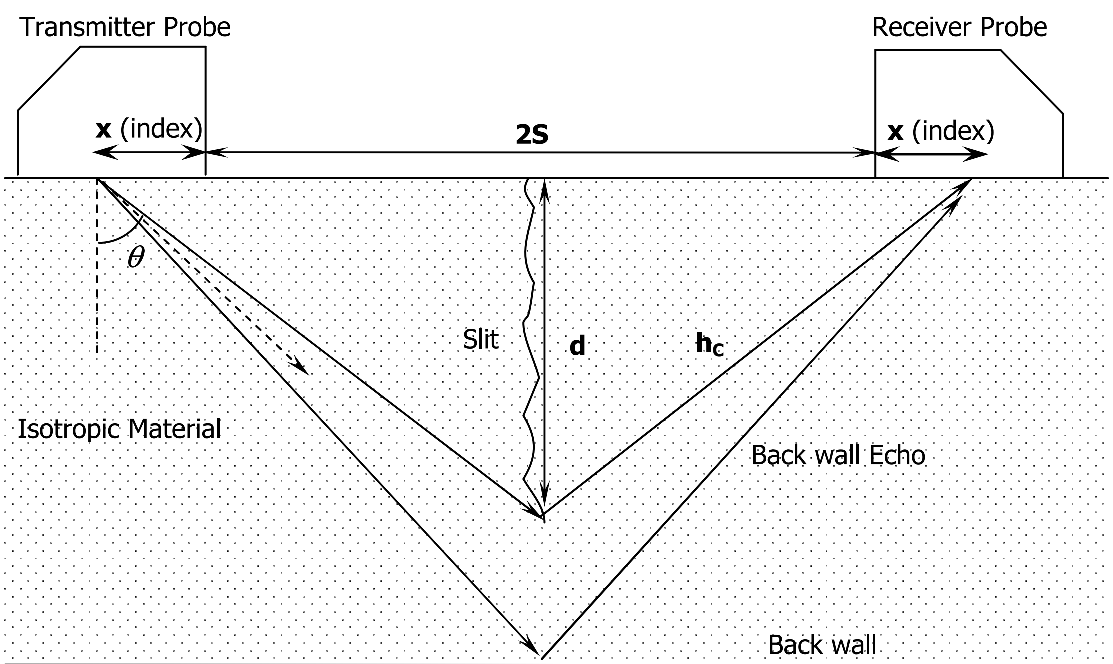


**Figure 4.6** The TOFD Method

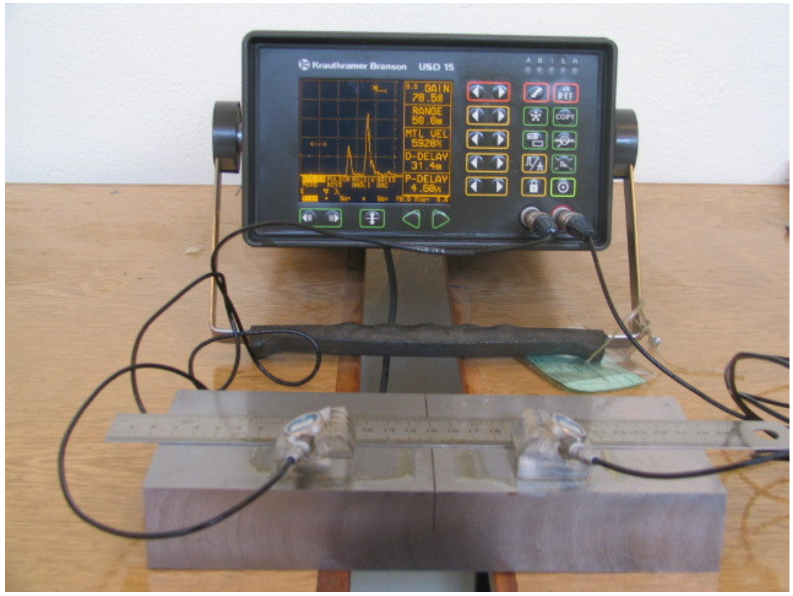


**Figure 4.7** The TOFD Method test setup

As physical lengths are important in calculations of slit heights in TOFD method, the index points of each wedge probe pairs are measured during calibration before each test. In addition the sound beam travels not only in the test block but also in the Plexiglas wedge. So the travel time of sound in the wedge generates an additional time to the overall transit time and this value is also set during calibration process which is known as "*probe delay time*". The calibration process is discussed at the end of Chapter 2.

Another important physical length which is the distance between the slit tip and the index point of wedge probe pairs is directly measured by the oscillator as the known sound velocities for test blocks are set in the digital oscillator. Here the important point is to distinguish the diffracted sound wave signal between all the signals found on the LCD screen of the oscillator. That is why TOFD method is a hard method to apply. After the diffracted sound wave signal is determined, the measurements can be continued.

As the travel distance of diffracted sound wave is shorter than the sound wave reflecting from the back wall, it should be expected to receive a signal before the back wall echo signal. The back wall echo signal can easily be determined when the point on the back wall where the sound beam reflects back to the receiver probe is touched. This contact absorbs some of the energy of the sound beam which creates some flickering of the back wall echo signal. After determining this signal, it is easier to find the diffracted sound beam signal. The signal on the right hand side of the diffracted sound beam signal in Figure 4.8 is the back wall echo signal.

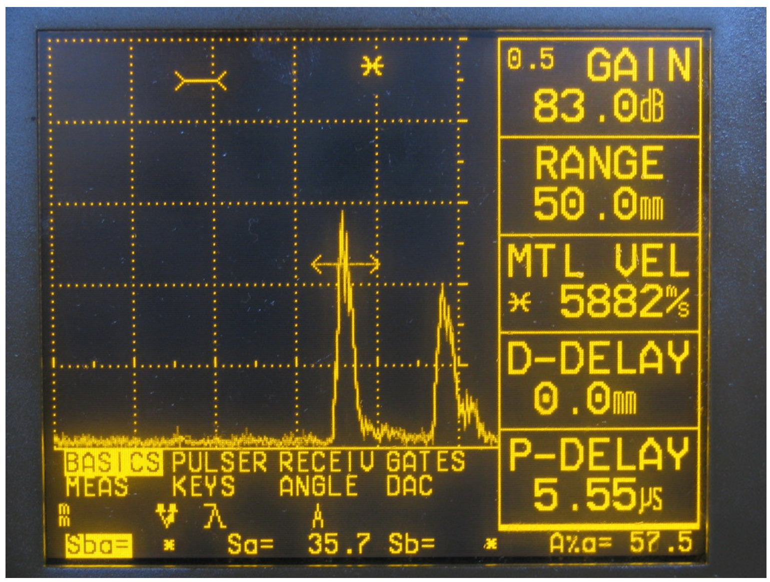


**Figure 4.8** Oscillator screen during the measurement of diffracted sound beam signal of 20 mm vertical slit with 4 MHz longitudinal wave probe and 67° wedge pair

During the tests it is also found that the probe delay time which is set straight eye for a value during calibration also affects the measurements drastically. So the tests are repeated for the same test blocks with different and proper probe delay times and an optimized value is selected for each wedge probe pair. This is also valid for the shear wave probes. The index and probe delay time values of these pairs and shear wave probes are given in Table 4.1.

**Table 4.1** Properties of Wedge - Compressional wave probe pairs and Shear wave probes

| | Probe | Probe Delay Time | Probe Index |
|---|---|---|---|
| Wedge Compressional wave Probe Pairs | 4 MHz 67° | 5.55 $\mu$sec | 15 mm |
| | 4 MHz 45° | 4.30 $\mu$sec | 16 mm |
| | 5 MHz 67° | 4.55 $\mu$sec | 17 mm |
| | 5 MHz 45° | 3.60 $\mu$sec | 18 mm |
| Shear Wave Probes | 4 MHz 70° | 6.50 $\mu$sec | 13 mm |
| | 4 MHz 45° | 4.70 $\mu$sec | 14 mm |
| | 2 MHz 45° | 5.60 $\mu$sec | 13 mm |

Many factors affect the measurements like some unavoidable small errors in the dimensions of test blocks, wedges; operator's skill in reading the measured values and holding the probes in fixed position; which cause again some errors during the calculation of slit heights.

For this reason in order to compare the results of each test, as many possible measurement points as possible were chosen. The points have been selected with 1 mm intervals starting from 0 and 20 mm and ending at 60 and 80 mm of probe separation distances for 45° and 70° probes respectively. The interval values are increased as the separation of probes get closer to the maximum chosen values.

Probe separation values are selected because of physical limitations caused by the dimensions of the wedges. The author tried to get accurate readings as close to the main axis of the sound beam as possible during the tests and the main axis locations and sound beam travel distance readings at these locations for each slit are also given in the test results. The results of TOFD tests are given in Appendix A as tables and compared in terms of slit heights and angle of wedge probe pairs according to the standard deviations of errors found in each test. It is also observed that the readings of inclined slits do not change from either side.

### 4.2.2 Reflection of Shear Wave Method

This method is the second method used to calculate the height of slits. It is based on the transit time of reflected shear waves from the slit tips. In this method single 4 MHz 70°, 4 MHz 45°, and 2 MHz 45° shear wave probes are used as in the pulse echo technique. Here different than the TOFD method, the slit heights are calculated from the opposite surface in order to receive the back wall echo and determine the reflected shear wave signal on oscillator screen. By measuring the distance between the slit tips and the index point of the probes, the depth of slit tips from the opposite surface are calculated. And then subtracting this value from the thickness of the test block, the heights of slits are found. The main picture of this method is given in Figure 4.9.

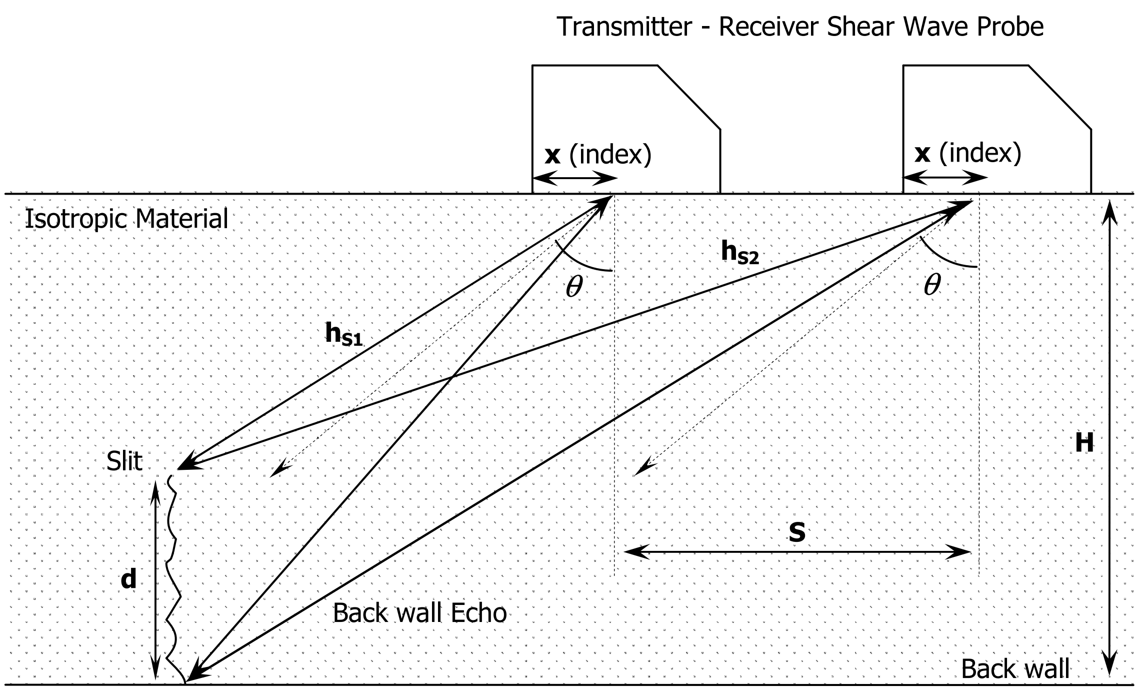


**Figure 4.9** Main picture of Reflection of Shear Wave Method [5]

Unfortunately the reflected shear wave signal is caught back by the probe only in a very small interval which restricts the author to get fewer readings than the TOFD method. As each reading includes some error, one or two readings may not be accurate and reliable to make comparisons between the test results. To overcome this problem, the author used equation (4.2) to calculate the height of slits with two readings taken from two different points [18].

$$d = H - \sqrt{(h_{S1})^2 - \left( \frac{(h_{S2})^2 - (h_{S1})^2 - S^2}{2S} \right)^2} \qquad (4.2)$$

$$( h_{S1} = t_{S1} \cdot V_S \, ; \quad h_{S2} = t_{S2} \cdot V_S )$$

These points are chosen as one point to be the peak value of the reflected shear wave signal set to the %80 screen height of the oscillator screen and another one when the signal height reduces to %40 screen height with the movement of the probe to either direction from the slit. So three points are used in each test and the results are given in Appendix B as tables.

As the heights are calculated with only the travel distances of the sound waves according to the equation (4.2), the probe indexes and angles do not have to be known in this method. But the readings do change from which side you choose to conduct the tests. When the inclination of the slits are away from the probes, the readings give better results, otherwise the reflected shear wave signals can not be determined between the ground noise signals.

## 4.3 TEST RESULTS

### 4.3.1 Results of TOFD Method

Three sets of test blocks including slits with angles 0°, 15°, 30° and having lengths of 5 mm, 10 mm, 15 mm, and 20 mm; are tested with 4 MHz and 5 MHz longitudinal wave probes attached to Plexiglas wedges of 20° and 26°. The resulting sound beams traveling in the test blocks have angle of incidence of 45° and 67°.

The results are very satisfactory with calculated mean errors of $\pm 1.5$ mm and standard deviation of 0.6 mm. It is found that the errors in estimating the height of slit tips increase as the height of the slits decrease just like found in a study of M.G. Silk shown in Figure 4.10. Hollow slits can be measured with less error. This is shown graphically with the test results of 5 MHz 67° probe with respect to the actual slit heights in Figure 4.11.

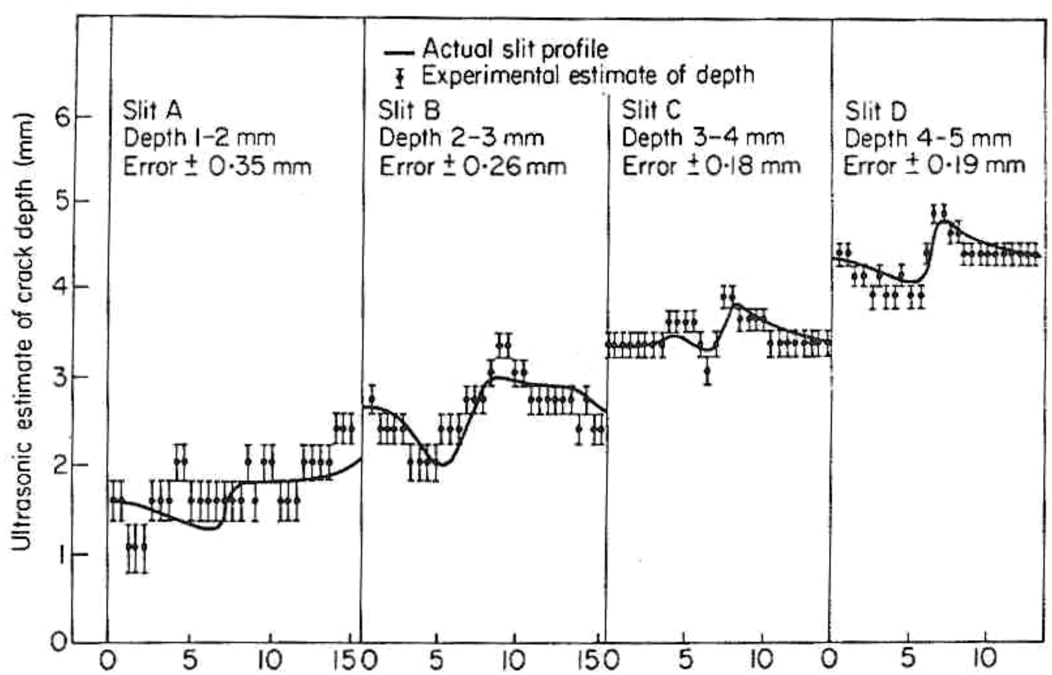


**Figure 4.10** Comparison of ultrasonic estimates of slit depth with the actual profile of the slit [5]

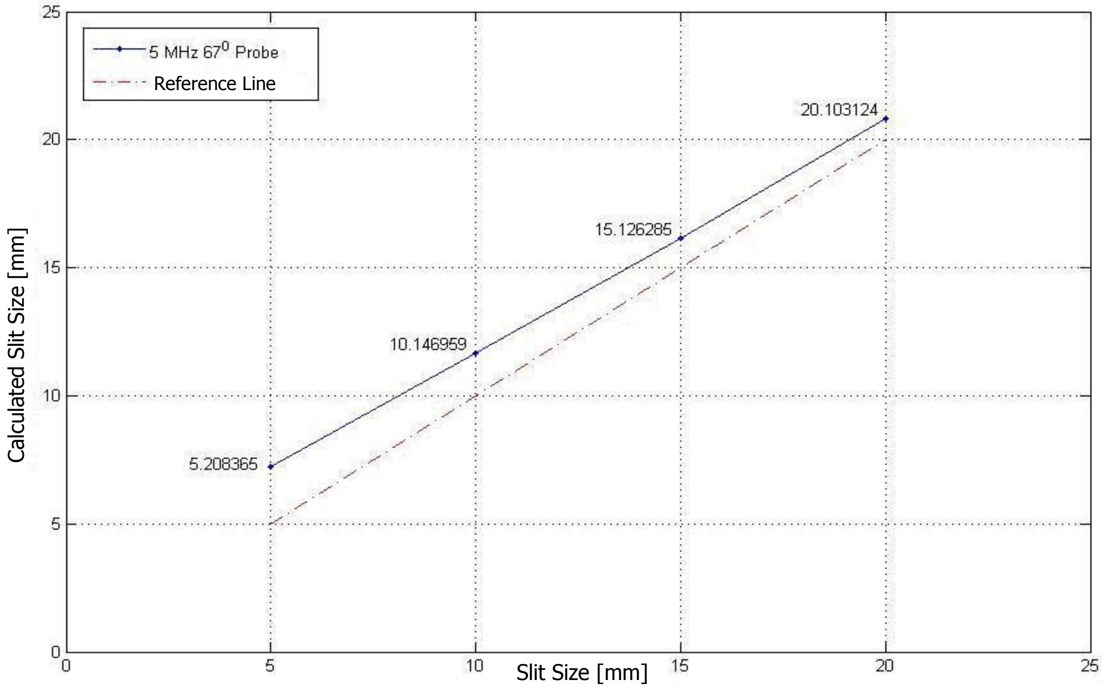


**Figure 4.11** The variation of calculated errors with changing Slit sizes

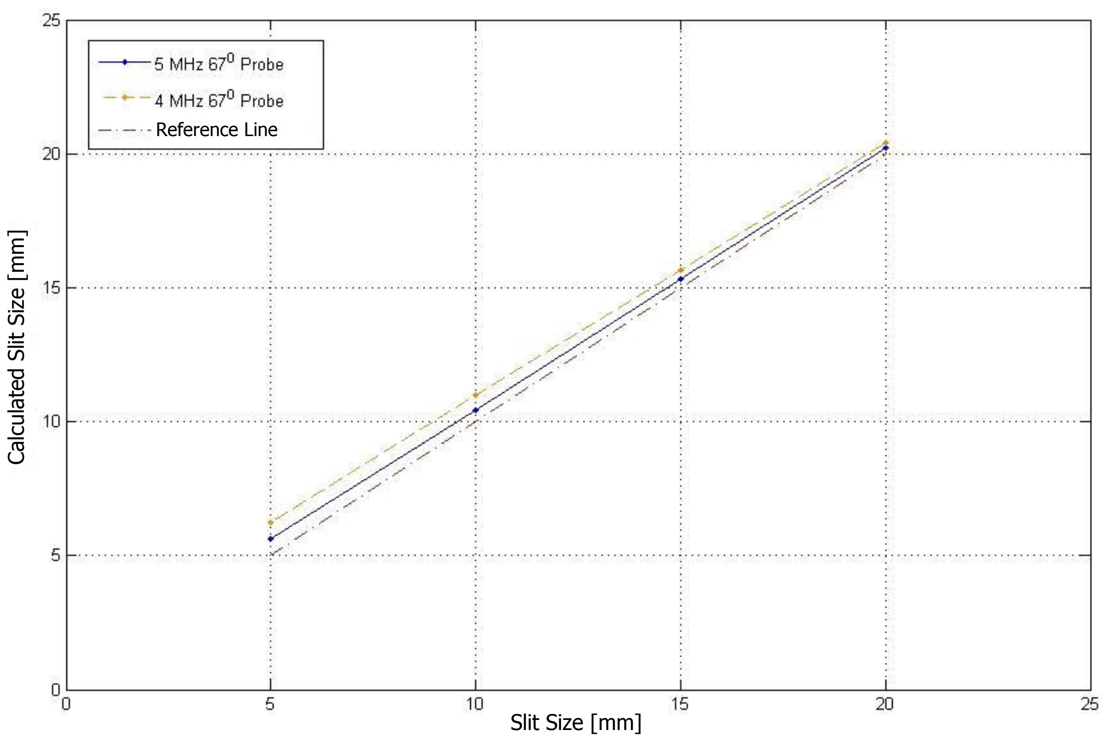


**Figure 4.12** The variation of calculated Slit sizes with changing probe frequency

Better readings can be obtained with increasing the frequency of the probes as in Figure 4.12. But there is a limit to that as the attenuation of sound beams and the near field length of the probes increase with frequency. It is also found that the probability of a probe malfunction increases with frequency, too [21].

Another result obtained is that, readings get better as the probe angles widens up and slit angles steepens. The change of readings according to the slit angles are shown in Figure 4.13. As the values are very small and close to each other, the graphics are exaggerated proportionally for a better visual representation. The summary of the test results are given in Tables 4.2, 4.3 and 4.4.

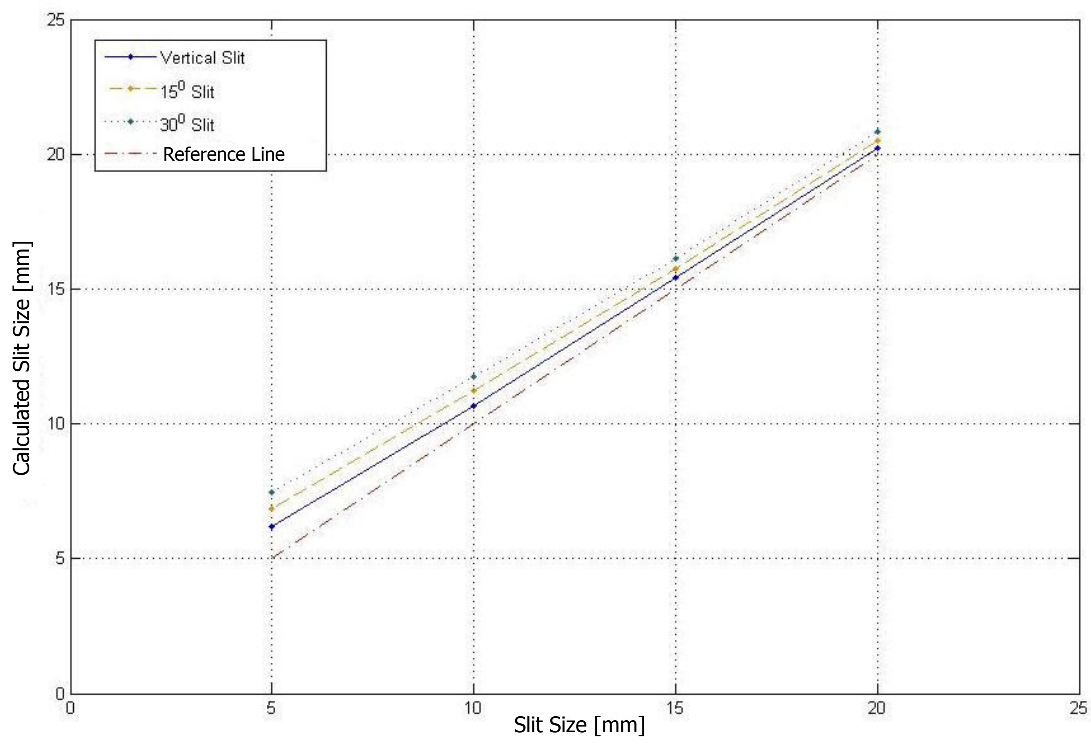


**Figure 4.13** The variation of calculated Slit sizes with changing Slit angles

**Table 4.2** Test Results of TOFD Method for Vertical Slits

| Frequency (MHz) | Angle (Degrees) | Slit Length (mm) | Mean Error (mm) | Standard Deviation (mm) |
|---|---|---|---|---|
| 4 | 45 | 5 | - | - |
| | | 10 | 0.29 | 0.24 |
| | | 15 | 0.14 | 0.19 |
| | | 20 | 0.13 | 0.18 |
| 4 | 67 | 5 | 0.50 | 0.23 |
| | | 10 | 0.42 | 0.19 |
| | | 15 | 0.53 | 0.13 |
| | | 20 | 0.49 | 0.10 |
| 5 | 45 | 5 | 0.89 | 0.60 |
| | | 10 | 0.26 | 0.18 |
| | | 15 | 0.26 | 0.17 |
| | | 20 | 0.39 | 0.17 |
| 5 | 67 | 5 | 0.33 | 0.20 |
| | | 10 | 0.47 | 0.14 |
| | | 15 | 0.25 | 0.12 |
| | | 20 | 0.20 | 0.10 |

**Table 4.3** Test Results of TOFD Method for 15° Slits

| Frequency (MHz) | Angle (Degrees) | Slit Length (mm) | Mean Error (mm) | Standard Deviation (mm) |
|---|---|---|---|---|
| 4 | 45 | 5 | - | - |
| | | 10 | 0.26 | 0.23 |
| | | 15 | 0.72 | 0.17 |
| | | 20 | 0.79 | 0.14 |
| 4 | 67 | 5 | 0.70 | 0.35 |
| | | 10 | 0.35 | 0.23 |
| | | 15 | 0.17 | 0.13 |
| | | 20 | 0.13 | 0.11 |
| 5 | 45 | 5 | 1.11 | 0.53 |
| | | 10 | 0.34 | 0.22 |
| | | 15 | 0.20 | 0.16 |
| | | 20 | 0.30 | 0.14 |
| 5 | 67 | 5 | 1.51 | 0.33 |
| | | 10 | 0.33 | 0.22 |
| | | 15 | 0.66 | 0.13 |
| | | 20 | 0.12 | 0.10 |

**Table 4.4** Test Results of TOFD Method for 30° Slits

| Frequency (MHz) | Angle (Degrees) | Slit Length (mm) | Mean Error (mm) | Standard Deviation (mm) |
|---|---|---|---|---|
| 4 | 45 | 5 | 1.38 | 0.57 |
| | | 10 | 1.54 | 0.52 |
| | | 15 | 1.03 | 0.47 |
| | | 20 | 1.12 | 0.37 |
| 4 | 67 | 5 | 0.70 | 0.46 |
| | | 10 | 0.26 | 0.23 |
| | | 15 | 0.41 | 0.14 |
| | | 20 | 0.32 | 0.13 |
| 5 | 45 | 5 | 0.79 | 0.44 |
| | | 10 | 0.54 | 0.41 |
| | | 15 | 0.63 | 0.46 |
| | | 20 | 1.29 | 0.28 |
| 5 | 67 | 5 | 0.60 | 0.37 |
| | | 10 | 1.00 | 0.31 |
| | | 15 | 0.51 | 0.17 |
| | | 20 | 0.40 | 0.15 |

### 4.3.2 Results of Reflection of Shear wave Method

Three sets of test blocks including slits with angles of 0°, 15°, 30° and having lengths of 5 mm, 10 mm, 15 mm, and 20 mm; are tested with 4 MHz 70° ,4 MHz 45°, and 2 MHz 45° shear wave probes. Even though less number of points is used during the tests, the results are also satisfactory with calculated mean errors of $\pm 1.6$ mm and standard deviation of 0.7 mm when compared with the TOFD method. The affects of changing slit sizes, probe frequencies, and slit angles to the test results are very similar to the ones found with TOFD method.

**Table 4.5** Test Results of Reflection of Shear wave Method for Vertical Slits

| Frequency (MHz) | Angle (Degrees) | Slit Length (mm) | Mean Error (mm) | Standard Deviation (mm) |
|---|---|---|---|---|
| 4 | 70 | 5 | 0.54 | 0.38 |
| | | 10 | 0.33 | 0.35 |
| | | 15 | 0.25 | 0.26 |
| | | 20 | 0.43 | 0.16 |
| 4 | 45 | 5 | 0.85 | 0.61 |
| | | 10 | 0.45 | 0.35 |
| | | 15 | 0.43 | 0.26 |
| | | 20 | 0.57 | 0.25 |
| 2 | 45 | 5 | 0.82 | 0.59 |
| | | 10 | 0.40 | 0.31 |
| | | 15 | 0.30 | 0.19 |
| | | 20 | 0.31 | 0.26 |

**Table 4.6** Test Results of Reflection of Shear wave Method for 15° Slit

| Frequency (MHz) | Angle (Degrees) | Slit Length (mm) | Mean Error (mm) | Standard Deviation (mm) |
|---|---|---|---|---|
| 4 | 70 | 5 | 1.06 | 0.64 |
| | | 10 | 0.59 | 0.48 |
| | | 15 | 0.55 | 0.35 |
| | | 20 | 0.46 | 0.07 |
| 4 | 45 | 5 | 0.91 | 0.62 |
| | | 10 | 0.54 | 0.43 |
| | | 15 | 0.57 | 0.35 |
| | | 20 | 0.19 | 0.16 |
| 2 | 45 | 5 | 0.97 | 0.65 |
| | | 10 | 0.81 | 0.48 |
| | | 15 | 0.76 | 0.45 |
| | | 20 | 0.21 | 0.28 |

**Table 4.7** Test Results of Reflection of Shear wave Method for 30° Slit

| Frequency (MHz) | Angle (Degrees) | Slit Length (mm) | Mean Error (mm) | Standard Deviation (mm) |
|---|---|---|---|---|
| 4 | 70 | 5 | 1.64 | 0.73 |
| | | 10 | 1.01 | 0.50 |
| | | 15 | 1.15 | 0.49 |
| | | 20 | 0.87 | 0.34 |
| 4 | 45 | 5 | 1.73 | 0.70 |
| | | 10 | 1.51 | 0.54 |
| | | 15 | 1.48 | 0.51 |
| | | 20 | 1.29 | 0.47 |
| 2 | 45 | 5 | - | - |
| | | 10 | 1.66 | 0.73 |
| | | 15 | 1.36 | 0.69 |
| | | 20 | 1.21 | 0.62 |

# CHAPTER 5

# DISCUSSIONS AND CONCLUSIONS

## 5.1 Selection of Methods for Thesis Study

In this thesis, TOFD and Reflection of Shear wave Ultrasonic Timing Methods are selected for estimating the heights of surface breaking cracks. The reasons of this selection are discussed in this section.

The challenge for ultrasonics is to provide quantitative information needed to distinguish between small non propagating defects which are benign and propagating, crack like defects which are critical with respect to failure. For this reason the objective of the thesis is to estimate the height of surface breaking cracks which is the most critical size parameter. But in reality, inspections are subject to errors that are related to many parameters so the most accurate techniques should be chosen. There have been many studies especially after the invention of diffracted sound waves for measurements of flaw dimensions after 1970s, and TOFD Method is found to be one of the most accurate measurement techniques.

A number of other techniques are now available which use the diffraction of sound waves from crack tips like the ALOC technique developed by IZfP in Saarbrucken, the FET technique developed by De Vadder at the Ecole Centrale in Paris, and the SLIC techniques used generally for reactor pressure vessel inspections developed by Gruber et al [3]. The precision of some of the ultrasonic NDT techniques are given in Table 5.1 for comparison.

Calibrated TOFD and Reflection of Shear wave techniques have been selected for the thesis study and according to the results, they are found to be very accurate techniques as shown in Table 5.1.

**Table 5.1** Precision of some ultrasonic NDT techniques [3, 13]

| Inspection Techniques | Precision [mm] | Comments |
|---|---|---|
| Conventional (Pulse Echo) | 3.0 – 5.0 | Flaws must be larger than the ultrasonic beam |
| TOFD etc. | 1.0 – 1.5 | Internal Flaws |
| | 0.7 – 1.0 | Flaws close to opposite surface |
| FET | 0.4 – 0.8 | Scanning will be slow, Focusing probes are needed |
| Calibrated TOFD | 0.5 – 0.7 | |
| Flaw Monitoring | 0.2 – 0.3 | Monitoring tasks only |
| Pitch and Catch | 3.0 – 4.0 | Requires the details of the specimen, the likely flaws, and their location |
| Surface Wave Transmission | 0.30 | Using Rayleigh waves |
| Short pulse Shear Wave (Reflection of Shear Wave) | 0.21 | |

## 5.2 Crack Simulation

Another important point for the thesis study is the simulation of cracks. In order to get reliable information from the measurements, the cracks should be simulated under the same conditions. To achieve this kind of cracks, slits are created with spark erosion technique in METU CAD CAM Robotics Center. By this way many parameters like the surface quality, tightness, tip roundness, and accuracy in length and angle of every slit were almost identical. But even though spark eroded slits mimic real crack surfaces more closely than any other production method, the data received from these slits may still be subject to large and unpredictable errors [16].

As it is very hard to create internal, semi elliptical or semi circular surface cracks by controlling all these parameters and in order to simplify the experiments, the study is firstly focused on the lateral surface breaking cracks.

During the study, the author thought about closing some of the slits' mouths by welding, rearranging the surface quality to be suitable for ultrasonic measurements by grinding, and then conduct the tests again. But as the conditions would not be the same for each slit face, the author decided not to carry out this idea. The results would probably not be reliable. But it is believed that better measurements for crack sizing can be made by measuring the height of the slit with a method which is not affected by the top of the slit in a situation like this [31].

## 5.3 Test Accuracies

Besides many parameters affecting the measurements during tests discussed in the previous chapters, the accuracy in calculating the height of cracks never fell off certain limits. The readings obtained with both methods gave reasonable results and the results are found to be very satisfactory within the range of $\pm 0.5$ mm for average mean error from the original slit heights. This value was found for vertical slits which increase slightly with the increasing slit angle.

The signal amplitudes are also important even though they do not play a role in the calculations. But as detecting the diffraction signals is required, they are desired to be as distinct as possible among the ground noise. As the amplitude values of diffracted signals from shallow and angled slits are smaller, higher gain values are used during the tests which also increased the amplitude of ground noise and made distinguishing diffraction signals a harder operation.

## 5.4 Material of Wedges

The wedge material is chosen to be Plexiglas because of some reasons. These can be summarized as follows:

- Plexiglas material has one of the smallest impedance values of solid materials which results in smaller incidence angle of probes when embedded in the wedges. This minimizes the physical restriction of probe usage during tests. If the same material with the test blocks has been chosen, the incidence and refraction angles would be almost the same which would also increase the physical lengths of wedges.

- It is a transparent material which allows the operator to see any internal defect occurred during manufacturing.

- It is a soft material which is easy to manufacture.

- As the quality of inspection surfaces is important, any damage caused by abrasion of the wedges is prevented by the usage of a softer material like Plexiglas. It is widely used in industry for this very reason.

## 5.5 Limitations

Methods, based on the usage of travel time of ultrasonic waves for sizing defects, are being used since 1980s especially in safety critical applications such as nuclear industry, offshore oilrigs, chemical plants, pipelines etc. They are found to be very accurate and reliable methods with the evidence of idealised trials in laboratory conditions followed by accumulations of satisfactory field experiences. But as the complexity of applications increase, it reduces the accuracy of these methods, too. The factors affecting the complexity of any application can be listed as follows and thought to be the limitations of these methods.

- Geometry
- Material
- Defect type
- Component access

More complex geometries; anisotropic and non homogeneous materials like austenitic steels or forged materials; rough, or branched defects like stress corrosion cracks; defects in very hard to reach places of components increase the complexity and make the detection and sizing of defects very difficult. Special applications of these methods can be designed depending on each situation, to minimize the effects of these factors and to achieve a desired accuracy.

## 5.6 Recommendations for Future Works

The readings of the tests are taken with Krautkramer Branson USD 15 digital oscillator which can measure the sound beam paths to an accuracy of 0.1 mm. Even though the results can give a general idea about the methods, by using an oscillator capable of measuring sound paths to an accuracy of 0.01 mm or lower, will reduce the amount of errors in calculations.

The angles of wedges are adjusted manually because of the number of axes of CNC machines used during their production. Better CNC machines with revolving tool heads can be used to overcome this inaccuracy and more precise angles can be acquired. If possible the test blocks should also be produced with CNC machines.

All the tests are performed manually by the author. This added another type of inaccuracy to readings and may caused some part of the overall errors in calculations. Even though most of the ultrasonic testing operations are still conducted manually in industry, a rigid mechanism which can move the probes smoothly across the inspection surfaces of test blocks can be designed and this kind of errors can be reduced.

The variety of probes, wedges, and test blocks having different frequencies, angles, crack heights, etc.  can be increased in order to observe the effect of all these parameters to the errors in calculations. But as the errors are very small with respect to the actual lengths, these effects can only be observed clearly with numerous test points.

# APPENDIX A

# TEST RESULTS OF TOFD METHOD

**Table A.1** Test Results of Vertical Slits with 4 Mhz Compressional Wave Probe of 45°

| **20 mm Slit** | **Distance btw Probes:** 8 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 28.284271 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi - Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 25.7 | 20.111937 | 0.111937 | 0.111937 | -0.024523 | 0.024523 | 0.000601 |
| 1 | 26 | 20.093531 | 0.093531 | 0.093531 | -0.042928 | 0.042928 | 0.001843 |
| 2 | 26.3 | 20.067137 | 0.067137 | 0.067137 | -0.069322 | 0.069322 | 0.004806 |
| 3 | 26.6 | 20.032723 | 0.032723 | 0.032723 | -0.103736 | 0.103736 | 0.010761 |
| 4 | 26.9 | 19.990248 | -0.009752 | 0.009752 | -0.126707 | 0.126707 | 0.016055 |
| 5 | 27.3 | 20.075856 | 0.075856 | 0.075856 | -0.060603 | 0.060603 | 0.003673 |
| 6 | 27.6 | 20.018991 | 0.018991 | 0.018991 | -0.117468 | 0.117468 | 0.013799 |
| 7 | 28 | 20.093531 | 0.093531 | 0.093531 | -0.042928 | 0.042928 | 0.001843 |
| 8 | 28.4 | 20.163333 | 0.163333 | 0.163333 | 0.026874 | 0.026874 | 0.000722 |
| 9 | 28.8 | 20.228445 | 0.228445 | 0.228445 | 0.091986 | 0.091986 | 0.008461 |
| 10 | 29.1 | 20.144726 | 0.144726 | 0.144726 | 0.008267 | 0.008267 | 0.000068 |
| 11 | 29.5 | 20.199010 | 0.199010 | 0.199010 | 0.062550 | 0.062550 | 0.003913 |
| 12 | 29.8 | 20.100746 | 0.100746 | 0.100746 | -0.035713 | 0.035713 | 0.001275 |
| 13 | 30.2 | 20.144230 | 0.144230 | 0.144230 | 0.007771 | 0.007771 | 0.000060 |
| 14 | 30.6 | 20.183161 | 0.183161 | 0.183161 | 0.046702 | 0.046702 | 0.002181 |
| 15 | 31 | 20.217567 | 0.217567 | 0.217567 | 0.081107 | 0.081107 | 0.006578 |
| 16 | 31.3 | 20.092038 | 0.092038 | 0.092038 | -0.044421 | 0.044421 | 0.001973 |
| 17 | 31.7 | 20.115666 | 0.115666 | 0.115666 | -0.020794 | 0.020794 | 0.000432 |
| 18 | 32 | 19.974984 | -0.025016 | 0.025016 | -0.111444 | 0.111444 | 0.012420 |
| 19 | 32.4 | 19.987746 | -0.012254 | 0.012254 | -0.124206 | 0.124206 | 0.015427 |
| 20 | 32.8 | 19.996000 | -0.004000 | 0.004000 | -0.132459 | 0.132459 | 0.017545 |
| 22 | 33.6 | 19.999000 | -0.001000 | 0.001000 | -0.135459 | 0.135459 | 0.018349 |
| 25 | 34.9 | 20.143485 | 0.143485 | 0.143485 | 0.007026 | 0.007026 | 0.000049 |
| 27 | 35.8 | 20.282751 | 0.282751 | 0.282751 | 0.146292 | 0.146292 | 0.021401 |
| 30 | 36.9 | 20.015244 | 0.015244 | 0.015244 | -0.121215 | 0.121215 | 0.014693 |
| 35 | 39 | 19.968726 | -0.031274 | 0.031274 | -0.105185 | 0.105185 | 0.011064 |
| 40 | 41.1 | 19.829523 | -0.170477 | 0.170477 | 0.034017 | 0.034017 | 0.001157 |
| 45 | 42.9 | 18.925116 | -1.074884 | 1.074884 | 0.938425 | 0.938425 | 0.880642 |
| 50 | 45.6 | 19.958958 | -0.041042 | 0.041042 | -0.095417 | 0.095417 | 0.009104 |
| 55 | 47.8 | 19.813884 | -0.186116 | 0.186116 | 0.049657 | 0.049657 | 0.002466 |
| 60 | 50.1 | 19.849685 | -0.150315 | 0.150315 | 0.013855 | 0.013855 | 0.000192 |
| **Average Error [mm]:** | 0.136459 | **Variance [mm$^2$]:** | 0.034953 | **Standard Deviation [mm]:** | **0.186958** | | |

**Table A.2** Test Results of Vertical Slits with 4 Mhz Compressional Wave Probe of 45°

| **15 mm Slit** | **Distance btw Probes:** -2 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 21.213203 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 21.9 | 14.953595 | -0.046405 | 0.046405 | -0.095503 | 0.095503 | 0.009121 |
| 1 | 22.2 | 14.852273 | -0.147727 | 0.147727 | 0.005819 | 0.005819 | 0.000034 |
| 2 | 22.6 | 14.891608 | -0.108392 | 0.108392 | -0.033516 | 0.033516 | 0.001123 |
| 3 | 23 | 14.924812 | -0.075188 | 0.075188 | -0.066720 | 0.066720 | 0.004452 |
| 4 | 23.4 | 14.951923 | -0.048077 | 0.048077 | -0.093831 | 0.093831 | 0.008804 |
| 5 | 23.8 | 14.972976 | -0.027024 | 0.027024 | -0.114884 | 0.114884 | 0.013198 |
| 6 | 24.2 | 14.987995 | -0.012005 | 0.012005 | -0.129903 | 0.129903 | 0.016875 |
| 7 | 24.6 | 14.997000 | -0.003000 | 0.003000 | -0.138908 | 0.138908 | 0.019295 |
| 8 | 25 | 15.000000 | 0.000000 | 0.000000 | -0.141908 | 0.141908 | 0.020138 |
| 9 | 25.4 | 14.997000 | -0.003000 | 0.003000 | -0.138908 | 0.138908 | 0.019295 |
| 10 | 25.7 | 14.815195 | -0.184805 | 0.184805 | 0.042897 | 0.042897 | 0.001840 |
| 11 | 26.1 | 14.797297 | -0.202703 | 0.202703 | 0.060795 | 0.060795 | 0.003696 |
| 12 | 26.5 | 14.773287 | -0.226713 | 0.226713 | 0.084805 | 0.084805 | 0.007192 |
| 13 | 26.9 | 14.743134 | -0.256866 | 0.256866 | 0.114958 | 0.114958 | 0.013215 |
| 14 | 27.4 | 14.891608 | -0.108392 | 0.108392 | -0.033516 | 0.033516 | 0.001123 |
| 15 | 27.8 | 14.852273 | -0.147727 | 0.147727 | 0.005819 | 0.005819 | 0.000034 |
| 16 | 28.2 | 14.806755 | -0.193245 | 0.193245 | 0.051337 | 0.051337 | 0.002635 |
| 17 | 28.7 | 14.947910 | -0.052090 | 0.052090 | -0.089818 | 0.089818 | 0.008067 |
| 18 | 29.1 | 14.893287 | -0.106713 | 0.106713 | -0.035195 | 0.035195 | 0.001239 |
| 19 | 29.5 | 14.832397 | -0.167603 | 0.167603 | 0.025695 | 0.025695 | 0.000660 |
| 20 | 30 | 14.966630 | -0.033370 | 0.033370 | -0.108538 | 0.108538 | 0.011780 |
| 22 | 30.9 | 15.026976 | 0.026976 | 0.026976 | -0.114932 | 0.114932 | 0.013209 |
| 25 | 32.2 | 14.986327 | -0.013673 | 0.013673 | -0.128235 | 0.128235 | 0.016444 |
| 27 | 33.1 | 15.011995 | 0.011995 | 0.011995 | -0.129913 | 0.129913 | 0.016877 |
| 30 | 34.4 | 14.911740 | -0.088260 | 0.088260 | -0.053648 | 0.053648 | 0.002878 |
| 35 | 36.7 | 14.987995 | -0.012005 | 0.012005 | -0.129903 | 0.129903 | 0.016875 |
| 40 | 39 | 15.000000 | 0.000000 | 0.000000 | -0.141908 | 0.141908 | 0.020138 |
| 45 | 41.2 | 14.669356 | -0.330644 | 0.330644 | 0.188736 | 0.188736 | 0.035621 |
| 50 | 43.6 | 14.831049 | -0.168951 | 0.168951 | 0.027043 | 0.027043 | 0.000731 |
| 55 | 45.7 | 14.008569 | -0.991431 | 0.991431 | 0.849523 | 0.849523 | 0.721690 |
| 60 | 48.2 | 14.395833 | -0.604167 | 0.604167 | 0.462259 | 0.462259 | 0.213684 |
| **Average Error [mm]:** | 0.141908 | **Variance [mm$^2$]:** | 0.039418 | **Standard Deviation [mm]:** | **0.198540** | | |

**Table A.3** Test Results of Vertical Slits with 4 Mhz Compressional Wave Probe of 45°

| **10 mm Slit** | **Distance btw Probes:** -12 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 14.142135 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 18.9 | 10.060318 | 0.060318 | 0.060318 | -0.231843 | 0.231843 | 0.053751 |
| 1 | 19.4 | 10.203431 | 0.203431 | 0.203431 | -0.088731 | 0.088731 | 0.007873 |
| 2 | 19.8 | 10.150862 | 0.150862 | 0.150862 | -0.141299 | 0.141299 | 0.019966 |
| 3 | 20.3 | 10.287857 | 0.287857 | 0.287857 | -0.004304 | 0.004304 | 0.000019 |
| 4 | 20.6 | 10.017984 | 0.017984 | 0.017984 | -0.274178 | 0.274178 | 0.075173 |
| 5 | 21.1 | 10.146921 | 0.146921 | 0.146921 | -0.145241 | 0.145241 | 0.021095 |
| 6 | 21.4 | 9.846827 | -0.153173 | 0.153173 | -0.138988 | 0.138988 | 0.019318 |
| 7 | 22 | 10.185774 | 0.185774 | 0.185774 | -0.106387 | 0.106387 | 0.011318 |
| 8 | 22.4 | 10.087616 | 0.087616 | 0.087616 | -0.204545 | 0.204545 | 0.041839 |
| 9 | 22.9 | 10.205881 | 0.205881 | 0.205881 | -0.086281 | 0.086281 | 0.007444 |
| 10 | 23.4 | 10.322790 | 0.322790 | 0.322790 | 0.030629 | 0.030629 | 0.000938 |
| 11 | 23.8 | 10.207350 | 0.207350 | 0.207350 | -0.084811 | 0.084811 | 0.007193 |
| 12 | 24.1 | 9.839207 | -0.160793 | 0.160793 | -0.131369 | 0.131369 | 0.017258 |
| 13 | 24.6 | 9.945351 | -0.054649 | 0.054649 | -0.237512 | 0.237512 | 0.056412 |
| 14 | 24.9 | 9.539916 | -0.460084 | 0.460084 | 0.167922 | 0.167922 | 0.028198 |
| 15 | 25.4 | 9.638983 | -0.361017 | 0.361017 | 0.068855 | 0.068855 | 0.004741 |
| 16 | 25.9 | 9.737043 | -0.262957 | 0.262957 | -0.029204 | 0.029204 | 0.000853 |
| 17 | 26.4 | 9.834124 | -0.165876 | 0.165876 | -0.126286 | 0.126286 | 0.015948 |
| 18 | 26.9 | 9.930257 | -0.069743 | 0.069743 | -0.222418 | 0.222418 | 0.049470 |
| 19 | 27.4 | 10.025468 | 0.025468 | 0.025468 | -0.266694 | 0.266694 | 0.071126 |
| 20 | 27.9 | 10.119783 | 0.119783 | 0.119783 | -0.172379 | 0.172379 | 0.029714 |
| 22 | 28.8 | 10.021976 | 0.021976 | 0.021976 | -0.270186 | 0.270186 | 0.073000 |
| 25 | 30.4 | 10.578752 | 0.578752 | 0.578752 | 0.286591 | 0.286591 | 0.082134 |
| 27 | 31.4 | 10.756858 | 0.756858 | 0.756858 | 0.464697 | 0.464697 | 0.215943 |
| 30 | 32.7 | 10.406248 | 0.406248 | 0.406248 | 0.114087 | 0.114087 | 0.013016 |
| 35 | 35 | 10.136567 | 0.136567 | 0.136567 | -0.155594 | 0.155594 | 0.024209 |
| 40 | 37.5 | 10.500000 | 0.500000 | 0.500000 | 0.207839 | 0.207839 | 0.043197 |
| 45 | 40 | 10.851267 | 0.851267 | 0.851267 | 0.559106 | 0.559106 | 0.312599 |
| 50 | 42.4 | 10.805554 | 0.805554 | 0.805554 | 0.513393 | 0.513393 | 0.263572 |
| 55 | 44.8 | 10.714010 | 0.714010 | 0.714010 | 0.421848 | 0.421848 | 0.177956 |
| 60 | 47.2 | 10.575443 | 0.575443 | 0.575443 | 0.283282 | 0.283282 | 0.080249 |
| **Average Error [mm]:** | 0.292161 | **Variance [mm$^2$]:** | 0.058888 | **Standard Deviation [mm]:** | **0.242668** | | |

Table A.4 Test Results of Vertical Slits with 4 Mhz Compressional Wave Probe of 67°

| 20 mm Slit | Distance btw Probes: 64.234094 mm | | Probe Delay: 5.55 microseconds | | Sound Travel Time Distance: 51.186093 mm | | |
|---|---|---|---|---|---|---|---|
| Distance btw Probes (2S) [mm]: | Measured Sound Travel Distance ($h_c$) [mm]: | Calculated Slit Depth (d) [mm]: | Calculated Error [mm]: | Absolute Error (xi) [mm] | (xi – Average Error) [mm] | Absolute (xi – Average Error) [mm] | (xi – Average Error)$^2$ [mm$^2$] |
| 20 | 31.6 | 19.327700 | -0.672300 | 0.672300 | 0.173002 | 0.173002 | 0.029930 |
| 21 | 32 | 19.332615 | -0.667385 | 0.667385 | 0.168087 | 0.168087 | 0.028253 |
| 22 | 32.4 | 19.332874 | -0.667126 | 0.667126 | 0.167829 | 0.167829 | 0.028166 |
| 23 | 32.9 | 19.497692 | -0.502308 | 0.502308 | 0.003010 | 0.003010 | 0.000009 |
| 24 | 33.3 | 19.490767 | -0.509233 | 0.509233 | 0.009935 | 0.009935 | 0.000099 |
| 25 | 33.7 | 19.479220 | -0.520780 | 0.520780 | 0.021482 | 0.021482 | 0.000461 |
| 26 | 34.2 | 19.637719 | -0.362281 | 0.362281 | -0.137017 | 0.137017 | 0.018774 |
| 27 | 34.6 | 19.619123 | -0.380877 | 0.380877 | -0.118421 | 0.118421 | 0.014024 |
| 28 | 35 | 19.595918 | -0.404082 | 0.404082 | -0.095216 | 0.095216 | 0.009066 |
| 29 | 35.3 | 19.386593 | -0.613407 | 0.613407 | 0.114109 | 0.114109 | 0.013021 |
| 30 | 35.7 | 19.351744 | -0.648256 | 0.648256 | 0.148958 | 0.148958 | 0.022188 |
| 31 | 36.2 | 19.498461 | -0.501539 | 0.501539 | 0.002241 | 0.002241 | 0.000005 |
| 32 | 36.6 | 19.456618 | -0.543382 | 0.543382 | 0.044084 | 0.044084 | 0.001943 |
| 33 | 37 | 19.410049 | -0.589951 | 0.589951 | 0.090653 | 0.090653 | 0.008218 |
| 34 | 37.4 | 19.358719 | -0.641281 | 0.641281 | 0.141983 | 0.141983 | 0.020159 |
| 35 | 37.9 | 19.497692 | -0.502308 | 0.502308 | 0.003010 | 0.003010 | 0.000009 |
| 36 | 38.4 | 19.635682 | -0.364318 | 0.364318 | -0.134980 | 0.134980 | 0.018220 |
| 37 | 38.8 | 19.575239 | -0.424761 | 0.424761 | -0.074537 | 0.074537 | 0.005556 |
| 38 | 39.2 | 19.509997 | -0.490003 | 0.490003 | -0.009295 | 0.009295 | 0.000086 |
| 39 | 39.7 | 19.642810 | -0.357190 | 0.357190 | -0.142108 | 0.142108 | 0.020195 |
| 40 | 40.1 | 19.570641 | -0.429359 | 0.429359 | -0.069939 | 0.069939 | 0.004891 |
| 42 | 41 | 19.621417 | -0.378583 | 0.378583 | -0.120715 | 0.120715 | 0.014572 |
| 45 | 42.3 | 19.571408 | -0.428592 | 0.428592 | -0.070706 | 0.070706 | 0.004999 |
| 47 | 43.2 | 19.595663 | -0.404337 | 0.404337 | -0.094961 | 0.094961 | 0.009018 |
| 50 | 44.5 | 19.500000 | -0.500000 | 0.500000 | 0.000702 | 0.000702 | 0.000000 |
| 55 | 46.8 | 19.595663 | -0.404337 | 0.404337 | -0.094961 | 0.094961 | 0.009018 |
| 60 | 49.1 | 19.642047 | -0.357953 | 0.357953 | -0.141345 | 0.141345 | 0.019978 |
| 65 | 51.3 | 19.376274 | -0.623726 | 0.623726 | 0.124428 | 0.124428 | 0.015482 |
| 70 | 53.7 | 19.588007 | -0.411993 | 0.411993 | -0.087304 | 0.087304 | 0.007622 |
| 75 | 56 | 19.487175 | -0.512825 | 0.512825 | 0.013527 | 0.013527 | 0.000183 |
| 80 | 58.3 | 19.336235 | -0.663765 | 0.663765 | 0.164467 | 0.164467 | 0.027049 |
| **Average Error [mm]:** | 0.499298 | **Variance [mm$^2$]:** | 0.011329 | **Standard Deviation [mm]:** | **0.106437** | | |

**Table A.5** Test Results of Vertical Slits with 4 Mhz Compressional Wave Probe of 67°

| **15 mm Slit** | **Distance btw Probes:** 40.67557 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 38.389569 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 28.9 | 14.498621 | -0.501379 | 0.501379 | -0.033202 | 0.033202 | 0.001102 |
| 21 | 29.3 | 14.430523 | -0.569477 | 0.569477 | 0.034895 | 0.034895 | 0.001218 |
| 22 | 29.8 | 14.561593 | -0.438407 | 0.438407 | -0.096175 | 0.096175 | 0.009250 |
| 23 | 30.2 | 14.484129 | -0.515871 | 0.515871 | -0.018711 | 0.018711 | 0.000350 |
| 24 | 30.6 | 14.400000 | -0.600000 | 0.600000 | 0.065418 | 0.065418 | 0.004280 |
| 25 | 31.1 | 14.524462 | -0.475538 | 0.475538 | -0.059044 | 0.059044 | 0.003486 |
| 26 | 31.5 | 14.430870 | -0.569130 | 0.569130 | 0.034549 | 0.034549 | 0.001194 |
| 27 | 32 | 14.551632 | -0.448368 | 0.448368 | -0.086214 | 0.086214 | 0.007433 |
| 28 | 32.4 | 14.448529 | -0.551471 | 0.551471 | 0.016889 | 0.016889 | 0.000285 |
| 29 | 32.8 | 14.338410 | -0.661590 | 0.661590 | 0.127008 | 0.127008 | 0.016131 |
| 30 | 33.3 | 14.453027 | -0.546973 | 0.546973 | 0.012391 | 0.012391 | 0.000154 |
| 31 | 33.8 | 14.566743 | -0.433257 | 0.433257 | -0.101325 | 0.101325 | 0.010267 |
| 32 | 34.2 | 14.444376 | -0.555624 | 0.555624 | 0.021042 | 0.021042 | 0.000443 |
| 33 | 34.7 | 14.554724 | -0.445276 | 0.445276 | -0.089306 | 0.089306 | 0.007976 |
| 34 | 35.1 | 14.422552 | -0.577448 | 0.577448 | 0.042866 | 0.042866 | 0.001838 |
| 35 | 35.6 | 14.529625 | -0.470375 | 0.470375 | -0.064207 | 0.064207 | 0.004123 |
| 36 | 36 | 14.387495 | -0.612505 | 0.612505 | 0.077924 | 0.077924 | 0.006072 |
| 37 | 36.4 | 14.237626 | -0.762374 | 0.762374 | 0.227792 | 0.227792 | 0.051889 |
| 38 | 36.9 | 14.339107 | -0.660893 | 0.660893 | 0.126311 | 0.126311 | 0.015954 |
| 39 | 37.4 | 14.439875 | -0.560125 | 0.560125 | 0.025543 | 0.025543 | 0.000652 |
| 40 | 37.8 | 14.277255 | -0.722745 | 0.722745 | 0.188164 | 0.188164 | 0.035406 |
| 42 | 38.8 | 14.472042 | -0.527958 | 0.527958 | -0.006624 | 0.006624 | 0.000044 |
| 45 | 40.2 | 14.484129 | -0.515871 | 0.515871 | -0.018711 | 0.018711 | 0.000350 |
| 47 | 41.3 | 14.947910 | -0.052090 | 0.052090 | -0.482491 | 0.482491 | 0.232798 |
| 50 | 42.5 | 14.361407 | -0.638593 | 0.638593 | 0.104012 | 0.104012 | 0.010818 |
| 55 | 44.9 | 14.483094 | -0.516906 | 0.516906 | -0.017675 | 0.017675 | 0.000312 |
| 60 | 47.2 | 14.242191 | -0.757809 | 0.757809 | 0.223227 | 0.223227 | 0.049830 |
| 65 | 49.7 | 14.623269 | -0.376731 | 0.376731 | -0.157851 | 0.157851 | 0.024917 |
| 70 | 52 | 14.282857 | -0.717143 | 0.717143 | 0.182561 | 0.182561 | 0.033329 |
| 75 | 54.5 | 14.628739 | -0.371261 | 0.371261 | -0.163321 | 0.163321 | 0.026674 |
| 80 | 56.9 | 14.581152 | -0.418848 | 0.418848 | -0.115734 | 0.115734 | 0.013394 |
| **Average Error [mm]:** | 0.534582 | **Variance [mm$^2$]:** | 0.018451 | **Standard Deviation [mm]:** | **0.135833** | | |

**Table A.6** Test Results of Vertical Slits with 4 Mhz Compressional Wave Probe of 67°

| **10 mm Slit** | **Distance btw Probes:** 17.117046 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 25.593046 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)² [mm²]** |
| 20 | 26.9 | 9.930257 | -0.069743 | 0.069743 | -0.359262 | 0.359262 | 0.129069 |
| 21 | 27.3 | 9.748846 | -0.251154 | 0.251154 | -0.177852 | 0.177852 | 0.031631 |
| 22 | 27.7 | 9.554580 | -0.445420 | 0.445420 | 0.016414 | 0.016414 | 0.000269 |
| 23 | 28.2 | 9.643132 | -0.356868 | 0.356868 | -0.072138 | 0.072138 | 0.005204 |
| 24 | 28.6 | 9.431861 | -0.568139 | 0.568139 | 0.139133 | 0.139133 | 0.019358 |
| 25 | 29.1 | 9.516302 | -0.483698 | 0.483698 | 0.054693 | 0.054693 | 0.002991 |
| 26 | 29.6 | 9.600000 | -0.400000 | 0.400000 | -0.029006 | 0.029006 | 0.000841 |
| 27 | 30.1 | 9.682975 | -0.317025 | 0.317025 | -0.111980 | 0.111980 | 0.012540 |
| 28 | 30.5 | 9.447222 | -0.552778 | 0.552778 | 0.123773 | 0.123773 | 0.015320 |
| 29 | 31 | 9.526279 | -0.473721 | 0.473721 | 0.044715 | 0.044715 | 0.001999 |
| 30 | 31.5 | 9.604686 | -0.395314 | 0.395314 | -0.033692 | 0.033692 | 0.001135 |
| 31 | 32 | 9.682458 | -0.317542 | 0.317542 | -0.111464 | 0.111464 | 0.012424 |
| 32 | 32.4 | 9.421253 | -0.578747 | 0.578747 | 0.149742 | 0.149742 | 0.022423 |
| 33 | 32.9 | 9.495262 | -0.504738 | 0.504738 | 0.075732 | 0.075732 | 0.005735 |
| 34 | 33.4 | 9.568699 | -0.431301 | 0.431301 | 0.002295 | 0.002295 | 0.000005 |
| 35 | 33.9 | 9.641577 | -0.358423 | 0.358423 | -0.070582 | 0.070582 | 0.004982 |
| 36 | 34.4 | 9.713908 | -0.286092 | 0.286092 | -0.142913 | 0.142913 | 0.020424 |
| 37 | 34.9 | 9.785704 | -0.214296 | 0.214296 | -0.214709 | 0.214709 | 0.046100 |
| 38 | 35.3 | 9.491575 | -0.508425 | 0.508425 | 0.079419 | 0.079419 | 0.006307 |
| 39 | 35.8 | 9.559812 | -0.440188 | 0.440188 | 0.011183 | 0.011183 | 0.000125 |
| 40 | 36.2 | 9.243376 | -0.756624 | 0.756624 | 0.327618 | 0.327618 | 0.107334 |
| 42 | 37.2 | 9.372300 | -0.627700 | 0.627700 | 0.198695 | 0.198695 | 0.039480 |
| 45 | 38.7 | 9.562426 | -0.437574 | 0.437574 | 0.008568 | 0.008568 | 0.000073 |
| 47 | 39.7 | 9.687105 | -0.312895 | 0.312895 | -0.116110 | 0.116110 | 0.013482 |
| 50 | 41.1 | 9.445105 | -0.554895 | 0.554895 | 0.125890 | 0.125890 | 0.015848 |
| 55 | 43.5 | 9.273618 | -0.726382 | 0.726382 | 0.297376 | 0.297376 | 0.088432 |
| 60 | 46 | 9.539392 | -0.460608 | 0.460608 | 0.031602 | 0.031602 | 0.000999 |
| 65 | 48.5 | 9.797959 | -0.202041 | 0.202041 | -0.226965 | 0.226965 | 0.051513 |
| 70 | 50.8 | 8.979978 | -1.020022 | 1.020022 | 0.591017 | 0.591017 | 0.349301 |
| 75 | 53.4 | 9.762684 | -0.237316 | 0.237316 | -0.191690 | 0.191690 | 0.036745 |
| 80 | 55.9 | 9.990495 | -0.009505 | 0.009505 | -0.419501 | 0.419501 | 0.175981 |
| **Average Error [mm]:** | 0.429006 | **Variance [mm²]:** | 0.039293 | **Standard Deviation [mm]:** | **0.198224** | | |

**Table A.7** Test Results of Vertical Slits with 4 Mhz Compressional Wave Probe of 67°

| **5 mm Slit** | **Distance btw Probes:** -6.441478 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 12.796523 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 25.5 | 5.024938 | 0.024938 | 0.024938 | -0.483335 | 0.483335 | 0.233613 |
| 21 | 25.9 | 4.534314 | -0.465686 | 0.465686 | -0.042587 | 0.042587 | 0.001814 |
| 22 | 26.4 | 4.578209 | -0.421791 | 0.421791 | -0.086482 | 0.086482 | 0.007479 |
| 23 | 26.9 | 4.621688 | -0.378312 | 0.378312 | -0.129961 | 0.129961 | 0.016890 |
| 24 | 27.4 | 4.664762 | -0.335238 | 0.335238 | -0.173034 | 0.173034 | 0.029941 |
| 25 | 27.8 | 4.073082 | -0.926918 | 0.926918 | 0.418645 | 0.418645 | 0.175263 |
| 26 | 28.3 | 4.109745 | -0.890255 | 0.890255 | 0.381983 | 0.381983 | 0.145911 |
| 27 | 28.8 | 4.146082 | -0.853918 | 0.853918 | 0.345645 | 0.345645 | 0.119470 |
| 28 | 29.3 | 4.182105 | -0.817895 | 0.817895 | 0.309622 | 0.309622 | 0.095866 |
| 29 | 29.8 | 4.217819 | -0.782181 | 0.782181 | 0.273908 | 0.273908 | 0.075025 |
| 30 | 30.3 | 4.253234 | -0.746766 | 0.746766 | 0.238493 | 0.238493 | 0.056879 |
| 31 | 30.8 | 4.288356 | -0.711644 | 0.711644 | 0.203371 | 0.203371 | 0.041360 |
| 32 | 31.3 | 4.323193 | -0.676807 | 0.676807 | 0.168534 | 0.168534 | 0.028404 |
| 33 | 31.8 | 4.357752 | -0.642248 | 0.642248 | 0.133975 | 0.133975 | 0.017949 |
| 34 | 32.3 | 4.392038 | -0.607962 | 0.607962 | 0.099689 | 0.099689 | 0.009938 |
| 35 | 32.8 | 4.426059 | -0.573941 | 0.573941 | 0.065668 | 0.065668 | 0.004312 |
| 36 | 33.3 | 4.459821 | -0.540179 | 0.540179 | 0.031906 | 0.031906 | 0.001018 |
| 37 | 33.8 | 4.493328 | -0.506672 | 0.506672 | -0.001601 | 0.001601 | 0.000003 |
| 38 | 34.3 | 4.526588 | -0.473412 | 0.473412 | -0.034861 | 0.034861 | 0.001215 |
| 39 | 34.8 | 4.559605 | -0.440395 | 0.440395 | -0.067878 | 0.067878 | 0.004607 |
| 40 | 35.3 | 4.592385 | -0.407615 | 0.407615 | -0.100658 | 0.100658 | 0.010132 |
| 42 | 36.3 | 4.657252 | -0.342748 | 0.342748 | -0.165525 | 0.165525 | 0.027399 |
| 45 | 37.8 | 4.752894 | -0.247106 | 0.247106 | -0.261167 | 0.261167 | 0.068208 |
| 47 | 38.8 | 4.815600 | -0.184400 | 0.184400 | -0.323873 | 0.323873 | 0.104893 |
| 50 | 40.3 | 4.908156 | -0.091844 | 0.091844 | -0.416429 | 0.416429 | 0.173413 |
| 55 | 42.7 | 4.127953 | -0.872047 | 0.872047 | 0.363774 | 0.363774 | 0.132331 |
| 60 | 45.3 | 5.204805 | 0.204805 | 0.204805 | -0.303467 | 0.303467 | 0.092093 |
| 65 | 47.8 | 5.346962 | 0.346962 | 0.346962 | -0.161311 | 0.161311 | 0.026021 |
| 70 | 50.2 | 4.476606 | -0.523394 | 0.523394 | 0.015121 | 0.015121 | 0.000229 |
| 75 | 52.7 | 4.586938 | -0.413062 | 0.413062 | -0.095211 | 0.095211 | 0.009065 |
| 80 | 55.2 | 4.694678 | -0.305322 | 0.305322 | -0.202951 | 0.202951 | 0.041189 |
| **Average Error [mm]:** | 0.508273 | **Variance [mm$^2$]:** | 0.056514 | **Standard Deviation [mm]:** | **0.237727** | | |

**Table A.8** Test Results of Vertical Slits with 5 Mhz Compressional Wave Probes of 45°

| **20 mm Slit** | **Distance btw Probes:** 4 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 28.284271 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 26.5 | 19.448650 | -0.551350 | 0.551350 | 0.152485 | 0.152485 | 0.023252 |
| 1 | 26.8 | 19.390462 | -0.609538 | 0.609538 | 0.210674 | 0.210674 | 0.044384 |
| 2 | 27.2 | 19.463813 | -0.536187 | 0.536187 | 0.137323 | 0.137323 | 0.018858 |
| 3 | 27.6 | 19.532281 | -0.467719 | 0.467719 | 0.068855 | 0.068855 | 0.004741 |
| 4 | 27.9 | 19.452763 | -0.547237 | 0.547237 | 0.148372 | 0.148372 | 0.022014 |
| 5 | 28.3 | 19.509997 | -0.490003 | 0.490003 | 0.091138 | 0.091138 | 0.008306 |
| 6 | 28.7 | 19.562464 | -0.437536 | 0.437536 | 0.038672 | 0.038672 | 0.001496 |
| 7 | 29.1 | 19.610201 | -0.389799 | 0.389799 | -0.009066 | 0.009066 | 0.000082 |
| 8 | 29.5 | 19.653244 | -0.346756 | 0.346756 | -0.052108 | 0.052108 | 0.002715 |
| 9 | 29.8 | 19.539447 | -0.460553 | 0.460553 | 0.061689 | 0.061689 | 0.003805 |
| 10 | 30.2 | 19.571408 | -0.428592 | 0.428592 | 0.029728 | 0.029728 | 0.000884 |
| 11 | 30.6 | 19.598724 | -0.401276 | 0.401276 | 0.002411 | 0.002411 | 0.000006 |
| 12 | 30.9 | 19.463042 | -0.536958 | 0.536958 | 0.138094 | 0.138094 | 0.019070 |
| 13 | 31.3 | 19.479220 | -0.520780 | 0.520780 | 0.121916 | 0.121916 | 0.014864 |
| 14 | 31.6 | 19.327700 | -0.672300 | 0.672300 | 0.273435 | 0.273435 | 0.074767 |
| 15 | 32 | 19.332615 | -0.667385 | 0.667385 | 0.268521 | 0.268521 | 0.072103 |
| 16 | 32.4 | 19.332874 | -0.667126 | 0.667126 | 0.268262 | 0.268262 | 0.071965 |
| 17 | 33 | 19.665960 | -0.334040 | 0.334040 | -0.064825 | 0.064825 | 0.004202 |
| 18 | 33.4 | 19.661129 | -0.338871 | 0.338871 | -0.059993 | 0.059993 | 0.003599 |
| 19 | 33.9 | 19.823219 | -0.176781 | 0.176781 | -0.222083 | 0.222083 | 0.049321 |
| 20 | 34.3 | 19.811360 | -0.188640 | 0.188640 | -0.210225 | 0.210225 | 0.044194 |
| 22 | 35 | 19.595918 | -0.404082 | 0.404082 | 0.005218 | 0.005218 | 0.000027 |
| 25 | 36.3 | 19.683496 | -0.316504 | 0.316504 | -0.082360 | 0.082360 | 0.006783 |
| 27 | 37.1 | 19.600000 | -0.400000 | 0.400000 | 0.001136 | 0.001136 | 0.000001 |
| 30 | 38.5 | 19.830532 | -0.169468 | 0.169468 | -0.229396 | 0.229396 | 0.052623 |
| 35 | 40.7 | 19.905778 | -0.094222 | 0.094222 | -0.304642 | 0.304642 | 0.092807 |
| 40 | 42.9 | 19.910048 | -0.089952 | 0.089952 | -0.308912 | 0.308912 | 0.095427 |
| 45 | 45.2 | 20.069629 | 0.069629 | 0.069629 | -0.329235 | 0.329235 | 0.108396 |
| 50 | 47.2 | 19.463813 | -0.536187 | 0.536187 | 0.137323 | 0.137323 | 0.018858 |
| 55 | 49.6 | 19.746139 | -0.253861 | 0.253861 | -0.145003 | 0.145003 | 0.021026 |
| 60 | 51.9 | 19.738541 | -0.261459 | 0.261459 | -0.137405 | 0.137405 | 0.018880 |
| **Average Error [mm]:** | 0.398864 | **Variance [mm$^2$]:** | 0.029015 | **Standard Deviation [mm]:** | **0.170337** | | |

**Table A.9** Test Results of Vertical Slits with 5 Mhz Compressional Wave Probes of 45°

| **15 mm Slit** | **Distance btw Probes:** -8 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 21.213203 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 23.4 | 14.951923 | -0.048077 | 0.048077 | -0.220015 | 0.220015 | 0.048407 |
| 1 | 23.8 | 14.972976 | -0.027024 | 0.027024 | -0.241067 | 0.241067 | 0.058114 |
| 2 | 24 | 14.662878 | -0.337122 | 0.337122 | 0.069030 | 0.069030 | 0.004765 |
| 3 | 24.4 | 14.666629 | -0.333371 | 0.333371 | 0.065279 | 0.065279 | 0.004261 |
| 4 | 24.8 | 14.664242 | -0.335758 | 0.335758 | 0.067666 | 0.067666 | 0.004579 |
| 5 | 25.2 | 14.655716 | -0.344284 | 0.344284 | 0.076193 | 0.076193 | 0.005805 |
| 6 | 25.6 | 14.641038 | -0.358962 | 0.358962 | 0.090870 | 0.090870 | 0.008257 |
| 7 | 26 | 14.620192 | -0.379808 | 0.379808 | 0.111717 | 0.111717 | 0.012481 |
| 8 | 26.4 | 14.593149 | -0.406851 | 0.406851 | 0.138759 | 0.138759 | 0.019254 |
| 9 | 26.7 | 14.374978 | -0.625022 | 0.625022 | 0.356930 | 0.356930 | 0.127399 |
| 10 | 27.2 | 14.520331 | -0.479669 | 0.479669 | 0.211578 | 0.211578 | 0.044765 |
| 11 | 27.7 | 14.664242 | -0.335758 | 0.335758 | 0.067666 | 0.067666 | 0.004579 |
| 12 | 28 | 14.422205 | -0.577795 | 0.577795 | 0.309703 | 0.309703 | 0.095916 |
| 13 | 28.4 | 14.363495 | -0.636505 | 0.636505 | 0.368413 | 0.368413 | 0.135728 |
| 14 | 29.2 | 15.087743 | 0.087743 | 0.087743 | -0.180348 | 0.180348 | 0.032526 |
| 15 | 29.7 | 15.226293 | 0.226293 | 0.226293 | -0.041799 | 0.041799 | 0.001747 |
| 16 | 30.1 | 15.166081 | 0.166081 | 0.166081 | -0.102011 | 0.102011 | 0.010406 |
| 17 | 30.6 | 15.300654 | 0.300654 | 0.300654 | 0.032562 | 0.032562 | 0.001060 |
| 18 | 31 | 15.231546 | 0.231546 | 0.231546 | -0.036546 | 0.036546 | 0.001336 |
| 19 | 31.4 | 15.156187 | 0.156187 | 0.156187 | -0.111905 | 0.111905 | 0.012523 |
| 20 | 31.7 | 14.862369 | -0.137631 | 0.137631 | -0.130460 | 0.130460 | 0.017020 |
| 22 | 32.7 | 15.109269 | 0.109269 | 0.109269 | -0.158823 | 0.158823 | 0.025225 |
| 25 | 34 | 15.024979 | 0.024979 | 0.024979 | -0.243113 | 0.243113 | 0.059104 |
| 27 | 34.9 | 15.025312 | 0.025312 | 0.025312 | -0.242780 | 0.242780 | 0.058942 |
| 30 | 36.3 | 15.122500 | 0.122500 | 0.122500 | -0.145592 | 0.145592 | 0.021197 |
| 35 | 38.6 | 15.156187 | 0.156187 | 0.156187 | -0.111905 | 0.111905 | 0.012523 |
| 40 | 40.7 | 14.577037 | -0.422963 | 0.422963 | 0.154871 | 0.154871 | 0.023985 |
| 45 | 43.2 | 15.032964 | 0.032964 | 0.032964 | -0.235128 | 0.235128 | 0.055285 |
| 50 | 45.5 | 14.874475 | -0.125525 | 0.125525 | -0.142567 | 0.142567 | 0.020325 |
| 55 | 47.8 | 14.648891 | -0.351109 | 0.351109 | 0.083017 | 0.083017 | 0.006892 |
| 60 | 50.1 | 14.353048 | -0.646952 | 0.646952 | 0.378860 | 0.378860 | 0.143535 |
| **Average Error [mm]:** | 0.268092 | **Variance [mm$^2$]:** | 0.031843 | **Standard Deviation [mm]:** | **0.178446** | | |

**Table A.10** Test Results of Vertical Slits with 5 Mhz Compressional Wave Probes of 45°

| **10 mm Slit** | **Distance btw Probes:** -18 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 14.142135 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$[mm$^2$]** |
| 0 | 20.9 | 10.621205 | 0.621205 | 0.621205 | 0.361118 | 0.361118 | 0.130406 |
| 1 | 21.3 | 10.556515 | 0.556515 | 0.556515 | 0.296428 | 0.296428 | 0.087869 |
| 2 | 21.6 | 10.274240 | 0.274240 | 0.274240 | 0.014153 | 0.014153 | 0.000200 |
| 3 | 22.1 | 10.400000 | 0.400000 | 0.400000 | 0.139913 | 0.139913 | 0.019576 |
| 4 | 22.5 | 10.307764 | 0.307764 | 0.307764 | 0.047677 | 0.047677 | 0.002273 |
| 5 | 23 | 10.428327 | 0.428327 | 0.428327 | 0.168240 | 0.168240 | 0.028305 |
| 6 | 23.4 | 10.322790 | 0.322790 | 0.322790 | 0.062704 | 0.062704 | 0.003932 |
| 7 | 23.9 | 10.438391 | 0.438391 | 0.438391 | 0.178304 | 0.178304 | 0.031792 |
| 8 | 24.3 | 10.319399 | 0.319399 | 0.319399 | 0.059312 | 0.059312 | 0.003518 |
| 9 | 24.7 | 10.190191 | 0.190191 | 0.190191 | -0.069895 | 0.069895 | 0.004885 |
| 10 | 25.1 | 10.050373 | 0.050373 | 0.050373 | -0.209714 | 0.209714 | 0.043980 |
| 11 | 25.6 | 10.154309 | 0.154309 | 0.154309 | -0.105777 | 0.105777 | 0.011189 |
| 12 | 26 | 10.000000 | 0.000000 | 0.000000 | -0.260087 | 0.260087 | 0.067645 |
| 13 | 26.5 | 10.099505 | 0.099505 | 0.099505 | -0.160582 | 0.160582 | 0.025787 |
| 14 | 27 | 10.198039 | 0.198039 | 0.198039 | -0.062048 | 0.062048 | 0.003850 |
| 15 | 27.4 | 10.025468 | 0.025468 | 0.025468 | -0.234619 | 0.234619 | 0.055046 |
| 16 | 27.8 | 9.840732 | -0.159268 | 0.159268 | -0.100818 | 0.100818 | 0.010164 |
| 17 | 28.3 | 9.931767 | -0.068233 | 0.068233 | -0.191854 | 0.191854 | 0.036808 |
| 18 | 28.8 | 10.021976 | 0.021976 | 0.021976 | -0.238111 | 0.238111 | 0.056697 |
| 19 | 29.4 | 10.397596 | 0.397596 | 0.397596 | 0.137509 | 0.137509 | 0.018909 |
| 20 | 29.7 | 9.904040 | -0.095960 | 0.095960 | -0.164126 | 0.164126 | 0.026937 |
| 22 | 30.7 | 10.074225 | 0.074225 | 0.074225 | -0.185862 | 0.185862 | 0.034545 |
| 25 | 32 | 9.682458 | -0.317542 | 0.317542 | 0.057455 | 0.057455 | 0.003301 |
| 27 | 33.1 | 10.166612 | 0.166612 | 0.166612 | -0.093475 | 0.093475 | 0.008738 |
| 30 | 34.3 | 9.353609 | -0.646391 | 0.646391 | 0.386304 | 0.386304 | 0.149231 |
| 35 | 37 | 10.428327 | 0.428327 | 0.428327 | 0.168240 | 0.168240 | 0.028305 |
| 40 | 39.2 | 9.624968 | -0.375032 | 0.375032 | 0.114946 | 0.114946 | 0.013213 |
| 45 | 41.6 | 9.503157 | -0.496843 | 0.496843 | 0.236756 | 0.236756 | 0.056053 |
| 50 | 44.1 | 9.788258 | -0.211742 | 0.211742 | -0.048345 | 0.048345 | 0.002337 |
| 55 | 46.6 | 10.065287 | 0.065287 | 0.065287 | -0.194800 | 0.194800 | 0.037947 |
| 60 | 49 | 9.848858 | -0.151142 | 0.151142 | -0.108945 | 0.108945 | 0.011869 |
| **Average Error [mm]:** | 0.260087 | **Variance [mm$^2$]:** | 0.032752 | **Standard Deviation [mm]:** | **0.180975** | | |

**Table A.11** Test Results of Vertical Slits with 5 Mhz Compressional Wave Probes of 45°

| **5 mm Slit** | **Distance btw Probes:** -26 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 7.071067 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)² [mm²]** |
| 0 | 18.6 | 4.686150 | -0.313850 | 0.313850 | -0.579434 | 0.579434 | 0.335744 |
| 1 | 19.1 | 4.749737 | -0.250263 | 0.250263 | -0.643021 | 0.643021 | 0.413476 |
| 2 | 19.4 | 3.919184 | -1.080816 | 1.080816 | 0.187532 | 0.187532 | 0.035168 |
| 3 | 20 | 4.444097 | -0.555903 | 0.555903 | -0.337381 | 0.337381 | 0.113826 |
| 4 | 20.5 | 4.500000 | -0.500000 | 0.500000 | -0.393284 | 0.393284 | 0.154672 |
| 5 | 21.1 | 4.995998 | -0.004002 | 0.004002 | -0.889283 | 0.889283 | 0.790823 |
| 6 | 21.6 | 5.055690 | 0.055690 | 0.055690 | -0.837594 | 0.837594 | 0.701564 |
| 7 | 22.1 | 5.114685 | 0.114685 | 0.114685 | -0.778599 | 0.778599 | 0.606217 |
| 8 | 22.5 | 4.716991 | -0.283009 | 0.283009 | -0.610275 | 0.610275 | 0.372435 |
| 9 | 22.9 | 4.261455 | -0.738545 | 0.738545 | -0.154739 | 0.154739 | 0.023944 |
| 10 | 23.4 | 4.308132 | -0.691868 | 0.691868 | -0.201416 | 0.201416 | 0.040568 |
| 11 | 23.9 | 4.354308 | -0.645692 | 0.645692 | -0.247592 | 0.247592 | 0.061302 |
| 12 | 24.3 | 3.806573 | -1.193427 | 1.193427 | 0.300143 | 0.300143 | 0.090086 |
| 13 | 24.8 | 3.845777 | -1.154223 | 1.154223 | 0.260939 | 0.260939 | 0.068089 |
| 14 | 25.3 | 3.884585 | -1.115415 | 1.115415 | 0.222131 | 0.222131 | 0.049342 |
| 15 | 25.8 | 3.923009 | -1.076991 | 1.076991 | 0.183707 | 0.183707 | 0.033748 |
| 16 | 26.2 | 3.231099 | -1.768901 | 1.768901 | 0.875617 | 0.875617 | 0.766705 |
| 17 | 26.7 | 3.261901 | -1.738099 | 1.738099 | 0.844815 | 0.844815 | 0.713712 |
| 18 | 27.2 | 3.292416 | -1.707584 | 1.707584 | 0.814300 | 0.814300 | 0.663085 |
| 19 | 27.7 | 3.322650 | -1.677350 | 1.677350 | 0.784066 | 0.784066 | 0.614760 |
| 20 | 28.3 | 4.109745 | -0.890255 | 0.890255 | -0.003029 | 0.003029 | 0.000009 |
| 22 | 29.1 | 2.410394 | -2.589606 | 2.589606 | 1.696322 | 1.696322 | 2.877507 |
| 25 | 30.7 | 3.498571 | -1.501429 | 1.501429 | 0.608145 | 0.608145 | 0.369840 |
| 27 | 31.8 | 4.357752 | -0.642248 | 0.642248 | -0.251036 | 0.251036 | 0.063019 |
| 30 | 33.2 | 3.638681 | -1.361319 | 1.361319 | 0.468035 | 0.468035 | 0.219057 |
| 35 | 35.8 | 4.624932 | -0.375068 | 0.375068 | -0.518217 | 0.518217 | 0.268548 |
| 40 | 38.2 | 3.903844 | -1.096156 | 1.096156 | 0.202872 | 0.202872 | 0.041157 |
| 45 | 40.8 | 4.938623 | -0.061377 | 0.061377 | -0.831907 | 0.831907 | 0.692070 |
| 50 | 43.2 | 4.152108 | -0.847892 | 0.847892 | -0.045392 | 0.045392 | 0.002060 |
| 55 | 45.9 | 6.046487 | 1.046487 | 1.046487 | 0.153202 | 0.153202 | 0.023471 |
| 60 | 48.2 | 4.386342 | -0.613658 | 0.613658 | -0.279627 | 0.279627 | 0.078191 |
| **Average Error [mm]:** | 0.893284 | **Variance [mm²]:** | 0.364006 | **Standard Deviation [mm]:** | **0.603329** | | |

**Table A.12** Test Results of Vertical Slits with 5 Mhz Compressional Wave Probes of 67°

| **20 mm Slit** | **Distance btw Probes:** 60.234094 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 51.186093 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 33.7 | 20.166556 | 0.166556 | 0.166556 | -0.038466 | 0.038466 | 0.001480 |
| 21 | 34.2 | 20.331994 | 0.331994 | 0.331994 | 0.126972 | 0.126972 | 0.016122 |
| 22 | 34.6 | 20.326338 | 0.326338 | 0.326338 | 0.121315 | 0.121315 | 0.014717 |
| 23 | 35 | 20.316250 | 0.316250 | 0.316250 | 0.111227 | 0.111227 | 0.012371 |
| 24 | 35.4 | 20.301724 | 0.301724 | 0.301724 | 0.096701 | 0.096701 | 0.009351 |
| 25 | 35.8 | 20.282751 | 0.282751 | 0.282751 | 0.077729 | 0.077729 | 0.006042 |
| 26 | 35.9 | 19.718266 | -0.281734 | 0.281734 | 0.076712 | 0.076712 | 0.005885 |
| 27 | 36.3 | 19.683496 | -0.316504 | 0.316504 | 0.111482 | 0.111482 | 0.012428 |
| 28 | 36.8 | 19.830280 | -0.169720 | 0.169720 | -0.035303 | 0.035303 | 0.001246 |
| 29 | 37.3 | 19.975986 | -0.024014 | 0.024014 | -0.181008 | 0.181008 | 0.032764 |
| 30 | 37.7 | 19.932135 | -0.067865 | 0.067865 | -0.137158 | 0.137158 | 0.018812 |
| 31 | 38.1 | 19.883662 | -0.116338 | 0.116338 | -0.088684 | 0.088684 | 0.007865 |
| 32 | 38.5 | 19.830532 | -0.169468 | 0.169468 | -0.035555 | 0.035555 | 0.001264 |
| 33 | 39 | 19.968726 | -0.031274 | 0.031274 | -0.173748 | 0.173748 | 0.030188 |
| 34 | 39.4 | 19.908792 | -0.091208 | 0.091208 | -0.113815 | 0.113815 | 0.012954 |
| 35 | 39.9 | 20.043952 | 0.043952 | 0.043952 | -0.161071 | 0.161071 | 0.025944 |
| 36 | 40.4 | 20.178206 | 0.178206 | 0.178206 | -0.026817 | 0.026817 | 0.000719 |
| 37 | 40.9 | 20.311573 | 0.311573 | 0.311573 | 0.106550 | 0.106550 | 0.011353 |
| 38 | 41.3 | 20.240800 | 0.240800 | 0.240800 | 0.035778 | 0.035778 | 0.001280 |
| 39 | 41.8 | 20.371303 | 0.371303 | 0.371303 | 0.166281 | 0.166281 | 0.027649 |
| 40 | 42.1 | 20.085069 | 0.085069 | 0.085069 | -0.119954 | 0.119954 | 0.014389 |
| 42 | 43 | 20.124612 | 0.124612 | 0.124612 | -0.080411 | 0.080411 | 0.006466 |
| 45 | 44.3 | 20.055922 | 0.055922 | 0.055922 | -0.149101 | 0.149101 | 0.022231 |
| 47 | 45.3 | 20.293841 | 0.293841 | 0.293841 | 0.088819 | 0.088819 | 0.007889 |
| 50 | 46.6 | 20.188115 | 0.188115 | 0.188115 | -0.016907 | 0.016907 | 0.000286 |
| 55 | 48.9 | 20.272148 | 0.272148 | 0.272148 | 0.067126 | 0.067126 | 0.004506 |
| 60 | 51.2 | 20.308619 | 0.308619 | 0.308619 | 0.103596 | 0.103596 | 0.010732 |
| 65 | 53.3 | 19.764615 | -0.235385 | 0.235385 | 0.030362 | 0.030362 | 0.000922 |
| 70 | 55.8 | 20.239565 | 0.239565 | 0.239565 | 0.034542 | 0.034542 | 0.001193 |
| 75 | 58.1 | 20.133554 | 0.133554 | 0.133554 | -0.071469 | 0.071469 | 0.005108 |
| 80 | 60.5 | 20.279300 | 0.279300 | 0.279300 | 0.074277 | 0.074277 | 0.005517 |
| **Average Error [mm]:** | 0.205023 | **Variance [mm$^2$]:** | 0.010635 | **Standard Deviation [mm]:** | **0.103124** | | |

**Table A.13** Test Results of Vertical Slits with 5 Mhz Compressional Wave Probe of 67°

| **15 mm Slit** | **Distance btw Probes:** 36.67557 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 38.389569 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 30.9 | 15.026976 | 0.026976 | 0.026976 | -0.229557 | 0.229557 | 0.052696 |
| 21 | 31.4 | 15.156187 | 0.156187 | 0.156187 | -0.100346 | 0.100346 | 0.010069 |
| 22 | 31.8 | 15.074482 | 0.074482 | 0.074482 | -0.182051 | 0.182051 | 0.033143 |
| 23 | 32.3 | 15.200000 | 0.200000 | 0.200000 | -0.056533 | 0.056533 | 0.003196 |
| 24 | 32.8 | 15.324490 | 0.324490 | 0.324490 | 0.067957 | 0.067957 | 0.004618 |
| 25 | 33.2 | 15.231218 | 0.231218 | 0.231218 | -0.025315 | 0.025315 | 0.000641 |
| 26 | 33.6 | 15.131424 | 0.131424 | 0.131424 | -0.125109 | 0.125109 | 0.015652 |
| 27 | 34.1 | 15.249918 | 0.249918 | 0.249918 | -0.006615 | 0.006615 | 0.000044 |
| 28 | 34.6 | 15.367498 | 0.367498 | 0.367498 | 0.110965 | 0.110965 | 0.012313 |
| 29 | 35.1 | 15.484185 | 0.484185 | 0.484185 | 0.227653 | 0.227653 | 0.051826 |
| 30 | 35.4 | 15.138032 | 0.138032 | 0.138032 | -0.118501 | 0.118501 | 0.014043 |
| 31 | 35.8 | 15.012994 | 0.012994 | 0.012994 | -0.243538 | 0.243538 | 0.059311 |
| 32 | 36.3 | 15.122500 | 0.122500 | 0.122500 | -0.134033 | 0.134033 | 0.017965 |
| 33 | 36.8 | 15.231218 | 0.231218 | 0.231218 | -0.025315 | 0.025315 | 0.000641 |
| 34 | 37.2 | 15.094370 | 0.094370 | 0.094370 | -0.162163 | 0.162163 | 0.026297 |
| 35 | 37.7 | 15.200000 | 0.200000 | 0.200000 | -0.056533 | 0.056533 | 0.003196 |
| 36 | 38.2 | 15.304901 | 0.304901 | 0.304901 | 0.048368 | 0.048368 | 0.002339 |
| 37 | 38.7 | 15.409088 | 0.409088 | 0.409088 | 0.152555 | 0.152555 | 0.023273 |
| 38 | 39.2 | 15.512576 | 0.512576 | 0.512576 | 0.256043 | 0.256043 | 0.065558 |
| 39 | 39.6 | 15.359362 | 0.359362 | 0.359362 | 0.102829 | 0.102829 | 0.010574 |
| 40 | 40 | 15.198684 | 0.198684 | 0.198684 | -0.057849 | 0.057849 | 0.003346 |
| 42 | 41 | 15.394804 | 0.394804 | 0.394804 | 0.138271 | 0.138271 | 0.019119 |
| 45 | 42.4 | 15.411359 | 0.411359 | 0.411359 | 0.154827 | 0.154827 | 0.023971 |
| 47 | 43.3 | 15.317963 | 0.317963 | 0.317963 | 0.061430 | 0.061430 | 0.003774 |
| 50 | 44.7 | 15.300000 | 0.300000 | 0.300000 | 0.043467 | 0.043467 | 0.001889 |
| 55 | 47.1 | 15.432433 | 0.432433 | 0.432433 | 0.175901 | 0.175901 | 0.030941 |
| 60 | 49.4 | 15.210523 | 0.210523 | 0.210523 | -0.046010 | 0.046010 | 0.002117 |
| 65 | 51.8 | 15.264010 | 0.264010 | 0.264010 | 0.007477 | 0.007477 | 0.000056 |
| 70 | 54.2 | 15.285287 | 0.285287 | 0.285287 | 0.028754 | 0.028754 | 0.000827 |
| 75 | 56.6 | 15.274489 | 0.274489 | 0.274489 | 0.017956 | 0.017956 | 0.000322 |
| 80 | 59 | 15.231546 | 0.231546 | 0.231546 | -0.024987 | 0.024987 | 0.000624 |
| **Average Error [mm]:** | 0.256533 | **Variance [mm$^2$]:** | 0.015948 | **Standard Deviation [mm]:** | **0.126285** | | |

**Table A.14** Test Results of Vertical Slits with 5 Mhz Compressional Wave Probe of 67º

| **10 mm Slit** | **Distance btw Probes:** 13.117046 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 25.593046 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 29 | 10.583005 | 0.583005 | 0.583005 | 0.109120 | 0.109120 | 0.011907 |
| 21 | 29.4 | 10.397596 | 0.397596 | 0.397596 | -0.076289 | 0.076289 | 0.005820 |
| 22 | 29.8 | 10.200000 | 0.200000 | 0.200000 | -0.273885 | 0.273885 | 0.075013 |
| 23 | 30.4 | 10.578752 | 0.578752 | 0.578752 | 0.104867 | 0.104867 | 0.010997 |
| 24 | 30.8 | 10.374970 | 0.374970 | 0.374970 | -0.098915 | 0.098915 | 0.009784 |
| 25 | 31.3 | 10.461357 | 0.461357 | 0.461357 | -0.012528 | 0.012528 | 0.000157 |
| 26 | 31.7 | 10.241582 | 0.241582 | 0.241582 | -0.232303 | 0.232303 | 0.053965 |
| 27 | 32.2 | 10.324243 | 0.324243 | 0.324243 | -0.149642 | 0.149642 | 0.022393 |
| 28 | 32.8 | 10.716343 | 0.716343 | 0.716343 | 0.242457 | 0.242457 | 0.058786 |
| 29 | 33.2 | 10.487612 | 0.487612 | 0.487612 | 0.013726 | 0.013726 | 0.000188 |
| 30 | 33.7 | 10.568349 | 0.568349 | 0.568349 | 0.094464 | 0.094464 | 0.008923 |
| 31 | 34.2 | 10.648474 | 0.648474 | 0.648474 | 0.174589 | 0.174589 | 0.030481 |
| 32 | 34.7 | 10.728001 | 0.728001 | 0.728001 | 0.254115 | 0.254115 | 0.064575 |
| 33 | 35.1 | 10.476641 | 0.476641 | 0.476641 | 0.002755 | 0.002755 | 0.000008 |
| 34 | 35.6 | 10.552725 | 0.552725 | 0.552725 | 0.078839 | 0.078839 | 0.006216 |
| 35 | 36 | 10.283482 | 0.283482 | 0.283482 | -0.190403 | 0.190403 | 0.036253 |
| 36 | 36.5 | 10.356158 | 0.356158 | 0.356158 | -0.117728 | 0.117728 | 0.013860 |
| 37 | 37 | 10.428327 | 0.428327 | 0.428327 | -0.045559 | 0.045559 | 0.002076 |
| 38 | 37.5 | 10.500000 | 0.500000 | 0.500000 | 0.026115 | 0.026115 | 0.000682 |
| 39 | 38 | 10.571187 | 0.571187 | 0.571187 | 0.097302 | 0.097302 | 0.009468 |
| 40 | 38.4 | 10.274240 | 0.274240 | 0.274240 | -0.199646 | 0.199646 | 0.039858 |
| 42 | 39.4 | 10.409611 | 0.409611 | 0.409611 | -0.064274 | 0.064274 | 0.004131 |
| 45 | 40.9 | 10.609430 | 0.609430 | 0.609430 | 0.135544 | 0.135544 | 0.018372 |
| 47 | 41.8 | 10.343597 | 0.343597 | 0.343597 | -0.130288 | 0.130288 | 0.016975 |
| 50 | 43.3 | 10.530432 | 0.530432 | 0.530432 | 0.056547 | 0.056547 | 0.003198 |
| 55 | 45.7 | 10.403845 | 0.403845 | 0.403845 | -0.070040 | 0.070040 | 0.004906 |
| 60 | 48.2 | 10.688311 | 0.688311 | 0.688311 | 0.214426 | 0.214426 | 0.045979 |
| 65 | 50.6 | 10.493331 | 0.493331 | 0.493331 | 0.019446 | 0.019446 | 0.000378 |
| 70 | 53 | 10.246951 | 0.246951 | 0.246951 | -0.226935 | 0.226935 | 0.051499 |
| 75 | 55.5 | 10.488088 | 0.488088 | 0.488088 | 0.014203 | 0.014203 | 0.000202 |
| 80 | 58 | 10.723805 | 0.723805 | 0.723805 | 0.249920 | 0.249920 | 0.062460 |
| **Average Error [mm]:** | 0.473885 | **Variance [mm$^2$]:** | 0.021597 | **Standard Deviation [mm]:** | **0.146959** | | |

**Table A.15** Test Results of Vertical Slits with 5 Mhz Compressional Wave Probe of 67º

| **5 mm Slit** | **Distance btw Probes:** -10.441478 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 12.796523 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 27.5 | 5.220153 | 0.220153 | 0.220153 | -0.116517 | 0.116517 | 0.013576 |
| 21 | 28 | 5.267827 | 0.267827 | 0.267827 | -0.068844 | 0.068844 | 0.004739 |
| 22 | 28.5 | 5.315073 | 0.315073 | 0.315073 | -0.021598 | 0.021598 | 0.000466 |
| 23 | 29 | 5.361903 | 0.361903 | 0.361903 | 0.025232 | 0.025232 | 0.000637 |
| 24 | 29.5 | 5.408327 | 0.408327 | 0.408327 | 0.071656 | 0.071656 | 0.005135 |
| 25 | 30 | 5.454356 | 0.454356 | 0.454356 | 0.117685 | 0.117685 | 0.013850 |
| 26 | 30.5 | 5.500000 | 0.500000 | 0.500000 | 0.163329 | 0.163329 | 0.026676 |
| 27 | 31 | 5.545268 | 0.545268 | 0.545268 | 0.208598 | 0.208598 | 0.043513 |
| 28 | 31.4 | 4.995998 | -0.004002 | 0.004002 | -0.332669 | 0.332669 | 0.110669 |
| 29 | 31.9 | 5.035871 | 0.035871 | 0.035871 | -0.300799 | 0.300799 | 0.090480 |
| 30 | 32.4 | 5.075431 | 0.075431 | 0.075431 | -0.261240 | 0.261240 | 0.068246 |
| 31 | 32.9 | 5.114685 | 0.114685 | 0.114685 | -0.221986 | 0.221986 | 0.049278 |
| 32 | 33.4 | 5.153639 | 0.153639 | 0.153639 | -0.183031 | 0.183031 | 0.033500 |
| 33 | 33.9 | 5.192302 | 0.192302 | 0.192302 | -0.144369 | 0.144369 | 0.020842 |
| 34 | 34.4 | 5.230679 | 0.230679 | 0.230679 | -0.105992 | 0.105992 | 0.011234 |
| 35 | 34.9 | 5.268776 | 0.268776 | 0.268776 | -0.067895 | 0.067895 | 0.004610 |
| 36 | 35.4 | 5.306600 | 0.306600 | 0.306600 | -0.030071 | 0.030071 | 0.000904 |
| 37 | 35.9 | 5.344156 | 0.344156 | 0.344156 | 0.007485 | 0.007485 | 0.000056 |
| 38 | 36.4 | 5.381450 | 0.381450 | 0.381450 | 0.044779 | 0.044779 | 0.002005 |
| 39 | 36.9 | 5.418487 | 0.418487 | 0.418487 | 0.081816 | 0.081816 | 0.006694 |
| 40 | 37.4 | 5.455273 | 0.455273 | 0.455273 | 0.118602 | 0.118602 | 0.014066 |
| 42 | 38.4 | 5.528110 | 0.528110 | 0.528110 | 0.191439 | 0.191439 | 0.036649 |
| 45 | 39.9 | 5.635601 | 0.635601 | 0.635601 | 0.298930 | 0.298930 | 0.089359 |
| 47 | 40.8 | 4.938623 | -0.061377 | 0.061377 | -0.275294 | 0.275294 | 0.075787 |
| 50 | 42.3 | 5.028916 | 0.028916 | 0.028916 | -0.307754 | 0.307754 | 0.094713 |
| 55 | 44.8 | 5.175906 | 0.175906 | 0.175906 | -0.160765 | 0.160765 | 0.025845 |
| 60 | 47.3 | 5.318834 | 0.318834 | 0.318834 | -0.017836 | 0.017836 | 0.000318 |
| 65 | 49.8 | 5.458022 | 0.458022 | 0.458022 | 0.121351 | 0.121351 | 0.014726 |
| 70 | 52.3 | 5.593747 | 0.593747 | 0.593747 | 0.257076 | 0.257076 | 0.066088 |
| 75 | 54.8 | 5.726255 | 0.726255 | 0.726255 | 0.389585 | 0.389585 | 0.151776 |
| 80 | 57.3 | 5.855766 | 0.855766 | 0.855766 | 0.519096 | 0.519096 | 0.269460 |
| **Average Error [mm]:** | 0.336671 | **Variance [mm$^2$]:** | 0.043416 | **Standard Deviation [mm]:** | **0.208365** | | |

**Table A.16** Test Results of 15 Degree Slits with 4 Mhz Compressional Wave Probe of 45°

| 20 (19.318516) mm Slit 15° | **Distance btw Probes:** 8 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 27.320507 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 25.7 | 20.111937 | 0.793421 | 0.793421 | -0.004954 | 0.004954 | 0.000025 |
| 1 | 26.1 | 20.222759 | 0.904243 | 0.904243 | 0.105869 | 0.105869 | 0.011208 |
| 2 | 26.4 | 20.198020 | 0.879504 | 0.879504 | 0.081129 | 0.081129 | 0.006582 |
| 3 | 26.8 | 20.297537 | 0.979021 | 0.979021 | 0.180646 | 0.180646 | 0.032633 |
| 4 | 27.1 | 20.258578 | 0.940062 | 0.940062 | 0.141688 | 0.141688 | 0.020075 |
| 5 | 27.4 | 20.211630 | 0.893114 | 0.893114 | 0.094740 | 0.094740 | 0.008976 |
| 6 | 27.8 | 20.293841 | 0.975325 | 0.975325 | 0.176951 | 0.176951 | 0.031312 |
| 7 | 28.1 | 20.232647 | 0.914131 | 0.914131 | 0.115756 | 0.115756 | 0.013400 |
| 8 | 28.4 | 20.163333 | 0.844817 | 0.844817 | 0.046442 | 0.046442 | 0.002157 |
| 9 | 28.7 | 20.085816 | 0.767300 | 0.767300 | -0.031075 | 0.031075 | 0.000966 |
| 10 | 29 | 20.000000 | 0.681484 | 0.681484 | -0.116891 | 0.116891 | 0.013663 |
| 11 | 29.5 | 20.199010 | 0.880494 | 0.880494 | 0.082119 | 0.082119 | 0.006744 |
| 12 | 29.8 | 20.100746 | 0.782230 | 0.782230 | -0.016144 | 0.016144 | 0.000261 |
| 13 | 30.1 | 19.993999 | 0.675483 | 0.675483 | -0.122892 | 0.122892 | 0.015102 |
| 14 | 30.5 | 20.031226 | 0.712710 | 0.712710 | -0.085665 | 0.085665 | 0.007338 |
| 15 | 31 | 20.217567 | 0.899051 | 0.899051 | 0.100676 | 0.100676 | 0.010136 |
| 16 | 31.4 | 20.247469 | 0.928953 | 0.928953 | 0.130578 | 0.130578 | 0.017051 |
| 17 | 31.7 | 20.115666 | 0.797150 | 0.797150 | -0.001225 | 0.001225 | 0.000002 |
| 18 | 32.1 | 20.134796 | 0.816280 | 0.816280 | 0.017905 | 0.017905 | 0.000321 |
| 19 | 32.5 | 20.149442 | 0.830926 | 0.830926 | 0.032551 | 0.032551 | 0.001060 |
| 20 | 32.9 | 20.159613 | 0.841097 | 0.841097 | 0.042722 | 0.042722 | 0.001825 |
| 22 | 33.7 | 20.166556 | 0.848040 | 0.848040 | 0.049666 | 0.049666 | 0.002467 |
| 25 | 34.9 | 20.143485 | 0.824969 | 0.824969 | 0.026595 | 0.026595 | 0.000707 |
| 27 | 35.8 | 20.282751 | 0.964235 | 0.964235 | 0.165861 | 0.165861 | 0.027510 |
| 30 | 37 | 20.199010 | 0.880494 | 0.880494 | 0.082119 | 0.082119 | 0.006744 |
| 35 | 39 | 19.968726 | 0.650210 | 0.650210 | -0.148165 | 0.148165 | 0.021953 |
| 40 | 41.2 | 20.035968 | 0.717452 | 0.717452 | -0.080923 | 0.080923 | 0.006549 |
| 45 | 43.4 | 20.032723 | 0.714207 | 0.714207 | -0.084167 | 0.084167 | 0.007084 |
| 50 | 45.6 | 19.958958 | 0.640442 | 0.640442 | -0.157933 | 0.157933 | 0.024943 |
| 55 | 47.8 | 19.813884 | 0.495368 | 0.495368 | -0.303007 | 0.303007 | 0.091813 |
| 60 | 50 | 19.595918 | 0.277402 | 0.277402 | -0.520973 | 0.520973 | 0.271413 |
| **Average Error [mm]:** | 0.798375 | **Variance [mm$^2$]:** | 0.021355 | **Standard Deviation [mm]:** | **0.146135** | | |

**Table A.17** Test Results of 15 Degree Slits with 4 Mhz Compressional Wave Probes of 45°

| **15 (14.488887) mm Slit 15°** | **Distance btw Probes:** -2 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 20.490381 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 22.1 | 15.244999 | 0.756112 | 0.756112 | 0.030534 | 0.030534 | 0.000932 |
| 1 | 22.6 | 15.443769 | 0.954882 | 0.954882 | 0.229304 | 0.229304 | 0.052580 |
| 2 | 22.9 | 15.343077 | 0.854190 | 0.854190 | 0.128611 | 0.128611 | 0.016541 |
| 3 | 23.3 | 15.383108 | 0.894221 | 0.894221 | 0.168642 | 0.168642 | 0.028440 |
| 4 | 23.7 | 15.417198 | 0.928311 | 0.928311 | 0.202733 | 0.202733 | 0.041101 |
| 5 | 24 | 15.288885 | 0.799998 | 0.799998 | 0.074420 | 0.074420 | 0.005538 |
| 6 | 24.4 | 15.308821 | 0.819934 | 0.819934 | 0.094356 | 0.094356 | 0.008903 |
| 7 | 24.8 | 15.322859 | 0.833972 | 0.833972 | 0.108394 | 0.108394 | 0.011749 |
| 8 | 25.2 | 15.331014 | 0.842127 | 0.842127 | 0.116549 | 0.116549 | 0.013584 |
| 9 | 25.6 | 15.333297 | 0.844410 | 0.844410 | 0.118832 | 0.118832 | 0.014121 |
| 10 | 26 | 15.329710 | 0.840823 | 0.840823 | 0.115245 | 0.115245 | 0.013281 |
| 11 | 26.4 | 15.320248 | 0.831361 | 0.831361 | 0.105783 | 0.105783 | 0.011190 |
| 12 | 26.8 | 15.304901 | 0.816014 | 0.816014 | 0.090436 | 0.090436 | 0.008179 |
| 13 | 27.2 | 15.283651 | 0.794764 | 0.794764 | 0.069186 | 0.069186 | 0.004787 |
| 14 | 27.6 | 15.256474 | 0.767587 | 0.767587 | 0.042009 | 0.042009 | 0.001765 |
| 15 | 28 | 15.223337 | 0.734450 | 0.734450 | 0.008872 | 0.008872 | 0.000079 |
| 16 | 28.5 | 15.370426 | 0.881539 | 0.881539 | 0.155961 | 0.155961 | 0.024324 |
| 17 | 28.9 | 15.328405 | 0.839518 | 0.839518 | 0.113940 | 0.113940 | 0.012982 |
| 18 | 29.3 | 15.280380 | 0.791493 | 0.791493 | 0.065914 | 0.065914 | 0.004345 |
| 19 | 29.7 | 15.226293 | 0.737406 | 0.737406 | 0.011828 | 0.011828 | 0.000140 |
| 20 | 30.1 | 15.166081 | 0.677194 | 0.677194 | -0.048385 | 0.048385 | 0.002341 |
| 22 | 31 | 15.231546 | 0.742659 | 0.742659 | 0.017081 | 0.017081 | 0.000292 |
| 25 | 32.2 | 14.986327 | 0.497440 | 0.497440 | -0.228138 | 0.228138 | 0.052047 |
| 27 | 33.1 | 15.011995 | 0.523108 | 0.523108 | -0.202470 | 0.202470 | 0.040994 |
| 30 | 34.4 | 14.911740 | 0.422853 | 0.422853 | -0.302725 | 0.302725 | 0.091642 |
| 35 | 36.8 | 15.231218 | 0.742331 | 0.742331 | 0.016753 | 0.016753 | 0.000281 |
| 40 | 39 | 15.000000 | 0.511113 | 0.511113 | -0.214465 | 0.214465 | 0.045995 |
| 45 | 41.3 | 14.947910 | 0.459023 | 0.459023 | -0.266556 | 0.266556 | 0.071052 |
| 50 | 43.7 | 15.122500 | 0.633613 | 0.633613 | -0.091965 | 0.091965 | 0.008458 |
| 55 | 45.8 | 14.331434 | -0.157453 | 0.157453 | -0.568125 | 0.568125 | 0.322766 |
| 60 | 48.4 | 15.051910 | 0.563023 | 0.563023 | -0.162555 | 0.162555 | 0.026424 |
| **Average Error [mm]:** | 0.725578 | **Variance [mm$^2$]:** | 0.030221 | **Standard Deviation [mm]:** | **0.173842** | | |

**Table A.18** Test Results of 15 Degree Slits with 4 Mhz Compressional Wave Probes of 45°

| **10 (9.659258) mm Slit 15°** | **Distance btw Probes:** -12 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 13.660253 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 18.8 | 9.871170 | 0.211912 | 0.211912 | -0.049814 | 0.049814 | 0.002481 |
| 1 | 19.2 | 9.817841 | 0.158583 | 0.158583 | -0.103144 | 0.103144 | 0.010639 |
| 2 | 19.6 | 9.754999 | 0.095741 | 0.095741 | -0.165986 | 0.165986 | 0.027551 |
| 3 | 20 | 9.682458 | 0.023200 | 0.023200 | -0.238526 | 0.238526 | 0.056895 |
| 4 | 20.5 | 9.810708 | 0.151450 | 0.151450 | -0.110276 | 0.110276 | 0.012161 |
| 5 | 21 | 9.937303 | 0.278045 | 0.278045 | 0.016319 | 0.016319 | 0.000266 |
| 6 | 21.4 | 9.846827 | 0.187569 | 0.187569 | -0.074158 | 0.074158 | 0.005499 |
| 7 | 21.8 | 9.746281 | 0.087023 | 0.087023 | -0.174703 | 0.174703 | 0.030521 |
| 8 | 22.3 | 9.863569 | 0.204311 | 0.204311 | -0.057415 | 0.057415 | 0.003297 |
| 9 | 22.7 | 9.748846 | 0.089588 | 0.089588 | -0.172139 | 0.172139 | 0.029632 |
| 10 | 23.1 | 9.623409 | -0.035849 | 0.035849 | -0.225878 | 0.225878 | 0.051021 |
| 11 | 23.5 | 9.486833 | -0.172425 | 0.172425 | -0.089302 | 0.089302 | 0.007975 |
| 12 | 24 | 9.591663 | -0.067595 | 0.067595 | -0.194132 | 0.194132 | 0.037687 |
| 13 | 24.4 | 9.439809 | -0.219449 | 0.219449 | -0.042278 | 0.042278 | 0.001787 |
| 14 | 24.8 | 9.275775 | -0.383483 | 0.383483 | 0.121757 | 0.121757 | 0.014825 |
| 15 | 25.3 | 9.372300 | -0.286958 | 0.286958 | 0.025232 | 0.025232 | 0.000637 |
| 16 | 25.7 | 9.191844 | -0.467414 | 0.467414 | 0.205687 | 0.205687 | 0.042307 |
| 17 | 26.2 | 9.283857 | -0.375401 | 0.375401 | 0.113674 | 0.113674 | 0.012922 |
| 18 | 26.7 | 9.374967 | -0.284291 | 0.284291 | 0.022565 | 0.022565 | 0.000509 |
| 19 | 27.2 | 9.465199 | -0.194059 | 0.194059 | -0.067668 | 0.067668 | 0.004579 |
| 20 | 27.6 | 9.260670 | -0.398588 | 0.398588 | 0.136862 | 0.136862 | 0.018731 |
| 22 | 28.7 | 9.730879 | 0.071621 | 0.071621 | -0.190106 | 0.190106 | 0.036140 |
| 25 | 30.5 | 10.862780 | 1.203522 | 1.203522 | 0.941796 | 0.941796 | 0.886980 |
| 27 | 31.3 | 10.461357 | 0.802099 | 0.802099 | 0.540373 | 0.540373 | 0.292003 |
| 30 | 32.6 | 10.087616 | 0.428358 | 0.428358 | 0.166632 | 0.166632 | 0.027766 |
| 35 | 34.9 | 9.785704 | 0.126446 | 0.126446 | -0.135281 | 0.135281 | 0.018301 |
| 40 | 37.3 | 9.761660 | 0.102402 | 0.102402 | -0.159325 | 0.159325 | 0.025384 |
| 45 | 39.7 | 9.687105 | 0.027847 | 0.027847 | -0.233880 | 0.233880 | 0.054700 |
| 50 | 42.2 | 9.991997 | 0.332739 | 0.332739 | 0.071012 | 0.071012 | 0.005043 |
| 55 | 44.6 | 9.844288 | 0.185030 | 0.185030 | -0.076697 | 0.076697 | 0.005882 |
| 60 | 47.1 | 10.119783 | 0.460525 | 0.460525 | 0.198798 | 0.198798 | 0.039521 |
| **Average Error [mm]:** | 0.261727 | **Variance [mm$^2$]:** | 0.056892 | **Standard Deviation [mm]:** | **0.238520** | | |

**Table A.19** Test Results of 15° Slits with 4 Mhz Compressional Wave Probes of 67°

| **20 (19.318516) mm Slit 15°** | **Distance btw Probes:** 63.617047 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 51.186093 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 31.5 | 19.163768 | -0.154748 | 0.154748 | 0.018715 | 0.018715 | 0.000350 |
| 21 | 32 | 19.332615 | 0.014099 | 0.014099 | -0.121934 | 0.121934 | 0.014868 |
| 22 | 32.4 | 19.332874 | 0.014358 | 0.014358 | -0.121676 | 0.121676 | 0.014805 |
| 23 | 32.8 | 19.328476 | 0.009960 | 0.009960 | -0.126073 | 0.126073 | 0.015894 |
| 24 | 33.1 | 19.147062 | -0.171454 | 0.171454 | 0.035420 | 0.035420 | 0.001255 |
| 25 | 33.6 | 19.305699 | -0.012817 | 0.012817 | -0.123216 | 0.123216 | 0.015182 |
| 26 | 34 | 19.287302 | -0.031214 | 0.031214 | -0.104819 | 0.104819 | 0.010987 |
| 27 | 34.5 | 19.442222 | 0.123706 | 0.123706 | -0.012327 | 0.012327 | 0.000152 |
| 28 | 34.9 | 19.416745 | 0.098229 | 0.098229 | -0.037804 | 0.037804 | 0.001429 |
| 29 | 35.3 | 19.386593 | 0.068077 | 0.068077 | -0.067956 | 0.067956 | 0.004618 |
| 30 | 35.7 | 19.351744 | 0.033228 | 0.033228 | -0.102805 | 0.102805 | 0.010569 |
| 31 | 36.2 | 19.498461 | 0.179945 | 0.179945 | 0.043912 | 0.043912 | 0.001928 |
| 32 | 36.6 | 19.456618 | 0.138102 | 0.138102 | 0.002069 | 0.002069 | 0.000004 |
| 33 | 37 | 19.410049 | 0.091533 | 0.091533 | -0.044500 | 0.044500 | 0.001980 |
| 34 | 37.4 | 19.358719 | 0.040203 | 0.040203 | -0.095830 | 0.095830 | 0.009183 |
| 35 | 37.9 | 19.497692 | 0.179176 | 0.179176 | 0.043143 | 0.043143 | 0.001861 |
| 36 | 38.3 | 19.439393 | 0.120877 | 0.120877 | -0.015156 | 0.015156 | 0.000230 |
| 37 | 38.7 | 19.376274 | 0.057758 | 0.057758 | -0.078275 | 0.078275 | 0.006127 |
| 38 | 39.2 | 19.509997 | 0.191481 | 0.191481 | 0.055448 | 0.055448 | 0.003075 |
| 39 | 39.6 | 19.439907 | 0.121391 | 0.121391 | -0.014642 | 0.014642 | 0.000214 |
| 40 | 40.1 | 19.570641 | 0.252125 | 0.252125 | 0.116092 | 0.116092 | 0.013477 |
| 42 | 40.9 | 19.411594 | 0.093078 | 0.093078 | -0.042955 | 0.042955 | 0.001845 |
| 45 | 42.3 | 19.571408 | 0.252892 | 0.252892 | 0.116859 | 0.116859 | 0.013656 |
| 47 | 43.1 | 19.374210 | 0.055694 | 0.055694 | -0.080339 | 0.080339 | 0.006454 |
| 50 | 44.4 | 19.270703 | -0.047813 | 0.047813 | -0.088220 | 0.088220 | 0.007783 |
| 55 | 46.8 | 19.595663 | 0.277147 | 0.277147 | 0.141114 | 0.141114 | 0.019913 |
| 60 | 49.1 | 19.642047 | 0.323531 | 0.323531 | 0.187498 | 0.187498 | 0.035155 |
| 65 | 51.4 | 19.639501 | 0.320985 | 0.320985 | 0.184952 | 0.184952 | 0.034207 |
| 70 | 53.7 | 19.588007 | 0.269491 | 0.269491 | 0.133457 | 0.133457 | 0.017811 |
| 75 | 56.1 | 19.772708 | 0.454192 | 0.454192 | 0.318159 | 0.318159 | 0.101225 |
| 80 | 58.3 | 19.336235 | 0.017719 | 0.017719 | -0.118314 | 0.118314 | 0.013998 |
| **Average Error [mm]:** | 0.136033 | **Variance [mm$^2$]:** | 0.012266 | **Standard Deviation [mm]:** | **0.110751** | | |

**Table A.20** Test Results of 15° Slits with 4 Mhz Compressional Wave Probes of 67°

| 15 (14.488887) mm Slit 15° | **Distance btw Probes:** 40.67557 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 38.389569 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)² [mm²]** |
| 20 | 28.9 | 14.498621 | 0.009734 | 0.009734 | -0.168147 | 0.168147 | 0.028273 |
| 21 | 29.3 | 14.430523 | -0.058364 | 0.058364 | -0.119517 | 0.119517 | 0.014284 |
| 22 | 29.7 | 14.355835 | -0.133052 | 0.133052 | -0.044829 | 0.044829 | 0.002010 |
| 23 | 30.2 | 14.484129 | -0.004758 | 0.004758 | -0.173123 | 0.173123 | 0.029972 |
| 24 | 30.7 | 14.611297 | 0.122410 | 0.122410 | -0.055471 | 0.055471 | 0.003077 |
| 25 | 31.2 | 14.737367 | 0.248480 | 0.248480 | 0.070600 | 0.070600 | 0.004984 |
| 26 | 31.6 | 14.647867 | 0.158980 | 0.158980 | -0.018901 | 0.018901 | 0.000357 |
| 27 | 32.1 | 14.770240 | 0.281353 | 0.281353 | 0.103473 | 0.103473 | 0.010707 |
| 28 | 32.5 | 14.671401 | 0.182514 | 0.182514 | 0.004633 | 0.004633 | 0.000021 |
| 29 | 33 | 14.790199 | 0.301312 | 0.301312 | 0.123432 | 0.123432 | 0.015235 |
| 30 | 33.4 | 14.681962 | 0.193075 | 0.193075 | 0.015194 | 0.015194 | 0.000231 |
| 31 | 33.9 | 14.797297 | 0.308410 | 0.308410 | 0.130529 | 0.130529 | 0.017038 |
| 32 | 34.2 | 14.444376 | -0.044511 | 0.044511 | -0.133370 | 0.133370 | 0.017787 |
| 33 | 34.8 | 14.791552 | 0.302665 | 0.302665 | 0.124784 | 0.124784 | 0.015571 |
| 34 | 35.1 | 14.422552 | -0.066335 | 0.066335 | -0.111545 | 0.111545 | 0.012442 |
| 35 | 35.5 | 14.282857 | -0.206030 | 0.206030 | 0.028150 | 0.028150 | 0.000792 |
| 36 | 36 | 14.387495 | -0.101392 | 0.101392 | -0.076488 | 0.076488 | 0.005850 |
| 37 | 36.5 | 14.491377 | 0.002490 | 0.002490 | -0.175391 | 0.175391 | 0.030762 |
| 38 | 37 | 14.594520 | 0.105633 | 0.105633 | -0.072248 | 0.072248 | 0.005220 |
| 39 | 37.4 | 14.439875 | -0.049012 | 0.049012 | -0.128869 | 0.128869 | 0.016607 |
| 40 | 37.9 | 14.539945 | 0.051058 | 0.051058 | -0.126823 | 0.126823 | 0.016084 |
| 42 | 38.8 | 14.472042 | -0.016845 | 0.016845 | -0.161036 | 0.161036 | 0.025932 |
| 45 | 40.3 | 14.759404 | 0.270517 | 0.270517 | 0.092636 | 0.092636 | 0.008581 |
| 47 | 41.3 | 14.947910 | 0.459023 | 0.459023 | 0.281142 | 0.281142 | 0.079041 |
| 50 | 42.5 | 14.361407 | -0.127480 | 0.127480 | -0.050400 | 0.050400 | 0.002540 |
| 55 | 45 | 14.790199 | 0.301312 | 0.301312 | 0.123432 | 0.123432 | 0.015235 |
| 60 | 47.3 | 14.570175 | 0.081288 | 0.081288 | -0.096593 | 0.096593 | 0.009330 |
| 65 | 49.7 | 14.623269 | 0.134382 | 0.134382 | -0.043499 | 0.043499 | 0.001892 |
| 70 | 52 | 14.282857 | -0.206030 | 0.206030 | 0.028150 | 0.028150 | 0.000792 |
| 75 | 54.6 | 14.997000 | 0.508113 | 0.508113 | 0.330232 | 0.330232 | 0.109053 |
| 80 | 57 | 14.966630 | 0.477743 | 0.477743 | 0.299862 | 0.299862 | 0.089917 |
| **Average Error [mm]:** | 0.177881 | **Variance [mm²]:** | 0.019020 | **Standard Deviation [mm]:** | **0.137913** | | |

**Table A.21** Test Results of 15º Slits with 4 Mhz Compressional Wave Probes of 67º

| **10 (9.659258) mm Slit 15°** | **Distance btw Probes:** 17.117046 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 25.593046 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 26.6 | 9.086253 | -0.573005 | 0.573005 | 0.215135 | 0.215135 | 0.046283 |
| 21 | 27.1 | 9.173876 | -0.485382 | 0.485382 | 0.127512 | 0.127512 | 0.016259 |
| 22 | 27.5 | 8.958236 | -0.701022 | 0.701022 | 0.343152 | 0.343152 | 0.117753 |
| 23 | 27.9 | 8.726970 | -0.932288 | 0.932288 | 0.574418 | 0.574418 | 0.329956 |
| 24 | 28.4 | 8.806816 | -0.852442 | 0.852442 | 0.494573 | 0.494573 | 0.244602 |
| 25 | 28.9 | 8.885944 | -0.773314 | 0.773314 | 0.415444 | 0.415444 | 0.172594 |
| 26 | 29.4 | 8.964374 | -0.694884 | 0.694884 | 0.337014 | 0.337014 | 0.113579 |
| 27 | 30 | 9.367497 | -0.291761 | 0.291761 | -0.066109 | 0.066109 | 0.004370 |
| 28 | 30.4 | 9.119210 | -0.540048 | 0.540048 | 0.182178 | 0.182178 | 0.033189 |
| 29 | 30.9 | 9.195651 | -0.463607 | 0.463607 | 0.105737 | 0.105737 | 0.011180 |
| 30 | 31.4 | 9.271462 | -0.387796 | 0.387796 | 0.029926 | 0.029926 | 0.000896 |
| 31 | 31.9 | 9.346657 | -0.312601 | 0.312601 | -0.045269 | 0.045269 | 0.002049 |
| 32 | 32.4 | 9.421253 | -0.238005 | 0.238005 | -0.119865 | 0.119865 | 0.014368 |
| 33 | 32.9 | 9.495262 | -0.163996 | 0.163996 | -0.193874 | 0.193874 | 0.037587 |
| 34 | 33.3 | 9.213577 | -0.445681 | 0.445681 | 0.087811 | 0.087811 | 0.007711 |
| 35 | 33.8 | 9.283857 | -0.375401 | 0.375401 | 0.017531 | 0.017531 | 0.000307 |
| 36 | 34.3 | 9.353609 | -0.305649 | 0.305649 | -0.052221 | 0.052221 | 0.002727 |
| 37 | 34.9 | 9.785704 | 0.126446 | 0.126446 | -0.231424 | 0.231424 | 0.053557 |
| 38 | 35.3 | 9.491575 | -0.167683 | 0.167683 | -0.190187 | 0.190187 | 0.036171 |
| 39 | 35.8 | 9.559812 | -0.099446 | 0.099446 | -0.258424 | 0.258424 | 0.066783 |
| 40 | 36.2 | 9.243376 | -0.415882 | 0.415882 | 0.058012 | 0.058012 | 0.003365 |
| 42 | 37.2 | 9.372300 | -0.286958 | 0.286958 | -0.070912 | 0.070912 | 0.005028 |
| 45 | 38.7 | 9.562426 | -0.096832 | 0.096832 | -0.261038 | 0.261038 | 0.068141 |
| 47 | 39.7 | 9.687105 | 0.027847 | 0.027847 | -0.330023 | 0.330023 | 0.108915 |
| 50 | 41.1 | 9.445105 | -0.214153 | 0.214153 | -0.143716 | 0.143716 | 0.020654 |
| 55 | 43.5 | 9.273618 | -0.385640 | 0.385640 | 0.027770 | 0.027770 | 0.000771 |
| 60 | 46 | 9.539392 | -0.119866 | 0.119866 | -0.238004 | 0.238004 | 0.056646 |
| 65 | 48.5 | 9.797959 | 0.138701 | 0.138701 | -0.219169 | 0.219169 | 0.048035 |
| 70 | 50.9 | 9.529428 | -0.129830 | 0.129830 | -0.228040 | 0.228040 | 0.052002 |
| 75 | 53.4 | 9.762684 | 0.103426 | 0.103426 | -0.254444 | 0.254444 | 0.064742 |
| 80 | 55.8 | 9.414882 | -0.244376 | 0.244376 | -0.113494 | 0.113494 | 0.012881 |
| **Average Error [mm]:** | 0.357870 | **Variance [mm$^2$]:** | 0.056552 | **Standard Deviation [mm]:** | **0.237806** | | |

**Table A.22** Test Results of 15° Slits with 4 Mhz Compressional Wave Probes of 67°

| **5 (4.829629) mm Slit 15°** | **Distance btw Probes:** -6.441478 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 12.796523 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 25.5 | 5.024938 | 0.195309 | 0.195309 | -0.504861 | 0.504861 | 0.254885 |
| 21 | 26 | 5.074446 | 0.244817 | 0.244817 | -0.455353 | 0.455353 | 0.207347 |
| 22 | 26.5 | 5.123475 | 0.293846 | 0.293846 | -0.406324 | 0.406324 | 0.165099 |
| 23 | 27 | 5.172040 | 0.342411 | 0.342411 | -0.357759 | 0.357759 | 0.127992 |
| 24 | 27.5 | 5.220153 | 0.390524 | 0.390524 | -0.309646 | 0.309646 | 0.095881 |
| 25 | 28 | 5.267827 | 0.438198 | 0.438198 | -0.261972 | 0.261972 | 0.068630 |
| 26 | 28.5 | 5.315073 | 0.485444 | 0.485444 | -0.214726 | 0.214726 | 0.046107 |
| 27 | 29 | 5.361903 | 0.532274 | 0.532274 | -0.167897 | 0.167897 | 0.028189 |
| 28 | 29.5 | 5.408327 | 0.578698 | 0.578698 | -0.121472 | 0.121472 | 0.014756 |
| 29 | 30 | 5.454356 | 0.624727 | 0.624727 | -0.075443 | 0.075443 | 0.005692 |
| 30 | 30.4 | 4.915282 | 0.085653 | 0.085653 | -0.614517 | 0.614517 | 0.377631 |
| 31 | 31 | 5.545268 | 0.715639 | 0.715639 | 0.015469 | 0.015469 | 0.000239 |
| 32 | 31.5 | 5.590170 | 0.760541 | 0.760541 | 0.060371 | 0.060371 | 0.003645 |
| 33 | 32 | 5.634714 | 0.805085 | 0.805085 | 0.104915 | 0.104915 | 0.011007 |
| 34 | 32.5 | 5.678908 | 0.849279 | 0.849279 | 0.149109 | 0.149109 | 0.022234 |
| 35 | 32.9 | 5.114685 | 0.285056 | 0.285056 | -0.415115 | 0.415115 | 0.172320 |
| 36 | 33.4 | 5.153639 | 0.324010 | 0.324010 | -0.376160 | 0.376160 | 0.141496 |
| 37 | 34 | 5.809475 | 0.979846 | 0.979846 | 0.279676 | 0.279676 | 0.078219 |
| 38 | 34.5 | 5.852350 | 1.022721 | 1.022721 | 0.322551 | 0.322551 | 0.104039 |
| 39 | 35 | 5.894913 | 1.065284 | 1.065284 | 0.365114 | 0.365114 | 0.133308 |
| 40 | 35.5 | 5.937171 | 1.107542 | 1.107542 | 0.407372 | 0.407372 | 0.165952 |
| 42 | 36.4 | 5.381450 | 0.551821 | 0.551821 | -0.148350 | 0.148350 | 0.022008 |
| 45 | 37.9 | 5.491812 | 0.662183 | 0.662183 | -0.037987 | 0.037987 | 0.001443 |
| 47 | 38.9 | 5.564171 | 0.734542 | 0.734542 | 0.034372 | 0.034372 | 0.001181 |
| 50 | 40.4 | 5.670979 | 0.841350 | 0.841350 | 0.141179 | 0.141179 | 0.019932 |
| 55 | 42.9 | 5.844656 | 1.015027 | 1.015027 | 0.314856 | 0.314856 | 0.099135 |
| 60 | 45.4 | 6.013319 | 1.183690 | 1.183690 | 0.483519 | 0.483519 | 0.233791 |
| 65 | 47.9 | 6.177378 | 1.347749 | 1.347749 | 0.647579 | 0.647579 | 0.419358 |
| 70 | 50.3 | 5.485435 | 0.655806 | 0.655806 | -0.044364 | 0.044364 | 0.001968 |
| 75 | 52.9 | 6.493073 | 1.663444 | 1.663444 | 0.963274 | 0.963274 | 0.927897 |
| 80 | 55.3 | 5.752391 | 0.922762 | 0.922762 | 0.222592 | 0.222592 | 0.049547 |
| **Average Error [mm]:** | 0.700170 | **Variance [mm$^2$]:** | 0.129062 | **Standard Deviation [mm]:** | **0.359252** | | |

**Table A.23** Test Results of 15° Slits with 5 Mhz Compressional Wave Probes of 45°

| 20 (19.318516) mm Slit 15° | **Distance btw Probes:** 8 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 28.284271 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 26.4 | 19.312172 | -0.006344 | 0.006344 | -0.293813 | 0.293813 | 0.086326 |
| 1 | 26.8 | 19.390462 | 0.071946 | 0.071946 | -0.228212 | 0.228212 | 0.052081 |
| 2 | 27.2 | 19.463813 | 0.145297 | 0.145297 | -0.154861 | 0.154861 | 0.023982 |
| 3 | 27.7 | 19.673332 | 0.354816 | 0.354816 | 0.054659 | 0.054659 | 0.002988 |
| 4 | 28.1 | 19.738541 | 0.420025 | 0.420025 | 0.119868 | 0.119868 | 0.014368 |
| 5 | 28.5 | 19.798990 | 0.480474 | 0.480474 | 0.180317 | 0.180317 | 0.032514 |
| 6 | 28.8 | 19.708881 | 0.390365 | 0.390365 | 0.090208 | 0.090208 | 0.008138 |
| 7 | 29.2 | 19.758289 | 0.439773 | 0.439773 | 0.139616 | 0.139616 | 0.019493 |
| 8 | 29.6 | 19.803030 | 0.484514 | 0.484514 | 0.184357 | 0.184357 | 0.033987 |
| 9 | 30 | 19.843135 | 0.524619 | 0.524619 | 0.224462 | 0.224462 | 0.050383 |
| 10 | 30.3 | 19.725364 | 0.406848 | 0.406848 | 0.106691 | 0.106691 | 0.011383 |
| 11 | 30.7 | 19.754493 | 0.435977 | 0.435977 | 0.135820 | 0.135820 | 0.018447 |
| 12 | 31.1 | 19.779029 | 0.460513 | 0.460513 | 0.160356 | 0.160356 | 0.025714 |
| 13 | 31.5 | 19.798990 | 0.480474 | 0.480474 | 0.180317 | 0.180317 | 0.032514 |
| 14 | 31.8 | 19.652990 | 0.334474 | 0.334474 | 0.034316 | 0.034316 | 0.001178 |
| 15 | 32.2 | 19.661892 | 0.343376 | 0.343376 | 0.043219 | 0.043219 | 0.001868 |
| 16 | 32.6 | 19.666215 | 0.347699 | 0.347699 | 0.047542 | 0.047542 | 0.002260 |
| 17 | 33 | 19.665960 | 0.347444 | 0.347444 | 0.047287 | 0.047287 | 0.002236 |
| 18 | 33.4 | 19.661129 | 0.342613 | 0.342613 | 0.042456 | 0.042456 | 0.001803 |
| 19 | 33.8 | 19.651717 | 0.333201 | 0.333201 | 0.033044 | 0.033044 | 0.001092 |
| 20 | 34.1 | 19.463042 | 0.144526 | 0.144526 | -0.155631 | 0.155631 | 0.024221 |
| 22 | 34.9 | 19.416745 | 0.098229 | 0.098229 | -0.201928 | 0.201928 | 0.040775 |
| 25 | 36.2 | 19.498461 | 0.179945 | 0.179945 | -0.120212 | 0.120212 | 0.014451 |
| 27 | 37 | 19.410049 | 0.091533 | 0.091533 | -0.208624 | 0.208624 | 0.043524 |
| 30 | 38.4 | 19.635682 | 0.317166 | 0.317166 | 0.017009 | 0.017009 | 0.000289 |
| 35 | 40.5 | 19.493589 | 0.175073 | 0.175073 | -0.125084 | 0.125084 | 0.015646 |
| 40 | 42.8 | 19.693654 | 0.375138 | 0.375138 | 0.074981 | 0.074981 | 0.005622 |
| 45 | 45 | 19.615045 | 0.296529 | 0.296529 | -0.003628 | 0.003628 | 0.000013 |
| 50 | 47.2 | 19.463813 | 0.145297 | 0.145297 | -0.154861 | 0.154861 | 0.023982 |
| 55 | 49.5 | 19.493589 | 0.175073 | 0.175073 | -0.125084 | 0.125084 | 0.015646 |
| 60 | 51.8 | 19.474085 | 0.155569 | 0.155569 | -0.144588 | 0.144588 | 0.020906 |
| **Average Error [mm]:** | 0.300157 | **Variance [mm$^2$]:** | 0.020253 | **Standard Deviation [mm]:** | **0.142311** | | |

**Table A.24** Test Results of 15° Slits with 5 Mhz Compressional Wave Probes of 45°

| **15 (14.488887) mm Slit 15°** | **Distance btw Probes:** -2 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 21.213203 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 23.1 | 14.477914 | -0.010973 | 0.010973 | -0.194575 | 0.194575 | 0.037859 |
| 1 | 23.5 | 14.491377 | 0.002490 | 0.002490 | -0.203058 | 0.203058 | 0.041232 |
| 2 | 23.9 | 14.498621 | 0.009734 | 0.009734 | -0.195814 | 0.195814 | 0.038343 |
| 3 | 24.2 | 14.331434 | -0.157453 | 0.157453 | -0.048094 | 0.048094 | 0.002313 |
| 4 | 24.6 | 14.323407 | -0.165480 | 0.165480 | -0.040068 | 0.040068 | 0.001605 |
| 5 | 25 | 14.309088 | -0.179799 | 0.179799 | -0.025748 | 0.025748 | 0.000663 |
| 6 | 25.3 | 14.109926 | -0.378961 | 0.378961 | 0.173414 | 0.173414 | 0.030072 |
| 7 | 25.7 | 14.079773 | -0.409114 | 0.409114 | 0.203567 | 0.203567 | 0.041439 |
| 8 | 26.1 | 14.043148 | -0.445739 | 0.445739 | 0.240192 | 0.240192 | 0.057692 |
| 9 | 26.5 | 14.000000 | -0.488887 | 0.488887 | 0.283340 | 0.283340 | 0.080281 |
| 10 | 26.9 | 13.950269 | -0.538618 | 0.538618 | 0.333071 | 0.333071 | 0.110936 |
| 11 | 27.4 | 14.089358 | -0.399529 | 0.399529 | 0.193982 | 0.193982 | 0.037629 |
| 12 | 27.9 | 14.227087 | -0.261800 | 0.261800 | 0.056253 | 0.056253 | 0.003164 |
| 13 | 28.3 | 14.164745 | -0.324142 | 0.324142 | 0.118595 | 0.118595 | 0.014065 |
| 14 | 28.7 | 14.095744 | -0.393143 | 0.393143 | 0.187596 | 0.187596 | 0.035192 |
| 15 | 29.3 | 14.430523 | -0.058364 | 0.058364 | -0.147184 | 0.147184 | 0.021663 |
| 16 | 29.7 | 14.355835 | -0.133052 | 0.133052 | -0.072495 | 0.072495 | 0.005256 |
| 17 | 30.2 | 14.484129 | -0.004758 | 0.004758 | -0.200790 | 0.200790 | 0.040316 |
| 18 | 30.6 | 14.400000 | -0.088887 | 0.088887 | -0.116660 | 0.116660 | 0.013610 |
| 19 | 31 | 14.309088 | -0.179799 | 0.179799 | -0.025748 | 0.025748 | 0.000663 |
| 20 | 31.4 | 14.211263 | -0.277624 | 0.277624 | 0.072076 | 0.072076 | 0.005195 |
| 22 | 32.4 | 14.448529 | -0.040358 | 0.040358 | -0.165190 | 0.165190 | 0.027288 |
| 25 | 33.8 | 14.566743 | 0.077856 | 0.077856 | -0.127691 | 0.127691 | 0.016305 |
| 27 | 34.7 | 14.554724 | 0.065837 | 0.065837 | -0.139710 | 0.139710 | 0.019519 |
| 30 | 36 | 14.387495 | -0.101392 | 0.101392 | -0.104155 | 0.104155 | 0.010848 |
| 35 | 38.4 | 14.639331 | 0.150444 | 0.150444 | -0.055104 | 0.055104 | 0.003036 |
| 40 | 40.7 | 14.577037 | 0.088150 | 0.088150 | -0.117398 | 0.117398 | 0.013782 |
| 45 | 43 | 14.448183 | -0.040704 | 0.040704 | -0.164844 | 0.164844 | 0.027173 |
| 50 | 45.4 | 14.565713 | 0.076826 | 0.076826 | -0.128721 | 0.128721 | 0.016569 |
| 55 | 47.7 | 14.319218 | -0.169669 | 0.169669 | -0.035878 | 0.035878 | 0.001287 |
| 60 | 50 | 14.000000 | -0.488887 | 0.488887 | 0.283340 | 0.283340 | 0.080281 |
| **Average Error [mm]:** | 0.205547 | **Variance [mm$^2$]:** | 0.026945 | **Standard Deviation [mm]:** | **0.164148** | | |

Table A.25 Test Results of 15º Slits with 5 Mhz Compressional Wave Probes of 45º

| 10 (9.659258) mm Slit 15° | Distance btw Probes: -12 mm | | Probe Delay: 3.60 microseconds | | Sound Travel Distance: 14.142135 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 20.5 | 9.810708 | 0.151450 | 0.151450 | -0.191064 | 0.191064 | 0.036505 |
| 1 | 20.8 | 9.507366 | -0.151892 | 0.151892 | -0.190622 | 0.190622 | 0.036337 |
| 2 | 21.3 | 9.627565 | -0.031693 | 0.031693 | -0.310821 | 0.310821 | 0.096609 |
| 3 | 21.8 | 9.746281 | 0.087023 | 0.087023 | -0.255491 | 0.255491 | 0.065275 |
| 4 | 22.2 | 9.635352 | -0.023906 | 0.023906 | -0.318608 | 0.318608 | 0.101511 |
| 5 | 22.5 | 9.273618 | -0.385640 | 0.385640 | 0.043126 | 0.043126 | 0.001860 |
| 6 | 23 | 9.380832 | -0.278426 | 0.278426 | -0.064087 | 0.064087 | 0.004107 |
| 7 | 23.5 | 9.486833 | -0.172425 | 0.172425 | -0.170089 | 0.170089 | 0.028930 |
| 8 | 24 | 9.591663 | -0.067595 | 0.067595 | -0.274919 | 0.274919 | 0.075580 |
| 9 | 24.4 | 9.439809 | -0.219449 | 0.219449 | -0.123065 | 0.123065 | 0.015145 |
| 10 | 24.9 | 9.539916 | -0.119342 | 0.119342 | -0.223172 | 0.223172 | 0.049806 |
| 11 | 25.3 | 9.372300 | -0.286958 | 0.286958 | -0.055556 | 0.055556 | 0.003086 |
| 12 | 25.8 | 9.467840 | -0.191418 | 0.191418 | -0.151096 | 0.151096 | 0.022830 |
| 13 | 26.2 | 9.283857 | -0.375401 | 0.375401 | 0.032887 | 0.032887 | 0.001082 |
| 14 | 26.6 | 9.086253 | -0.573005 | 0.573005 | 0.230491 | 0.230491 | 0.053126 |
| 15 | 27.1 | 9.173876 | -0.485382 | 0.485382 | 0.142868 | 0.142868 | 0.020411 |
| 16 | 27.5 | 8.958236 | -0.701022 | 0.701022 | 0.358508 | 0.358508 | 0.128528 |
| 17 | 28.1 | 9.346657 | -0.312601 | 0.312601 | -0.029913 | 0.029913 | 0.000895 |
| 18 | 28.6 | 9.431861 | -0.227397 | 0.227397 | -0.115117 | 0.115117 | 0.013252 |
| 19 | 29.1 | 9.516302 | -0.142956 | 0.142956 | -0.199558 | 0.199558 | 0.039823 |
| 20 | 29.5 | 9.287088 | -0.372170 | 0.372170 | 0.029656 | 0.029656 | 0.000879 |
| 22 | 30.5 | 9.447222 | -0.212036 | 0.212036 | -0.130478 | 0.130478 | 0.017024 |
| 25 | 31.9 | 9.346657 | -0.312601 | 0.312601 | -0.029913 | 0.029913 | 0.000895 |
| 27 | 32.8 | 9.142757 | -0.516501 | 0.516501 | 0.173987 | 0.173987 | 0.030272 |
| 30 | 34.2 | 8.979978 | -0.679280 | 0.679280 | 0.336766 | 0.336766 | 0.113412 |
| 35 | 36.7 | 9.308061 | -0.351197 | 0.351197 | 0.008683 | 0.008683 | 0.000075 |
| 40 | 39 | 8.774964 | -0.884294 | 0.884294 | 0.541780 | 0.541780 | 0.293525 |
| 45 | 41.5 | 9.055385 | -0.603873 | 0.603873 | 0.261359 | 0.261359 | 0.068308 |
| 50 | 43.9 | 8.843642 | -0.815616 | 0.815616 | 0.473102 | 0.473102 | 0.223826 |
| 55 | 46.4 | 9.094504 | -0.564754 | 0.564754 | 0.222240 | 0.222240 | 0.049391 |
| 60 | 48.9 | 9.338629 | -0.320629 | 0.320629 | -0.021885 | 0.021885 | 0.000479 |
| **Average Error [mm]:** | 0.342514 | **Variance [mm$^2$]:** | 0.051380 | **Standard Deviation [mm]:** | **0.226672** | | |

**Table A.26** Test Results of 15º Slits with 5 Mhz Compressional Wave Probes of 45º

| **5 (4.829629) mm Slit 15°** | **Distance btw Probes:** -22 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 7.071067 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi- Average Error)$^2$ [mm$^2$]** |
| 0 | 18.5 | 4.272002 | -0.557627 | 0.557627 | -0.552566 | 0.552566 | 0.305329 |
| 1 | 18.9 | 3.867816 | -0.961813 | 0.961813 | -0.148380 | 0.148380 | 0.022017 |
| 2 | 19.3 | 3.389690 | -1.439939 | 1.439939 | 0.329745 | 0.329745 | 0.108732 |
| 3 | 19.8 | 3.433657 | -1.395972 | 1.395972 | 0.285779 | 0.285779 | 0.081669 |
| 4 | 20.3 | 3.477068 | -1.352561 | 1.352561 | 0.242368 | 0.242368 | 0.058742 |
| 5 | 20.9 | 4.069398 | -0.760231 | 0.760231 | -0.349962 | 0.349962 | 0.122474 |
| 6 | 21.4 | 4.118252 | -0.711377 | 0.711377 | -0.398816 | 0.398816 | 0.159055 |
| 7 | 21.9 | 4.166533 | -0.663096 | 0.663096 | -0.447098 | 0.447098 | 0.199896 |
| 8 | 22.4 | 4.214262 | -0.615367 | 0.615367 | -0.494826 | 0.494826 | 0.244853 |
| 9 | 22.8 | 3.686462 | -1.143167 | 1.143167 | 0.032974 | 0.032974 | 0.001087 |
| 10 | 23.3 | 3.726929 | -1.102700 | 1.102700 | -0.007493 | 0.007493 | 0.000056 |
| 11 | 23.8 | 3.766962 | -1.062667 | 1.062667 | -0.047526 | 0.047526 | 0.002259 |
| 12 | 24.2 | 3.104835 | -1.724794 | 1.724794 | 0.614601 | 0.614601 | 0.377734 |
| 13 | 24.7 | 3.136877 | -1.692752 | 1.692752 | 0.582558 | 0.582558 | 0.339374 |
| 14 | 25.2 | 3.168596 | -1.661033 | 1.661033 | 0.550840 | 0.550840 | 0.303424 |
| 15 | 25.6 | 2.260531 | -2.569098 | 2.569098 | 1.458905 | 1.458905 | 2.128403 |
| 16 | 26.2 | 3.231099 | -1.598530 | 1.598530 | 0.488337 | 0.488337 | 0.238473 |
| 17 | 26.7 | 3.261901 | -1.567728 | 1.567728 | 0.457534 | 0.457534 | 0.209338 |
| 18 | 27.2 | 3.292416 | -1.537213 | 1.537213 | 0.427020 | 0.427020 | 0.182346 |
| 19 | 27.7 | 3.322650 | -1.506979 | 1.506979 | 0.396786 | 0.396786 | 0.157439 |
| 20 | 28.2 | 3.352611 | -1.477018 | 1.477018 | 0.366825 | 0.366825 | 0.134560 |
| 22 | 29.3 | 4.182105 | -0.647524 | 0.647524 | -0.462669 | 0.462669 | 0.214063 |
| 25 | 30.8 | 4.288356 | -0.541273 | 0.541273 | -0.568921 | 0.568921 | 0.323671 |
| 27 | 31.8 | 4.357752 | -0.471877 | 0.471877 | -0.638316 | 0.638316 | 0.407447 |
| 30 | 33.3 | 4.459821 | -0.369808 | 0.369808 | -0.740385 | 0.740385 | 0.548170 |
| 35 | 36 | 5.979130 | 1.149501 | 1.149501 | 0.039308 | 0.039308 | 0.001545 |
| 40 | 38.4 | 5.528110 | 0.698481 | 0.698481 | -0.411712 | 0.411712 | 0.169507 |
| 45 | 40.7 | 4.029888 | -0.799741 | 0.799741 | -0.310453 | 0.310453 | 0.096381 |
| 50 | 43.3 | 5.088222 | 0.258593 | 0.258593 | -0.851601 | 0.851601 | 0.725224 |
| 55 | 46 | 6.763875 | 1.934246 | 1.934246 | 0.824052 | 0.824052 | 0.679062 |
| 60 | 48.2 | 4.386342 | -0.443287 | 0.443287 | -0.666907 | 0.666907 | 0.444765 |
| **Average Error [mm]:** | 1.110193 | **Variance [mm$^2$]:** | 0.289906 | **Standard Deviation [mm]:** | **0.538429** | | |

**Table A.27** Test Results of 15° Slits with 5 Mhz Compressional Wave Probes of 67°

| **20 (19.318516) mm Slit 15°** | **Distance btw Probes:** 63.617047 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 51.186093 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 33.2 | 19.319420 | 0.000904 | 0.000904 | -0.127805 | 0.127805 | 0.016334 |
| 21 | 33.6 | 19.305699 | -0.012817 | 0.012817 | -0.115892 | 0.115892 | 0.013431 |
| 22 | 34 | 19.287302 | -0.031214 | 0.031214 | -0.097495 | 0.097495 | 0.009505 |
| 23 | 34.5 | 19.442222 | 0.123706 | 0.123706 | -0.005004 | 0.005004 | 0.000025 |
| 24 | 34.9 | 19.416745 | 0.098229 | 0.098229 | -0.030480 | 0.030480 | 0.000929 |
| 25 | 35.3 | 19.386593 | 0.068077 | 0.068077 | -0.060632 | 0.060632 | 0.003676 |
| 26 | 35.7 | 19.351744 | 0.033228 | 0.033228 | -0.095482 | 0.095482 | 0.009117 |
| 27 | 36.2 | 19.498461 | 0.179945 | 0.179945 | 0.051236 | 0.051236 | 0.002625 |
| 28 | 36.6 | 19.456618 | 0.138102 | 0.138102 | 0.009393 | 0.009393 | 0.000088 |
| 29 | 37 | 19.410049 | 0.091533 | 0.091533 | -0.037177 | 0.037177 | 0.001382 |
| 30 | 37.4 | 19.358719 | 0.040203 | 0.040203 | -0.088507 | 0.088507 | 0.007833 |
| 31 | 37.9 | 19.497692 | 0.179176 | 0.179176 | 0.050466 | 0.050466 | 0.002547 |
| 32 | 38.3 | 19.439393 | 0.120877 | 0.120877 | -0.007833 | 0.007833 | 0.000061 |
| 33 | 38.6 | 19.175766 | -0.142750 | 0.142750 | 0.014040 | 0.014040 | 0.000197 |
| 34 | 39.1 | 19.308288 | -0.010228 | 0.010228 | -0.118482 | 0.118482 | 0.014038 |
| 35 | 39.5 | 19.235384 | -0.083132 | 0.083132 | -0.045578 | 0.045578 | 0.002077 |
| 36 | 39.9 | 19.157505 | -0.161011 | 0.161011 | 0.032301 | 0.032301 | 0.001043 |
| 37 | 40.4 | 19.284968 | -0.033548 | 0.033548 | -0.095162 | 0.095162 | 0.009056 |
| 38 | 40.9 | 19.411594 | 0.093078 | 0.093078 | -0.035631 | 0.035631 | 0.001270 |
| 39 | 41.3 | 19.324596 | 0.006080 | 0.006080 | -0.122630 | 0.122630 | 0.015038 |
| 40 | 41.7 | 19.232525 | -0.085991 | 0.085991 | -0.042718 | 0.042718 | 0.001825 |
| 42 | 42.7 | 19.475369 | 0.156853 | 0.156853 | 0.028143 | 0.028143 | 0.000792 |
| 45 | 44.1 | 19.610201 | 0.291685 | 0.291685 | 0.162976 | 0.162976 | 0.026561 |
| 47 | 44.9 | 19.384530 | 0.066014 | 0.066014 | -0.062696 | 0.062696 | 0.003931 |
| 50 | 46.3 | 19.485636 | 0.167120 | 0.167120 | 0.038410 | 0.038410 | 0.001475 |
| 55 | 48.6 | 19.537400 | 0.218884 | 0.218884 | 0.090174 | 0.090174 | 0.008131 |
| 60 | 50.9 | 19.539959 | 0.221443 | 0.221443 | 0.092733 | 0.092733 | 0.008599 |
| 65 | 53.2 | 19.493332 | 0.174816 | 0.174816 | 0.046106 | 0.046106 | 0.002126 |
| 70 | 55.5 | 19.397165 | 0.078649 | 0.078649 | -0.050061 | 0.050061 | 0.002506 |
| 75 | 58 | 19.843135 | 0.524619 | 0.524619 | 0.395909 | 0.395909 | 0.156744 |
| 80 | 60.3 | 19.674603 | 0.356087 | 0.356087 | 0.227377 | 0.227377 | 0.051700 |
| **Average Error [mm]:** | 0.128710 | **Variance [mm$^2$]:** | 0.012086 | **Standard Deviation [mm]:** | **0.109936** | | |

**Table A.28** Test Results of 15° Slits with 5 Mhz Compressional Wave Probes of 67°

| **15 (14.488887) mm Slit 15°** | **Distance btw Probes:** 40.67557 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 38.389569 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 30.9 | 15.026976 | 0.538089 | 0.538089 | -0.125472 | 0.125472 | 0.015743 |
| 21 | 31.3 | 14.947910 | 0.459023 | 0.459023 | -0.204538 | 0.204538 | 0.041836 |
| 22 | 31.7 | 14.862369 | 0.373482 | 0.373482 | -0.290079 | 0.290079 | 0.084146 |
| 23 | 32.3 | 15.200000 | 0.711113 | 0.711113 | 0.047552 | 0.047552 | 0.002261 |
| 24 | 32.7 | 15.109269 | 0.620382 | 0.620382 | -0.043179 | 0.043179 | 0.001864 |
| 25 | 33.2 | 15.231218 | 0.742331 | 0.742331 | 0.078770 | 0.078770 | 0.006205 |
| 26 | 33.6 | 15.131424 | 0.642537 | 0.642537 | -0.021023 | 0.021023 | 0.000442 |
| 27 | 34 | 15.024979 | 0.536092 | 0.536092 | -0.127469 | 0.127469 | 0.016248 |
| 28 | 34.5 | 15.141004 | 0.652117 | 0.652117 | -0.011444 | 0.011444 | 0.000131 |
| 29 | 35 | 15.256146 | 0.767259 | 0.767259 | 0.103699 | 0.103699 | 0.010753 |
| 30 | 35.4 | 15.138032 | 0.649145 | 0.649145 | -0.014416 | 0.014416 | 0.000208 |
| 31 | 35.8 | 15.012994 | 0.524107 | 0.524107 | -0.139453 | 0.139453 | 0.019447 |
| 32 | 36.3 | 15.122500 | 0.633613 | 0.633613 | -0.029948 | 0.029948 | 0.000897 |
| 33 | 36.7 | 14.987995 | 0.499108 | 0.499108 | -0.164453 | 0.164453 | 0.027045 |
| 34 | 37.2 | 15.094370 | 0.605483 | 0.605483 | -0.058078 | 0.058078 | 0.003373 |
| 35 | 37.7 | 15.200000 | 0.711113 | 0.711113 | 0.047552 | 0.047552 | 0.002261 |
| 36 | 38.2 | 15.304901 | 0.816014 | 0.816014 | 0.152453 | 0.152453 | 0.023242 |
| 37 | 38.6 | 15.156187 | 0.667300 | 0.667300 | 0.003739 | 0.003739 | 0.000014 |
| 38 | 39 | 15.000000 | 0.511113 | 0.511113 | -0.152448 | 0.152448 | 0.023240 |
| 39 | 39.5 | 15.099669 | 0.610782 | 0.610782 | -0.052779 | 0.052779 | 0.002786 |
| 40 | 40 | 15.198684 | 0.709797 | 0.709797 | 0.046236 | 0.046236 | 0.002138 |
| 42 | 40.9 | 15.126467 | 0.637580 | 0.637580 | -0.025981 | 0.025981 | 0.000675 |
| 45 | 42.4 | 15.411359 | 0.922472 | 0.922472 | 0.258912 | 0.258912 | 0.067035 |
| 47 | 43.3 | 15.317963 | 0.829076 | 0.829076 | 0.165516 | 0.165516 | 0.027395 |
| 50 | 44.7 | 15.300000 | 0.811113 | 0.811113 | 0.147552 | 0.147552 | 0.021772 |
| 55 | 47.1 | 15.432433 | 0.943546 | 0.943546 | 0.279986 | 0.279986 | 0.078392 |
| 60 | 49.4 | 15.210523 | 0.721636 | 0.721636 | 0.058075 | 0.058075 | 0.003373 |
| 65 | 51.8 | 15.264010 | 0.775123 | 0.775123 | 0.111562 | 0.111562 | 0.012446 |
| 70 | 54.2 | 15.285287 | 0.796400 | 0.796400 | 0.132839 | 0.132839 | 0.017646 |
| 75 | 56.5 | 14.899664 | 0.410777 | 0.410777 | -0.252783 | 0.252783 | 0.063899 |
| 80 | 59 | 15.231546 | 0.742659 | 0.742659 | 0.079098 | 0.079098 | 0.006257 |
| **Average Error [mm]:** | 0.663561 | **Variance [mm$^2$]:** | 0.018812 | **Standard Deviation [mm]:** | **0.137157** | | |

**Table A.29** Test Results of 15° Slits with 5 Mhz Compressional Wave Probes of 67°

| **10 (9.659258) mm Slit 15°** | **Distance btw Probes:** 17.117046 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 25.593046 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 28.8 | 10.021976 | 0.362718 | 0.362718 | 0.031722 | 0.031722 | 0.001006 |
| 21 | 29.2 | 9.817841 | 0.158583 | 0.158583 | -0.172413 | 0.172413 | 0.029726 |
| 22 | 29.7 | 9.904040 | 0.244782 | 0.244782 | -0.086214 | 0.086214 | 0.007433 |
| 23 | 30.2 | 9.989494 | 0.330236 | 0.330236 | -0.000760 | 0.000760 | 0.000001 |
| 24 | 30.6 | 9.765244 | 0.105986 | 0.105986 | -0.225010 | 0.225010 | 0.050629 |
| 25 | 31.1 | 9.846827 | 0.187569 | 0.187569 | -0.143427 | 0.143427 | 0.020571 |
| 26 | 31.5 | 9.604686 | -0.054572 | 0.054572 | -0.276424 | 0.276424 | 0.076410 |
| 27 | 32 | 9.682458 | 0.023200 | 0.023200 | -0.307796 | 0.307796 | 0.094738 |
| 28 | 32.5 | 9.759611 | 0.100353 | 0.100353 | -0.230643 | 0.230643 | 0.053196 |
| 29 | 33.1 | 10.166612 | 0.507354 | 0.507354 | 0.176358 | 0.176358 | 0.031102 |
| 30 | 33.5 | 9.912114 | 0.252856 | 0.252856 | -0.078140 | 0.078140 | 0.006106 |
| 31 | 34 | 9.987492 | 0.328234 | 0.328234 | -0.002762 | 0.002762 | 0.000008 |
| 32 | 34.5 | 10.062306 | 0.403048 | 0.403048 | 0.072052 | 0.072052 | 0.005191 |
| 33 | 35 | 10.136567 | 0.477309 | 0.477309 | 0.146313 | 0.146313 | 0.021408 |
| 34 | 35.4 | 9.856977 | 0.197719 | 0.197719 | -0.133277 | 0.133277 | 0.017763 |
| 35 | 35.9 | 9.927739 | 0.268481 | 0.268481 | -0.062515 | 0.062515 | 0.003908 |
| 36 | 36.3 | 9.627565 | -0.031693 | 0.031693 | -0.299303 | 0.299303 | 0.089582 |
| 37 | 36.8 | 9.694844 | 0.035586 | 0.035586 | -0.295410 | 0.295410 | 0.087267 |
| 38 | 37.3 | 9.761660 | 0.102402 | 0.102402 | -0.228594 | 0.228594 | 0.052255 |
| 39 | 37.8 | 9.828021 | 0.168763 | 0.168763 | -0.162233 | 0.162233 | 0.026320 |
| 40 | 38.3 | 9.893938 | 0.234680 | 0.234680 | -0.096317 | 0.096317 | 0.009277 |
| 42 | 39.3 | 10.024470 | 0.365212 | 0.365212 | 0.034216 | 0.034216 | 0.001171 |
| 45 | 40.8 | 10.217142 | 0.557884 | 0.557884 | 0.226888 | 0.226888 | 0.051478 |
| 47 | 41.8 | 10.343597 | 0.684339 | 0.684339 | 0.353343 | 0.353343 | 0.124851 |
| 50 | 43.2 | 10.111380 | 0.452122 | 0.452122 | 0.121126 | 0.121126 | 0.014671 |
| 55 | 45.6 | 9.955401 | 0.296143 | 0.296143 | -0.034854 | 0.034854 | 0.001215 |
| 60 | 48.1 | 10.227903 | 0.568645 | 0.568645 | 0.237649 | 0.237649 | 0.056477 |
| 65 | 50.6 | 10.493331 | 0.834073 | 0.834073 | 0.503077 | 0.503077 | 0.253087 |
| 70 | 53 | 10.246951 | 0.587693 | 0.587693 | 0.256697 | 0.256697 | 0.065893 |
| 75 | 55.5 | 10.488088 | 0.828830 | 0.828830 | 0.497834 | 0.497834 | 0.247839 |
| 80 | 57.9 | 10.169071 | 0.509813 | 0.509813 | 0.178817 | 0.178817 | 0.031975 |
| **Average Error [mm]:** | 0.330996 | **Variance [mm$^2$]:** | 0.049437 | **Standard Deviation [mm]:** | **0.222345** | | |

**Table A.30** Test Results of 15º Slits with 5 Mhz Compressional Wave Probes of 67º

| **5 (4.829629) mm Slit 15°** | **Distance btw Probes:** -6.441478 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 12.796523 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 27.7 | 6.187891 | 1.358262 | 1.358262 | -0.159605 | 0.159605 | 0.025474 |
| 21 | 28.2 | 6.244197 | 1.414568 | 1.414568 | -0.103299 | 0.103299 | 0.010671 |
| 22 | 28.6 | 5.827521 | 0.997892 | 0.997892 | -0.519976 | 0.519976 | 0.270375 |
| 23 | 29.1 | 5.878775 | 1.049146 | 1.049146 | -0.468721 | 0.468721 | 0.219700 |
| 24 | 29.6 | 5.929587 | 1.099958 | 1.099958 | -0.417910 | 0.417910 | 0.174649 |
| 25 | 30.1 | 5.979967 | 1.150338 | 1.150338 | -0.367530 | 0.367530 | 0.135078 |
| 26 | 30.6 | 6.029925 | 1.200296 | 1.200296 | -0.317571 | 0.317571 | 0.100851 |
| 27 | 31.1 | 6.079474 | 1.249845 | 1.249845 | -0.268023 | 0.268023 | 0.071836 |
| 28 | 31.6 | 6.128621 | 1.298992 | 1.298992 | -0.218875 | 0.218875 | 0.047906 |
| 29 | 32.1 | 6.177378 | 1.347749 | 1.347749 | -0.170119 | 0.170119 | 0.028940 |
| 30 | 32.6 | 6.225753 | 1.396124 | 1.396124 | -0.121744 | 0.121744 | 0.014822 |
| 31 | 33.2 | 6.781593 | 1.951964 | 1.951964 | 0.434096 | 0.434096 | 0.188439 |
| 32 | 33.6 | 6.321392 | 1.491763 | 1.491763 | -0.026104 | 0.026104 | 0.000681 |
| 33 | 34.2 | 6.884040 | 2.054411 | 2.054411 | 0.536543 | 0.536543 | 0.287878 |
| 34 | 34.7 | 6.934695 | 2.105066 | 2.105066 | 0.587199 | 0.587199 | 0.344802 |
| 35 | 35.1 | 6.462198 | 1.632569 | 1.632569 | 0.114701 | 0.114701 | 0.013156 |
| 36 | 35.5 | 5.937171 | 1.107542 | 1.107542 | -0.410326 | 0.410326 | 0.168367 |
| 37 | 36.1 | 6.554388 | 1.724759 | 1.724759 | 0.206891 | 0.206891 | 0.042804 |
| 38 | 36.6 | 6.600000 | 1.770371 | 1.770371 | 0.252503 | 0.252503 | 0.063758 |
| 39 | 37.1 | 6.645299 | 1.815670 | 1.815670 | 0.297803 | 0.297803 | 0.088686 |
| 40 | 37.6 | 6.690291 | 1.860662 | 1.860662 | 0.342795 | 0.342795 | 0.117508 |
| 42 | 38.6 | 6.779381 | 1.949752 | 1.949752 | 0.431884 | 0.431884 | 0.186524 |
| 45 | 40 | 6.304760 | 1.475131 | 1.475131 | -0.042736 | 0.042736 | 0.001826 |
| 47 | 40.9 | 5.706137 | 0.876508 | 0.876508 | -0.641360 | 0.641360 | 0.411342 |
| 50 | 42.5 | 6.500000 | 1.670371 | 1.670371 | 0.152503 | 0.152503 | 0.023257 |
| 55 | 45 | 6.689544 | 1.859915 | 1.859915 | 0.342047 | 0.342047 | 0.116996 |
| 60 | 47.4 | 6.144917 | 1.315288 | 1.315288 | -0.202580 | 0.202580 | 0.041039 |
| 65 | 49.9 | 6.305553 | 1.475924 | 1.475924 | -0.041943 | 0.041943 | 0.001759 |
| 70 | 52.4 | 6.462198 | 1.632569 | 1.632569 | 0.114701 | 0.114701 | 0.013156 |
| 75 | 54.9 | 6.615134 | 1.785505 | 1.785505 | 0.267638 | 0.267638 | 0.071630 |
| 80 | 57.4 | 6.764614 | 1.934985 | 1.934985 | 0.417117 | 0.417117 | 0.173987 |
| **Average Error [mm]:** | 1.517868 | **Variance [mm$^2$]:** | 0.111545 | **Standard Deviation [mm]:** | **0.333984** | | |

**Table A.31** Test Results of 30º Slits with 4 Mhz Compressional Wave Probes of 45º

| **20 (17.320508) mm Slit 30°** | **Distance btw Probes:** 8 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 28.284271 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 24.3 | 18.289068 | 0.968560 | 0.968560 | -0.159059 | 0.159059 | 0.025300 |
| 1 | 24.7 | 18.380424 | 1.059916 | 1.059916 | -0.067703 | 0.067703 | 0.004584 |
| 2 | 25.1 | 18.466456 | 1.145948 | 1.145948 | 0.018329 | 0.018329 | 0.000336 |
| 3 | 25.5 | 18.547237 | 1.226729 | 1.226729 | 0.099110 | 0.099110 | 0.009823 |
| 4 | 25.8 | 18.483506 | 1.162998 | 1.162998 | 0.035379 | 0.035379 | 0.001252 |
| 5 | 26.2 | 18.552358 | 1.231850 | 1.231850 | 0.104231 | 0.104231 | 0.010864 |
| 6 | 26.6 | 18.616122 | 1.295614 | 1.295614 | 0.167995 | 0.167995 | 0.028222 |
| 7 | 27 | 18.674849 | 1.354341 | 1.354341 | 0.226722 | 0.226722 | 0.051403 |
| 8 | 27.4 | 18.728588 | 1.408080 | 1.408080 | 0.280461 | 0.280461 | 0.078658 |
| 9 | 27.7 | 18.629010 | 1.308502 | 1.308502 | 0.180883 | 0.180883 | 0.032718 |
| 10 | 28.1 | 18.671101 | 1.350593 | 1.350593 | 0.222974 | 0.222974 | 0.049717 |
| 11 | 28.5 | 18.708287 | 1.387779 | 1.387779 | 0.260160 | 0.260160 | 0.067683 |
| 12 | 28.9 | 18.740598 | 1.420090 | 1.420090 | 0.292471 | 0.292471 | 0.085539 |
| 13 | 29.3 | 18.768058 | 1.447550 | 1.447550 | 0.319931 | 0.319931 | 0.102356 |
| 14 | 29.6 | 18.632230 | 1.311722 | 1.311722 | 0.184103 | 0.184103 | 0.033894 |
| 15 | 30 | 18.648056 | 1.327548 | 1.327548 | 0.199929 | 0.199929 | 0.039972 |
| 16 | 30.3 | 18.495675 | 1.175167 | 1.175167 | 0.047548 | 0.047548 | 0.002261 |
| 17 | 30.8 | 18.665208 | 1.344700 | 1.344700 | 0.217081 | 0.217081 | 0.047124 |
| 18 | 31.2 | 18.666548 | 1.346040 | 1.346040 | 0.218421 | 0.218421 | 0.047708 |
| 19 | 31.5 | 18.493242 | 1.172734 | 1.172734 | 0.045115 | 0.045115 | 0.002035 |
| 20 | 31.8 | 18.309560 | 0.989052 | 0.989052 | -0.138567 | 0.138567 | 0.019201 |
| 22 | 32.6 | 18.269100 | 0.948592 | 0.948592 | -0.179027 | 0.179027 | 0.032051 |
| 25 | 33.3 | 17.223240 | -0.097268 | 0.097268 | -1.030351 | 1.030351 | 1.061624 |
| 27 | 34.1 | 17.104385 | -0.216123 | 0.216123 | -0.911496 | 0.911496 | 0.830826 |
| 30 | 35.4 | 17.092688 | -0.227820 | 0.227820 | -0.899800 | 0.899800 | 0.809639 |
| 35 | 37.4 | 16.628590 | -0.691918 | 0.691918 | -0.435701 | 0.435701 | 0.189835 |
| 40 | 39.6 | 16.497273 | -0.823235 | 0.823235 | -0.304384 | 0.304384 | 0.092649 |
| 45 | 41.8 | 16.278513 | -1.041995 | 1.041995 | -0.085625 | 0.085625 | 0.007332 |
| 50 | 44.1 | 16.242229 | -1.078279 | 1.078279 | -0.049340 | 0.049340 | 0.002434 |
| 55 | 46.2 | 15.562455 | -1.758053 | 1.758053 | 0.630434 | 0.630434 | 0.397447 |
| 60 | 48.6 | 15.683112 | -1.637396 | 1.637396 | 0.509777 | 0.509777 | 0.259873 |
| **Average Error [mm]:** | 1.127619 | **Variance [mm$^2$]:** | 0.142721 | **Standard Deviation [mm]:** | **0.377785** | | |

**Table A.32** Test Results of 30º Slits with 4 Mhz Compressional Wave Probes of 45º

| **15 (12.990381) mm Slit 30°** | **Distance btw Probes:** -2 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 21.213203 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)² [mm²]** |
| 0 | 21.4 | 14.211263 | 1.220882 | 1.220882 | 0.182083 | 0.182083 | 0.033154 |
| 1 | 21.8 | 14.247456 | 1.257075 | 1.257075 | 0.218276 | 0.218276 | 0.047644 |
| 2 | 22.2 | 14.277255 | 1.286874 | 1.286874 | 0.248075 | 0.248075 | 0.061541 |
| 3 | 22.6 | 14.300699 | 1.310318 | 1.310318 | 0.271519 | 0.271519 | 0.073723 |
| 4 | 23 | 14.317821 | 1.327440 | 1.327440 | 0.288641 | 0.288641 | 0.083314 |
| 5 | 23.4 | 14.328643 | 1.338262 | 1.338262 | 0.299463 | 0.299463 | 0.089678 |
| 6 | 23.8 | 14.333178 | 1.342797 | 1.342797 | 0.303998 | 0.303998 | 0.092415 |
| 7 | 24.1 | 14.161921 | 1.171540 | 1.171540 | 0.132741 | 0.132741 | 0.017620 |
| 8 | 24.5 | 14.150972 | 1.160591 | 1.160591 | 0.121792 | 0.121792 | 0.014833 |
| 9 | 24.8 | 13.956719 | 0.966338 | 0.966338 | -0.072461 | 0.072461 | 0.005251 |
| 10 | 25.2 | 13.929824 | 0.939443 | 0.939443 | -0.099356 | 0.099356 | 0.009872 |
| 11 | 25.6 | 13.896402 | 0.906021 | 0.906021 | -0.132778 | 0.132778 | 0.017630 |
| 12 | 26 | 13.856406 | 0.866025 | 0.866025 | -0.172774 | 0.172774 | 0.029851 |
| 13 | 25.8 | 12.624975 | -0.365406 | 0.365406 | -0.673393 | 0.673393 | 0.453459 |
| 14 | 26.3 | 12.754999 | -0.235382 | 0.235382 | -0.803417 | 0.803417 | 0.645479 |
| 15 | 26.7 | 12.674384 | -0.315997 | 0.315997 | -0.722802 | 0.722802 | 0.522442 |
| 16 | 27 | 12.369317 | -0.621064 | 0.621064 | -0.417735 | 0.417735 | 0.174502 |
| 17 | 27.5 | 12.489996 | -0.500385 | 0.500385 | -0.538414 | 0.538414 | 0.289890 |
| 18 | 27.9 | 12.385879 | -0.604502 | 0.604502 | -0.434297 | 0.434297 | 0.188614 |
| 19 | 28.4 | 12.502400 | -0.487981 | 0.487981 | -0.550818 | 0.550818 | 0.303400 |
| 20 | 28.8 | 12.387090 | -0.603291 | 0.603291 | -0.435508 | 0.435508 | 0.189667 |
| 22 | 29.7 | 12.372954 | -0.617427 | 0.617427 | -0.421372 | 0.421372 | 0.177555 |
| 25 | 31 | 12.196311 | -0.794070 | 0.794070 | -0.244729 | 0.244729 | 0.059892 |
| 27 | 31.8 | 11.873921 | -1.116460 | 1.116460 | 0.077661 | 0.077661 | 0.006031 |
| 30 | 33.1 | 11.602155 | -1.388226 | 1.388226 | 0.349427 | 0.349427 | 0.122099 |
| 35 | 35.4 | 11.441591 | -1.548790 | 1.548790 | 0.509991 | 0.509991 | 0.260091 |
| 40 | 37.8 | 11.525624 | -1.464757 | 1.464757 | 0.425958 | 0.425958 | 0.181440 |
| 45 | 40.1 | 11.214277 | -1.776104 | 1.776104 | 0.737305 | 0.737305 | 0.543619 |
| 50 | 42.3 | 10.406248 | -2.584133 | 2.584133 | 1.545334 | 1.545334 | 2.388057 |
| 55 | 45.7 | 14.008569 | 1.018188 | 1.018188 | -0.020611 | 0.020611 | 0.000425 |
| 60 | 48.1 | 14.057382 | 1.067001 | 1.067001 | 0.028202 | 0.028202 | 0.000795 |
| **Average Error [mm]:** | 1.038799 | **Variance [mm²]:** | 0.228516 | **Standard Deviation [mm]:** | **0.478033** | | |

**Table A.33** Test Results of 30º Slits with 4 Mhz Compressional Wave Probes of 45º

| **10 (8.660254) mm Slit 30°** | **Distance btw Probes:** -12 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 14.142135 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 17.8 | 7.800000 | -0.860254 | 0.860254 | -0.682601 | 0.682601 | 0.465944 |
| 1 | 18.3 | 7.914544 | -0.745710 | 0.745710 | -0.797144 | 0.797144 | 0.635439 |
| 2 | 18.6 | 7.547185 | -1.113069 | 1.113069 | -0.429786 | 0.429786 | 0.184716 |
| 3 | 19.1 | 7.652451 | -1.007803 | 1.007803 | -0.535051 | 0.535051 | 0.286280 |
| 4 | 19.6 | 7.756288 | -0.903966 | 0.903966 | -0.638889 | 0.638889 | 0.408179 |
| 5 | 20 | 7.599342 | -1.060912 | 1.060912 | -0.481943 | 0.481943 | 0.232269 |
| 6 | 20.4 | 7.426978 | -1.233276 | 1.233276 | -0.309579 | 0.309579 | 0.095839 |
| 7 | 20.9 | 7.520638 | -1.139616 | 1.139616 | -0.403239 | 0.403239 | 0.162602 |
| 8 | 21.3 | 7.327346 | -1.332908 | 1.332908 | -0.209947 | 0.209947 | 0.044078 |
| 9 | 21.8 | 7.415524 | -1.244730 | 1.244730 | -0.298125 | 0.298125 | 0.088879 |
| 10 | 22.2 | 7.200000 | -1.460254 | 1.460254 | -0.082601 | 0.082601 | 0.006823 |
| 11 | 22.7 | 7.282857 | -1.377397 | 1.377397 | -0.165457 | 0.165457 | 0.027376 |
| 12 | 23.1 | 7.043437 | -1.616817 | 1.616817 | 0.073962 | 0.073962 | 0.005470 |
| 13 | 23.6 | 7.121095 | -1.539159 | 1.539159 | -0.003696 | 0.003696 | 0.000014 |
| 14 | 24 | 6.855655 | -1.804599 | 1.804599 | 0.261745 | 0.261745 | 0.068510 |
| 15 | 24.5 | 6.928203 | -1.732051 | 1.732051 | 0.189196 | 0.189196 | 0.035795 |
| 16 | 24.9 | 6.634003 | -2.026251 | 2.026251 | 0.483396 | 0.483396 | 0.233672 |
| 17 | 25.4 | 6.701492 | -1.958762 | 1.958762 | 0.415907 | 0.415907 | 0.172978 |
| 18 | 25.8 | 6.374951 | -2.285303 | 2.285303 | 0.742448 | 0.742448 | 0.551229 |
| 19 | 26.3 | 6.437391 | -2.222863 | 2.222863 | 0.680008 | 0.680008 | 0.462411 |
| 20 | 26.7 | 6.073714 | -2.586540 | 2.586540 | 1.043685 | 1.043685 | 1.089279 |
| 22 | 27.7 | 6.187891 | -2.472363 | 2.472363 | 0.929508 | 0.929508 | 0.863985 |
| 25 | 29.2 | 6.355313 | -2.304941 | 2.304941 | 0.762086 | 0.762086 | 0.580776 |
| 27 | 30.2 | 6.464519 | -2.195735 | 2.195735 | 0.652881 | 0.652881 | 0.426253 |
| 30 | 31.8 | 7.088018 | -1.572236 | 1.572236 | 0.029381 | 0.029381 | 0.000863 |
| 35 | 34.2 | 6.884040 | -1.776214 | 1.776214 | 0.233360 | 0.233360 | 0.054457 |
| 40 | 36.7 | 7.133723 | -1.526531 | 1.526531 | -0.016324 | 0.016324 | 0.000266 |
| 45 | 39.2 | 7.374958 | -1.285296 | 1.285296 | -0.257558 | 0.257558 | 0.066336 |
| 50 | 42.2 | 9.991997 | 1.331743 | 1.331743 | -0.211112 | 0.211112 | 0.044568 |
| 55 | 44.7 | 10.287857 | 1.627603 | 1.627603 | 0.084748 | 0.084748 | 0.007182 |
| 60 | 46.9 | 9.143850 | 0.483596 | 0.483596 | -1.059258 | 1.059258 | 1.122028 |
| **Average Error [mm]:** | 1.542855 | **Variance [mm$^2$]:** | 0.271758 | **Standard Deviation [mm]:** | **0.521304** | | |

**Table A.34** Test Results of 30° Slits with 4 Mhz Compressional Wave Probes of 45°

| **5 (4.330127) mm Slit 30°** | **Distance btw Probes:** -6.441478 mm | | **Probe Delay:** 4.30 microseconds | | **Sound Travel Time Distance:** 12.796523 mm | |
|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error (xi) [mm]:** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 16.8 | 5.122499 | 0.792372 | -0.591833 | 0.591833 | 0.350266 |
| 1 | 17.2 | 4.856954 | 0.526827 | -0.857379 | 0.857379 | 0.735098 |
| 2 | 17.6 | 4.556314 | 0.226187 | -1.158018 | 1.158018 | 1.341006 |
| 3 | 18.2 | 4.999000 | 0.668873 | -0.715333 | 0.715333 | 0.511701 |
| 4 | 18.7 | 5.068530 | 0.738403 | -0.645802 | 0.645802 | 0.417060 |
| 5 | 19.3 | 5.499091 | 1.168964 | -0.215242 | 0.215242 | 0.046329 |
| 6 | 19.8 | 5.571355 | 1.241228 | -0.142977 | 0.142977 | 0.020442 |
| 7 | 20.2 | 5.271622 | 0.941495 | -0.442710 | 0.442710 | 0.195992 |
| 8 | 20.7 | 5.337602 | 1.007475 | -0.376730 | 0.376730 | 0.141926 |
| 9 | 21.3 | 5.782733 | 1.452606 | 0.068400 | 0.068400 | 0.004679 |
| 10 | 21.7 | 5.467175 | 1.137048 | -0.247158 | 0.247158 | 0.061087 |
| 11 | 22.3 | 5.919459 | 1.589332 | 0.205127 | 0.205127 | 0.042077 |
| 12 | 22.8 | 5.986652 | 1.656525 | 0.272319 | 0.272319 | 0.074158 |
| 13 | 23.3 | 6.053098 | 1.722971 | 0.338766 | 0.338766 | 0.114762 |
| 14 | 23.8 | 6.118823 | 1.788696 | 0.404491 | 0.404491 | 0.163613 |
| 15 | 24.1 | 5.344156 | 1.014029 | -0.370177 | 0.370177 | 0.137031 |
| 16 | 24.6 | 5.400000 | 1.069873 | -0.314333 | 0.314333 | 0.098805 |
| 17 | 25.1 | 5.455273 | 1.125146 | -0.259060 | 0.259060 | 0.067112 |
| 18 | 25.6 | 5.509991 | 1.179864 | -0.204342 | 0.204342 | 0.041755 |
| 19 | 26.1 | 5.564171 | 1.234044 | -0.150161 | 0.150161 | 0.022548 |
| 20 | 26.6 | 5.617829 | 1.287702 | -0.096504 | 0.096504 | 0.009313 |
| 22 | 27.6 | 5.723635 | 1.393508 | 0.009303 | 0.009303 | 0.000087 |
| 25 | 29.1 | 5.878775 | 1.548648 | 0.164443 | 0.164443 | 0.027041 |
| 27 | 30.2 | 6.464519 | 2.134392 | 0.750186 | 0.750186 | 0.562779 |
| 30 | 31.5 | 5.590170 | 1.260043 | -0.124163 | 0.124163 | 0.015416 |
| 35 | 34 | 5.809475 | 1.479348 | 0.095142 | 0.095142 | 0.009052 |
| 40 | 36.6 | 6.600000 | 2.269873 | 0.885667 | 0.885667 | 0.784407 |
| 45 | 39.1 | 6.823489 | 2.493362 | 1.109156 | 1.109156 | 1.230228 |
| 50 | 41.5 | 6.422616 | 2.092489 | 0.708284 | 0.708284 | 0.501666 |
| 55 | 44.1 | 7.249828 | 2.919701 | 1.535495 | 1.535495 | 2.357745 |
| 60 | 46.4 | 6.079474 | 1.749347 | 0.365141 | 0.365141 | 0.133328 |
| **Average Error [mm]:** | 1.384206 | **Variance [mm$^2$]:** | 0.329629 | **Standard Deviation [mm]:** | **0.574134** | |

**Table A.35** Test Results of 30° Slits with 4 Mhz Compressional Wave Probes of 67°

| **20 (17.320508) mm Slit 30°** | **Distance btw Probes:** 63.617047 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 51.186093 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 30.2 | 16.942255 | -0.378253 | 0.378253 | 0.052160 | 0.052160 | 0.002721 |
| 21 | 30.6 | 16.914786 | -0.405722 | 0.405722 | 0.079628 | 0.079628 | 0.006341 |
| 22 | 31 | 16.881943 | -0.438565 | 0.438565 | 0.112472 | 0.112472 | 0.012650 |
| 23 | 31.4 | 16.843693 | -0.476815 | 0.476815 | 0.150722 | 0.150722 | 0.022717 |
| 24 | 32.2 | 17.545370 | 0.224862 | 0.224862 | -0.101232 | 0.101232 | 0.010248 |
| 25 | 32.6 | 17.507427 | 0.186919 | 0.186919 | -0.139174 | 0.139174 | 0.019369 |
| 26 | 33.2 | 17.839282 | 0.518774 | 0.518774 | 0.192681 | 0.192681 | 0.037126 |
| 27 | 33.6 | 17.796348 | 0.475840 | 0.475840 | 0.149747 | 0.149747 | 0.022424 |
| 28 | 34 | 17.748239 | 0.427731 | 0.427731 | 0.101638 | 0.101638 | 0.010330 |
| 29 | 34.5 | 17.888544 | 0.568036 | 0.568036 | 0.241943 | 0.241943 | 0.058536 |
| 30 | 34.9 | 17.832835 | 0.512327 | 0.512327 | 0.186234 | 0.186234 | 0.034683 |
| 31 | 35.2 | 17.572422 | 0.251914 | 0.251914 | -0.074180 | 0.074180 | 0.005503 |
| 32 | 35.7 | 17.705649 | 0.385141 | 0.385141 | 0.059048 | 0.059048 | 0.003487 |
| 33 | 36.1 | 17.634058 | 0.313550 | 0.313550 | -0.012543 | 0.012543 | 0.000157 |
| 34 | 36.5 | 17.557050 | 0.236542 | 0.236542 | -0.089551 | 0.089551 | 0.008019 |
| 35 | 37 | 17.684739 | 0.364231 | 0.364231 | 0.038138 | 0.038138 | 0.001454 |
| 36 | 37.5 | 17.811513 | 0.491005 | 0.491005 | 0.164912 | 0.164912 | 0.027196 |
| 37 | 37.9 | 17.724559 | 0.404051 | 0.404051 | 0.077958 | 0.077958 | 0.006077 |
| 38 | 38.3 | 17.632073 | 0.311565 | 0.311565 | -0.014528 | 0.014528 | 0.000211 |
| 39 | 38.7 | 17.533967 | 0.213459 | 0.213459 | -0.112634 | 0.112634 | 0.012686 |
| 40 | 39.2 | 17.653328 | 0.332820 | 0.332820 | 0.006727 | 0.006727 | 0.000045 |
| 42 | 40.1 | 17.663805 | 0.343297 | 0.343297 | 0.017204 | 0.017204 | 0.000296 |
| 45 | 41.5 | 17.776389 | 0.455881 | 0.455881 | 0.129788 | 0.129788 | 0.016845 |
| 47 | 42.3 | 17.522557 | 0.202049 | 0.202049 | -0.124044 | 0.124044 | 0.015387 |
| 50 | 43.6 | 17.348199 | 0.027691 | 0.027691 | -0.298403 | 0.298403 | 0.089044 |
| 55 | 46 | 17.599716 | 0.279208 | 0.279208 | -0.046885 | 0.046885 | 0.002198 |
| 60 | 48.3 | 17.546795 | 0.226287 | 0.226287 | -0.099807 | 0.099807 | 0.009961 |
| 65 | 50.6 | 17.438750 | 0.118242 | 0.118242 | -0.207851 | 0.207851 | 0.043202 |
| 70 | 52.9 | 17.274548 | -0.045960 | 0.045960 | -0.280133 | 0.280133 | 0.078475 |
| 75 | 55.4 | 17.689262 | 0.368754 | 0.368754 | 0.042661 | 0.042661 | 0.001820 |
| 80 | 57.7 | 17.443910 | 0.123402 | 0.123402 | -0.202691 | 0.202691 | 0.041084 |
| **Average Error [mm]:** | 0.326093 | **Variance [mm$^2$]:** | 0.019364 | **Standard Deviation [mm]:** | **0.139156** | | |

**Table A.36** Test Results of 30° Slits with 4 Mhz Compressional Wave Probes of 67°

| **15 (12.990381) mm Slit 30°** | **Distance btw Probes:** 40.67557 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 38.389569 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 28.4 | 13.474420 | 0.484039 | 0.484039 | 0.072914 | 0.072914 | 0.005316 |
| 21 | 28.9 | 13.600000 | 0.609619 | 0.609619 | 0.198494 | 0.198494 | 0.039400 |
| 22 | 29.3 | 13.508886 | 0.518505 | 0.518505 | 0.107380 | 0.107380 | 0.011530 |
| 23 | 29.7 | 13.410444 | 0.420063 | 0.420063 | 0.008938 | 0.008938 | 0.000080 |
| 24 | 30.2 | 13.529228 | 0.538847 | 0.538847 | 0.127722 | 0.127722 | 0.016313 |
| 25 | 30.6 | 13.420507 | 0.430126 | 0.430126 | 0.019001 | 0.019001 | 0.000361 |
| 26 | 31 | 13.304135 | 0.313754 | 0.313754 | -0.097371 | 0.097371 | 0.009481 |
| 27 | 31.5 | 13.416408 | 0.426027 | 0.426027 | 0.014902 | 0.014902 | 0.000222 |
| 28 | 32 | 13.527749 | 0.537368 | 0.537368 | 0.126243 | 0.126243 | 0.015937 |
| 29 | 32.5 | 13.638182 | 0.647801 | 0.647801 | 0.236676 | 0.236676 | 0.056015 |
| 30 | 32.9 | 13.505925 | 0.515544 | 0.515544 | 0.104419 | 0.104419 | 0.010903 |
| 31 | 33.4 | 13.612862 | 0.622481 | 0.622481 | 0.211356 | 0.211356 | 0.044671 |
| 32 | 33.7 | 13.217034 | 0.226653 | 0.226653 | -0.184472 | 0.184472 | 0.034030 |
| 33 | 34.2 | 13.318784 | 0.328403 | 0.328403 | -0.082722 | 0.082722 | 0.006843 |
| 34 | 34.7 | 13.419762 | 0.429381 | 0.429381 | 0.018256 | 0.018256 | 0.000333 |
| 35 | 35.2 | 13.519985 | 0.529604 | 0.529604 | 0.118479 | 0.118479 | 0.014037 |
| 36 | 35.6 | 13.355149 | 0.364768 | 0.364768 | -0.046357 | 0.046357 | 0.002149 |
| 37 | 36 | 13.181426 | 0.191045 | 0.191045 | -0.220080 | 0.220080 | 0.048435 |
| 38 | 36.5 | 13.275918 | 0.285537 | 0.285537 | -0.125588 | 0.125588 | 0.015772 |
| 39 | 37 | 13.369742 | 0.379361 | 0.379361 | -0.031764 | 0.031764 | 0.001009 |
| 40 | 37.4 | 13.181806 | 0.191425 | 0.191425 | -0.219700 | 0.219700 | 0.048268 |
| 42 | 38.4 | 13.362634 | 0.372253 | 0.372253 | -0.038872 | 0.038872 | 0.001511 |
| 45 | 39.8 | 13.333792 | 0.343411 | 0.343411 | -0.067714 | 0.067714 | 0.004585 |
| 47 | 40.8 | 13.505184 | 0.514803 | 0.514803 | 0.103678 | 0.103678 | 0.010749 |
| 50 | 42.1 | 13.130499 | 0.140118 | 0.140118 | -0.271007 | 0.271007 | 0.073445 |
| 55 | 44.4 | 12.849514 | -0.140867 | 0.140867 | -0.270258 | 0.270258 | 0.073039 |
| 60 | 47 | 13.564660 | 0.574279 | 0.574279 | 0.163154 | 0.163154 | 0.026619 |
| 65 | 49.4 | 13.568714 | 0.578333 | 0.578333 | 0.167208 | 0.167208 | 0.027959 |
| 70 | 51.6 | 12.749902 | -0.240479 | 0.240479 | -0.170646 | 0.170646 | 0.029120 |
| 75 | 54.2 | 13.468110 | 0.477729 | 0.477729 | 0.066604 | 0.066604 | 0.004436 |
| 80 | 56.6 | 13.362634 | 0.372253 | 0.372253 | -0.038872 | 0.038872 | 0.001511 |
| **Average Error [mm]:** | 0.411125 | **Variance [mm$^2$]:** | 0.020454 | **Standard Deviation [mm]:** | **0.143018** | | |

**Table A.37** Test Results of 30º Slits with 4 Mhz Compressional Wave Probes of 67º

| **10 (8.660254) mm Slit 30°** | **Distance btw Probes:** 17.117046 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 25.593046 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 26.4 | 8.482924 | -0.177330 | 0.177330 | -0.090575 | 0.090575 | 0.008204 |
| 21 | 27 | 8.874120 | 0.213866 | 0.213866 | -0.054039 | 0.054039 | 0.002920 |
| 22 | 27.4 | 8.646387 | -0.013867 | 0.013867 | -0.254037 | 0.254037 | 0.064535 |
| 23 | 27.8 | 8.401786 | -0.258468 | 0.258468 | -0.009436 | 0.009436 | 0.000089 |
| 24 | 28.3 | 8.478797 | -0.181457 | 0.181457 | -0.086448 | 0.086448 | 0.007473 |
| 25 | 28.8 | 8.555115 | -0.105139 | 0.105139 | -0.162766 | 0.162766 | 0.026493 |
| 26 | 29.3 | 8.630759 | -0.029495 | 0.029495 | -0.238410 | 0.238410 | 0.056839 |
| 27 | 29.8 | 8.705745 | 0.045491 | 0.045491 | -0.222413 | 0.222413 | 0.049468 |
| 28 | 30.3 | 8.780091 | 0.119837 | 0.119837 | -0.148068 | 0.148068 | 0.021924 |
| 29 | 30.8 | 8.853813 | 0.193559 | 0.193559 | -0.074346 | 0.074346 | 0.005527 |
| 30 | 31.2 | 8.569714 | -0.090540 | 0.090540 | -0.177365 | 0.177365 | 0.031458 |
| 31 | 31.8 | 8.999444 | 0.339190 | 0.339190 | 0.071286 | 0.071286 | 0.005082 |
| 32 | 32.2 | 8.708616 | 0.048362 | 0.048362 | -0.219542 | 0.219542 | 0.048199 |
| 33 | 32.8 | 9.142757 | 0.482503 | 0.482503 | 0.214598 | 0.214598 | 0.046052 |
| 34 | 33.1 | 8.462269 | -0.197985 | 0.197985 | -0.069920 | 0.069920 | 0.004889 |
| 35 | 33.7 | 8.912912 | 0.252658 | 0.252658 | -0.015247 | 0.015247 | 0.000232 |
| 36 | 34.2 | 8.979978 | 0.319724 | 0.319724 | 0.051819 | 0.051819 | 0.002685 |
| 37 | 34.7 | 9.046546 | 0.386292 | 0.386292 | 0.118388 | 0.118388 | 0.014016 |
| 38 | 35.1 | 8.718371 | 0.058117 | 0.058117 | -0.209787 | 0.209787 | 0.044011 |
| 39 | 35.6 | 8.781230 | 0.120976 | 0.120976 | -0.146929 | 0.146929 | 0.021588 |
| 40 | 36 | 8.426150 | -0.234104 | 0.234104 | -0.033800 | 0.033800 | 0.001142 |
| 42 | 37 | 8.544004 | -0.116250 | 0.116250 | -0.151654 | 0.151654 | 0.022999 |
| 45 | 38.6 | 9.149317 | 0.489063 | 0.489063 | 0.221158 | 0.221158 | 0.048911 |
| 47 | 39.5 | 8.831761 | 0.171507 | 0.171507 | -0.096398 | 0.096398 | 0.009293 |
| 50 | 41 | 9.000000 | 0.339746 | 0.339746 | 0.071841 | 0.071841 | 0.005161 |
| 55 | 43.3 | 8.284926 | -0.375328 | 0.375328 | 0.107423 | 0.107423 | 0.011540 |
| 60 | 45.8 | 8.522910 | -0.137344 | 0.137344 | -0.130561 | 0.130561 | 0.017046 |
| 65 | 48.4 | 9.290318 | 0.630064 | 0.630064 | 0.362159 | 0.362159 | 0.131159 |
| 70 | 50.8 | 8.979978 | 0.319724 | 0.319724 | 0.051819 | 0.051819 | 0.002685 |
| 75 | 53.4 | 9.762684 | 1.102430 | 1.102430 | 0.834525 | 0.834525 | 0.696433 |
| 80 | 55.8 | 9.414882 | 0.754628 | 0.754628 | 0.486723 | 0.486723 | 0.236899 |
| **Average Error [mm]:** | 0.267905 | **Variance [mm$^2$]:** | 0.053063 | **Standard Deviation [mm]:** | **0.230354** | | |

**Table A.38** Test Results of 30° Slits with 4 Mhz Compressional Wave Probes of 67°

| **5 (4.330127) mm Slit 30°** | **Distance btw Probes:** -6.441478 mm | | **Probe Delay:** 5.55 microseconds | | **Sound Travel Time Distance:** 12.796523 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 25.4 | 4.489989 | 0.159862 | 0.159862 | -0.544184 | 0.544184 | 0.296136 |
| 21 | 25.9 | 4.534314 | 0.204187 | 0.204187 | -0.499859 | 0.499859 | 0.249859 |
| 22 | 26.5 | 5.123475 | 0.793348 | 0.793348 | 0.089302 | 0.089302 | 0.007975 |
| 23 | 26.9 | 4.621688 | 0.291561 | 0.291561 | -0.412485 | 0.412485 | 0.170144 |
| 24 | 27.4 | 4.664762 | 0.334635 | 0.334635 | -0.369411 | 0.369411 | 0.136465 |
| 25 | 27.8 | 4.073082 | -0.257045 | 0.257045 | -0.447001 | 0.447001 | 0.199810 |
| 26 | 28.3 | 4.109745 | -0.220382 | 0.220382 | -0.483663 | 0.483663 | 0.233930 |
| 27 | 28.7 | 3.382307 | -0.947820 | 0.947820 | 0.243774 | 0.243774 | 0.059426 |
| 28 | 29.3 | 4.182105 | -0.148022 | 0.148022 | -0.556024 | 0.556024 | 0.309162 |
| 29 | 29.8 | 4.217819 | -0.112308 | 0.112308 | -0.591738 | 0.591738 | 0.350154 |
| 30 | 30.3 | 4.253234 | -0.076893 | 0.076893 | -0.627153 | 0.627153 | 0.393321 |
| 31 | 30.9 | 4.955805 | 0.625678 | 0.625678 | -0.078368 | 0.078368 | 0.006142 |
| 32 | 31.4 | 4.995998 | 0.665871 | 0.665871 | -0.038174 | 0.038174 | 0.001457 |
| 33 | 31.9 | 5.035871 | 0.705744 | 0.705744 | 0.001698 | 0.001698 | 0.000003 |
| 34 | 32.4 | 5.075431 | 0.745304 | 0.745304 | 0.041258 | 0.041258 | 0.001702 |
| 35 | 32.9 | 5.114685 | 0.784558 | 0.784558 | 0.080512 | 0.080512 | 0.006482 |
| 36 | 33.4 | 5.153639 | 0.823512 | 0.823512 | 0.119467 | 0.119467 | 0.014272 |
| 37 | 33.9 | 5.192302 | 0.862175 | 0.862175 | 0.158129 | 0.158129 | 0.025005 |
| 38 | 34.4 | 5.230679 | 0.900552 | 0.900552 | 0.196506 | 0.196506 | 0.038615 |
| 39 | 35 | 5.894913 | 1.564786 | 1.564786 | 0.860740 | 0.860740 | 0.740874 |
| 40 | 35.4 | 5.306600 | 0.976473 | 0.976473 | 0.272427 | 0.272427 | 0.074216 |
| 42 | 36.3 | 4.657252 | 0.327125 | 0.327125 | -0.376920 | 0.376920 | 0.142069 |
| 45 | 37.9 | 5.491812 | 1.161685 | 1.161685 | 0.457639 | 0.457639 | 0.209434 |
| 47 | 38.8 | 4.815600 | 0.485473 | 0.485473 | -0.218573 | 0.218573 | 0.047774 |
| 50 | 40.4 | 5.670979 | 1.340852 | 1.340852 | 0.636806 | 0.636806 | 0.405522 |
| 55 | 42.8 | 5.058656 | 0.728529 | 0.728529 | 0.024483 | 0.024483 | 0.000599 |
| 60 | 45.3 | 5.204805 | 0.874678 | 0.874678 | 0.170633 | 0.170633 | 0.029115 |
| 65 | 47.9 | 6.177378 | 1.847251 | 1.847251 | 1.143205 | 1.143205 | 1.306918 |
| 70 | 50.2 | 4.476606 | 0.146479 | 0.146479 | -0.557567 | 0.557567 | 0.310881 |
| 75 | 52.8 | 5.620498 | 1.290371 | 1.290371 | 0.586325 | 0.586325 | 0.343777 |
| 80 | 55.3 | 5.752391 | 1.422264 | 1.422264 | 0.718218 | 0.718218 | 0.515837 |
| **Average Error [mm]:** | 0.704046 | **Variance [mm$^2$]:** | 0.213777 | **Standard Deviation [mm]:** | **0.462360** | | |

**Table A.39** Test Results of 30º Slits with 5 Mhz Compressional Wave Probes of 45º

| **20 (17.320508) mm Slit 30°** | **Distance btw Probes:** 8 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 28.284271 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 25.5 | 18.062392 | 0.741884 | 0.741884 | -0.554811 | 0.554811 | 0.307815 |
| 1 | 25.9 | 18.126224 | 0.805716 | 0.805716 | -0.490979 | 0.490979 | 0.241060 |
| 2 | 26.3 | 18.184884 | 0.864376 | 0.864376 | -0.432319 | 0.432319 | 0.186900 |
| 3 | 26.7 | 18.238421 | 0.917913 | 0.917913 | -0.378782 | 0.378782 | 0.143476 |
| 4 | 27 | 18.138357 | 0.817849 | 0.817849 | -0.478846 | 0.478846 | 0.229293 |
| 5 | 27.8 | 18.777380 | 1.456872 | 1.456872 | 0.160177 | 0.160177 | 0.025657 |
| 6 | 28.2 | 18.821265 | 1.500757 | 1.500757 | 0.204062 | 0.204062 | 0.041641 |
| 7 | 28.6 | 18.860276 | 1.539768 | 1.539768 | 0.243073 | 0.243073 | 0.059084 |
| 8 | 28.9 | 18.740598 | 1.420090 | 1.420090 | 0.123395 | 0.123395 | 0.015226 |
| 9 | 29.3 | 18.768058 | 1.447550 | 1.447550 | 0.150855 | 0.150855 | 0.022757 |
| 10 | 29.7 | 18.790689 | 1.470181 | 1.470181 | 0.173486 | 0.173486 | 0.030098 |
| 11 | 30.1 | 18.808509 | 1.488001 | 1.488001 | 0.191306 | 0.191306 | 0.036598 |
| 12 | 30.5 | 18.821530 | 1.501022 | 1.501022 | 0.204327 | 0.204327 | 0.041750 |
| 13 | 31 | 18.993420 | 1.672912 | 1.672912 | 0.376217 | 0.376217 | 0.141539 |
| 14 | 31.4 | 18.998947 | 1.678439 | 1.678439 | 0.381745 | 0.381745 | 0.145729 |
| 15 | 31.7 | 18.831888 | 1.511380 | 1.511380 | 0.214685 | 0.214685 | 0.046090 |
| 16 | 32.1 | 18.825780 | 1.505272 | 1.505272 | 0.208577 | 0.208577 | 0.043505 |
| 17 | 32.5 | 18.814888 | 1.494380 | 1.494380 | 0.197685 | 0.197685 | 0.039079 |
| 18 | 32.9 | 18.799202 | 1.478694 | 1.478694 | 0.181999 | 0.181999 | 0.033124 |
| 19 | 33.3 | 18.778711 | 1.458203 | 1.458203 | 0.161509 | 0.161509 | 0.026085 |
| 20 | 33.7 | 18.753400 | 1.432892 | 1.432892 | 0.136197 | 0.136197 | 0.018550 |
| 22 | 34.5 | 18.688232 | 1.367724 | 1.367724 | 0.071029 | 0.071029 | 0.005045 |
| 25 | 35.8 | 18.745399 | 1.424891 | 1.424891 | 0.128197 | 0.128197 | 0.016434 |
| 27 | 36.6 | 18.636255 | 1.315747 | 1.315747 | 0.019052 | 0.019052 | 0.000363 |
| 30 | 37.8 | 18.434750 | 1.114242 | 1.114242 | -0.182453 | 0.182453 | 0.033289 |
| 35 | 40.1 | 18.648324 | 1.327816 | 1.327816 | 0.031121 | 0.031121 | 0.000969 |
| 40 | 42.4 | 18.808509 | 1.488001 | 1.488001 | 0.191306 | 0.191306 | 0.036598 |
| 45 | 44.5 | 18.439089 | 1.118581 | 1.118581 | -0.178114 | 0.178114 | 0.031725 |
| 50 | 46.6 | 17.959955 | 0.639447 | 0.639447 | -0.657247 | 0.657247 | 0.431974 |
| 55 | 49.1 | 18.454268 | 1.133760 | 1.133760 | -0.162935 | 0.162935 | 0.026548 |
| 60 | 51.4 | 18.383688 | 1.063180 | 1.063180 | -0.233514 | 0.233514 | 0.054529 |
| **Average Error [mm]:** | 1.296695 | **Variance [mm$^2$]:** | 0.081049 | **Standard Deviation [mm]:** | **0.284692** | | |

**Table A.40** Test Results of 30° Slits with 5 Mhz Compressional Wave Probes of 45°

| **15 (12.990381) mm Slit 30°** | **Distance btw Probes:** -2 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 21.213203 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 22.5 | 13.500000 | 0.509619 | 0.509619 | -0.128253 | 0.128253 | 0.016449 |
| 1 | 22.9 | 13.496666 | 0.506285 | 0.506285 | -0.131587 | 0.131587 | 0.017315 |
| 2 | 23.3 | 13.486660 | 0.496279 | 0.496279 | -0.141593 | 0.141593 | 0.020049 |
| 3 | 23.7 | 13.469967 | 0.479586 | 0.479586 | -0.158287 | 0.158287 | 0.025055 |
| 4 | 24 | 13.266499 | 0.276118 | 0.276118 | -0.361754 | 0.361754 | 0.130866 |
| 5 | 24.4 | 13.232914 | 0.242533 | 0.242533 | -0.395340 | 0.395340 | 0.156293 |
| 6 | 24.8 | 13.192422 | 0.202041 | 0.202041 | -0.435831 | 0.435831 | 0.189949 |
| 7 | 25.2 | 13.144961 | 0.154580 | 0.154580 | -0.483292 | 0.483292 | 0.233571 |
| 8 | 25.6 | 13.090455 | 0.100074 | 0.100074 | -0.537799 | 0.537799 | 0.289227 |
| 9 | 26 | 13.028814 | 0.038433 | 0.038433 | -0.599439 | 0.599439 | 0.359327 |
| 10 | 26.4 | 12.959938 | -0.030443 | 0.030443 | -0.607429 | 0.607429 | 0.368970 |
| 11 | 26.8 | 12.883711 | -0.106670 | 0.106670 | -0.531202 | 0.531202 | 0.282175 |
| 12 | 27.2 | 12.800000 | -0.190381 | 0.190381 | -0.447491 | 0.447491 | 0.200248 |
| 13 | 27.6 | 12.708658 | -0.281723 | 0.281723 | -0.356150 | 0.356150 | 0.126843 |
| 14 | 28 | 12.609520 | -0.380861 | 0.380861 | -0.257011 | 0.257011 | 0.066055 |
| 15 | 29.1 | 14.019986 | 1.029605 | 1.029605 | 0.391733 | 0.391733 | 0.153454 |
| 16 | 29.5 | 13.937360 | 0.946979 | 0.946979 | 0.309107 | 0.309107 | 0.095547 |
| 17 | 30.1 | 14.274453 | 1.284072 | 1.284072 | 0.646200 | 0.646200 | 0.417574 |
| 18 | 30.6 | 14.400000 | 1.409619 | 1.409619 | 0.771747 | 0.771747 | 0.595593 |
| 19 | 31 | 14.309088 | 1.318707 | 1.318707 | 0.680835 | 0.680835 | 0.463536 |
| 20 | 31.5 | 14.430870 | 1.440489 | 1.440489 | 0.802617 | 0.802617 | 0.644193 |
| 22 | 32.2 | 13.994285 | 1.003904 | 1.003904 | 0.366031 | 0.366031 | 0.133979 |
| 25 | 33.7 | 14.333178 | 1.342797 | 1.342797 | 0.704925 | 0.704925 | 0.496920 |
| 27 | 34.5 | 14.071247 | 1.080866 | 1.080866 | 0.442994 | 0.442994 | 0.196244 |
| 30 | 35.8 | 13.879481 | 0.889100 | 0.889100 | 0.251228 | 0.251228 | 0.063116 |
| 35 | 38.1 | 13.833293 | 0.842912 | 0.842912 | 0.205040 | 0.205040 | 0.042041 |
| 40 | 40.3 | 13.419762 | 0.429381 | 0.429381 | -0.208492 | 0.208492 | 0.043469 |
| 45 | 42.6 | 13.210223 | 0.219842 | 0.219842 | -0.418030 | 0.418030 | 0.174749 |
| 50 | 45 | 13.266499 | 0.276118 | 0.276118 | -0.361754 | 0.361754 | 0.130866 |
| 55 | 47.3 | 12.924396 | -0.065985 | 0.065985 | -0.571887 | 0.571887 | 0.327054 |
| 60 | 49.8 | 13.268007 | 0.277626 | 0.277626 | -0.360246 | 0.360246 | 0.129778 |
| **Average Error [mm]:** | 0.637872 | **Variance [mm$^2$]:** | 0.212597 | **Standard Deviation [mm]:** | **0.461082** | | |

**Table A.41** Test Results of 30° Slits with 5 Mhz Compressional Wave Probes of 45°

| **10 (8.660254) mm Slit 30°** | **Distance btw Probes:** -12 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 14.142135 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 20.5 | 9.810708 | 1.150454 | 1.150454 | 0.601351 | 0.601351 | 0.361622 |
| 1 | 20.9 | 9.724197 | 1.063943 | 1.063943 | 0.514839 | 0.514839 | 0.265059 |
| 2 | 21.4 | 9.846827 | 1.186573 | 1.186573 | 0.637469 | 0.637469 | 0.406367 |
| 3 | 21.8 | 9.746281 | 1.086027 | 1.086027 | 0.536923 | 0.536923 | 0.288287 |
| 4 | 22.3 | 9.863569 | 1.203315 | 1.203315 | 0.654211 | 0.654211 | 0.427993 |
| 5 | 22.7 | 9.748846 | 1.088592 | 1.088592 | 0.539488 | 0.539488 | 0.291047 |
| 6 | 23.2 | 9.861034 | 1.200780 | 1.200780 | 0.651677 | 0.651677 | 0.424682 |
| 7 | 23.6 | 9.731906 | 1.071652 | 1.071652 | 0.522548 | 0.522548 | 0.273057 |
| 8 | 23.8 | 9.079648 | 0.419394 | 0.419394 | -0.129710 | 0.129710 | 0.016825 |
| 9 | 24.1 | 8.634813 | -0.025441 | 0.025441 | -0.523663 | 0.523663 | 0.274223 |
| 10 | 24.6 | 8.726970 | 0.066716 | 0.066716 | -0.482388 | 0.482388 | 0.232698 |
| 11 | 25.1 | 8.818163 | 0.157909 | 0.157909 | -0.391195 | 0.391195 | 0.153033 |
| 12 | 25.6 | 8.908423 | 0.248169 | 0.248169 | -0.300935 | 0.300935 | 0.090562 |
| 13 | 26.2 | 9.283857 | 0.623603 | 0.623603 | 0.074499 | 0.074499 | 0.005550 |
| 14 | 26.7 | 9.374967 | 0.714713 | 0.714713 | 0.165609 | 0.165609 | 0.027426 |
| 15 | 27.2 | 9.465199 | 0.804945 | 0.804945 | 0.255841 | 0.255841 | 0.065455 |
| 16 | 27.6 | 9.260670 | 0.600416 | 0.600416 | 0.051312 | 0.051312 | 0.002633 |
| 17 | 28.1 | 9.346657 | 0.686403 | 0.686403 | 0.137299 | 0.137299 | 0.018851 |
| 18 | 28.5 | 9.124144 | 0.463890 | 0.463890 | -0.085214 | 0.085214 | 0.007261 |
| 19 | 28.9 | 8.885944 | 0.225690 | 0.225690 | -0.323414 | 0.323414 | 0.104597 |
| 20 | 29.4 | 8.964374 | 0.304120 | 0.304120 | -0.244984 | 0.244984 | 0.060017 |
| 22 | 30.3 | 8.780091 | 0.119837 | 0.119837 | -0.429267 | 0.429267 | 0.184270 |
| 25 | 31.7 | 8.639444 | -0.020810 | 0.020810 | -0.528294 | 0.528294 | 0.279095 |
| 27 | 32.7 | 8.777243 | 0.116989 | 0.116989 | -0.432115 | 0.432115 | 0.186723 |
| 30 | 34.1 | 8.591275 | -0.068979 | 0.068979 | -0.480125 | 0.480125 | 0.230520 |
| 35 | 36.6 | 8.905616 | 0.245362 | 0.245362 | -0.303742 | 0.303742 | 0.092259 |
| 40 | 39 | 8.774964 | 0.114710 | 0.114710 | -0.434394 | 0.434394 | 0.188698 |
| 45 | 41.5 | 9.055385 | 0.395131 | 0.395131 | -0.153973 | 0.153973 | 0.023708 |
| 50 | 43.9 | 8.843642 | 0.183388 | 0.183388 | -0.365716 | 0.365716 | 0.133748 |
| 55 | 46.5 | 9.591663 | 0.931409 | 0.931409 | 0.382305 | 0.382305 | 0.146157 |
| 60 | 48.7 | 8.227393 | -0.432861 | 0.432861 | -0.116243 | 0.116243 | 0.013512 |
| **Average Error [mm]:** | 0.549104 | **Variance [mm$^2$]:** | 0.170191 | **Standard Deviation [mm]:** | **0.412543** | | |

**Table A.42** Test Results of 30° Slits with 5 Mhz Compressional Wave Probes of 45°

| **5 (4.330127) mm Slit 30°** | **Distance btw Probes:** -22 mm | | **Probe Delay:** 3.60 microseconds | | **Sound Travel Distance:** 7.071067 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 0 | 18.6 | 4.686150 | 0.356023 | 0.356023 | -0.443765 | 0.443765 | 0.196927 |
| 1 | 19.1 | 4.749737 | 0.419610 | 0.419610 | -0.380178 | 0.380178 | 0.144535 |
| 2 | 19.6 | 4.812484 | 0.482357 | 0.482357 | -0.317431 | 0.317431 | 0.100762 |
| 3 | 20.1 | 4.874423 | 0.544296 | 0.544296 | -0.255491 | 0.255491 | 0.065276 |
| 4 | 20.6 | 4.935585 | 0.605458 | 0.605458 | -0.194329 | 0.194329 | 0.037764 |
| 5 | 21.1 | 4.995998 | 0.665871 | 0.665871 | -0.133916 | 0.133916 | 0.017933 |
| 6 | 21.6 | 5.055690 | 0.725563 | 0.725563 | -0.074224 | 0.074224 | 0.005509 |
| 7 | 22.1 | 5.114685 | 0.784558 | 0.784558 | -0.015230 | 0.015230 | 0.000232 |
| 8 | 22.5 | 4.716991 | 0.386864 | 0.386864 | -0.412924 | 0.412924 | 0.170506 |
| 9 | 23.1 | 5.230679 | 0.900552 | 0.900552 | 0.100764 | 0.100764 | 0.010153 |
| 10 | 23.5 | 4.821825 | 0.491698 | 0.491698 | -0.308089 | 0.308089 | 0.094919 |
| 11 | 24 | 4.873397 | 0.543270 | 0.543270 | -0.256517 | 0.256517 | 0.065801 |
| 12 | 24.5 | 4.924429 | 0.594302 | 0.594302 | -0.205485 | 0.205485 | 0.042224 |
| 13 | 24.9 | 4.445222 | 0.115095 | 0.115095 | -0.684692 | 0.684692 | 0.468803 |
| 14 | 25.3 | 3.884585 | -0.445542 | 0.445542 | -0.354245 | 0.354245 | 0.125490 |
| 15 | 25.8 | 3.923009 | -0.407118 | 0.407118 | -0.392669 | 0.392669 | 0.154189 |
| 16 | 26.3 | 3.961060 | -0.369067 | 0.369067 | -0.430721 | 0.430721 | 0.185520 |
| 17 | 26.8 | 3.998750 | -0.331377 | 0.331377 | -0.468410 | 0.468410 | 0.219408 |
| 18 | 27.2 | 3.292416 | -1.037711 | 1.037711 | 0.237924 | 0.237924 | 0.056608 |
| 19 | 27.7 | 3.322650 | -1.007477 | 1.007477 | 0.207690 | 0.207690 | 0.043135 |
| 20 | 28.2 | 3.352611 | -0.977516 | 0.977516 | 0.177729 | 0.177729 | 0.031587 |
| 22 | 29.4 | 4.833218 | 0.503091 | 0.503091 | -0.296696 | 0.296696 | 0.088028 |
| 25 | 30.9 | 4.955805 | 0.625678 | 0.625678 | -0.174110 | 0.174110 | 0.030314 |
| 27 | 32 | 5.634714 | 1.304587 | 1.304587 | 0.504799 | 0.504799 | 0.254823 |
| 30 | 33.5 | 5.766281 | 1.436154 | 1.436154 | 0.636367 | 0.636367 | 0.404963 |
| 35 | 35.9 | 5.344156 | 1.014029 | 1.014029 | 0.214241 | 0.214241 | 0.045899 |
| 40 | 38.4 | 5.528110 | 1.197983 | 1.197983 | 0.398196 | 0.398196 | 0.158560 |
| 45 | 40.9 | 5.706137 | 1.376010 | 1.376010 | 0.576223 | 0.576223 | 0.332033 |
| 50 | 43.4 | 5.878775 | 1.548648 | 1.548648 | 0.748861 | 0.748861 | 0.560793 |
| 55 | 45.9 | 6.046487 | 1.716360 | 1.716360 | 0.916572 | 0.916572 | 0.840105 |
| 60 | 48.4 | 6.209670 | 1.879543 | 1.879543 | 1.079756 | 1.079756 | 1.165872 |
| **Average Error [mm]:** | 0.799787 | **Variance [mm$^2$]:** | 0.197377 | **Standard Deviation [mm]:** | **0.444271** | | |

**Table A.43** Test Results of 30° Slits with 5 Mhz Compressional Wave Probes of 67°

| **20 (17.320508) mm Slit 30°** | **Distance btw Probes:** 63.617047 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 51.186093 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_c$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 32.1 | 17.361164 | 0.040656 | 0.040656 | -0.367679 | 0.367679 | 0.135188 |
| 21 | 32.6 | 17.507427 | 0.186919 | 0.186919 | -0.221416 | 0.221416 | 0.049025 |
| 22 | 33.1 | 17.652479 | 0.331971 | 0.331971 | -0.076364 | 0.076364 | 0.005831 |
| 23 | 33.6 | 17.796348 | 0.475840 | 0.475840 | 0.067505 | 0.067505 | 0.004557 |
| 24 | 34 | 17.748239 | 0.427731 | 0.427731 | 0.019397 | 0.019397 | 0.000376 |
| 25 | 34.4 | 17.694915 | 0.374407 | 0.374407 | -0.033928 | 0.033928 | 0.001151 |
| 26 | 34.8 | 17.636326 | 0.315818 | 0.315818 | -0.092517 | 0.092517 | 0.008559 |
| 27 | 35.2 | 17.572422 | 0.251914 | 0.251914 | -0.156421 | 0.156421 | 0.024468 |
| 28 | 35.6 | 17.503143 | 0.182635 | 0.182635 | -0.225700 | 0.225700 | 0.050941 |
| 29 | 36.1 | 17.634058 | 0.313550 | 0.313550 | -0.094785 | 0.094785 | 0.008984 |
| 30 | 36.6 | 17.764009 | 0.443501 | 0.443501 | 0.035166 | 0.035166 | 0.001237 |
| 31 | 37 | 17.684739 | 0.364231 | 0.364231 | -0.044104 | 0.044104 | 0.001945 |
| 32 | 37.4 | 17.600000 | 0.279492 | 0.279492 | -0.128843 | 0.128843 | 0.016600 |
| 33 | 37.9 | 17.724559 | 0.404051 | 0.404051 | -0.004284 | 0.004284 | 0.000018 |
| 34 | 38.3 | 17.632073 | 0.311565 | 0.311565 | -0.096770 | 0.096770 | 0.009364 |
| 35 | 38.7 | 17.533967 | 0.213459 | 0.213459 | -0.194876 | 0.194876 | 0.037977 |
| 36 | 39.3 | 17.874283 | 0.553775 | 0.553775 | 0.145440 | 0.145440 | 0.021153 |
| 37 | 39.7 | 17.771888 | 0.451380 | 0.451380 | 0.043045 | 0.043045 | 0.001853 |
| 38 | 40.2 | 17.889662 | 0.569154 | 0.569154 | 0.160819 | 0.160819 | 0.025863 |
| 39 | 40.6 | 17.779483 | 0.458975 | 0.458975 | 0.050640 | 0.050640 | 0.002564 |
| 40 | 41 | 17.663522 | 0.343014 | 0.343014 | -0.065321 | 0.065321 | 0.004267 |
| 42 | 41.9 | 17.652479 | 0.331971 | 0.331971 | -0.076364 | 0.076364 | 0.005831 |
| 45 | 43.3 | 17.738095 | 0.417587 | 0.417587 | 0.009252 | 0.009252 | 0.000086 |
| 47 | 44.2 | 17.702825 | 0.382317 | 0.382317 | -0.026018 | 0.026018 | 0.000677 |
| 50 | 45.6 | 17.758378 | 0.437870 | 0.437870 | 0.029535 | 0.029535 | 0.000872 |
| 55 | 48 | 17.993054 | 0.672546 | 0.672546 | 0.264211 | 0.264211 | 0.069808 |
| 60 | 50.3 | 17.918984 | 0.598476 | 0.598476 | 0.190142 | 0.190142 | 0.036154 |
| 65 | 52.6 | 17.790728 | 0.470220 | 0.470220 | 0.061885 | 0.061885 | 0.003830 |
| 70 | 55 | 17.916473 | 0.595965 | 0.595965 | 0.187630 | 0.187630 | 0.035205 |
| 75 | 57.4 | 18.014161 | 0.693653 | 0.693653 | 0.285318 | 0.285318 | 0.081407 |
| 80 | 59.8 | 18.084247 | 0.763739 | 0.763739 | 0.355404 | 0.355404 | 0.126312 |
| **Average Error [mm]:** | 0.408335 | **Variance [mm$^2$]:** | 0.024907 | **Standard Deviation [mm]:** | **0.157818** | | |

**Table A.44** Test Results of 30° Slits with 5 Mhz Compressional Wave Probes of 67°

| **15 (12.990381) mm Slit 30°** | **Distance btw Probes:** 40.67557 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 38.389569 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 30.1 | 13.304511 | 0.314130 | 0.314130 | -0.200185 | 0.200185 | 0.040074 |
| 21 | 30.6 | 13.420507 | 0.430126 | 0.430126 | -0.084188 | 0.084188 | 0.007088 |
| 22 | 31 | 13.304135 | 0.313754 | 0.313754 | -0.200560 | 0.200560 | 0.040224 |
| 23 | 31.5 | 13.416408 | 0.426027 | 0.426027 | -0.088287 | 0.088287 | 0.007795 |
| 24 | 31.9 | 13.289470 | 0.299089 | 0.299089 | -0.215226 | 0.215226 | 0.046322 |
| 25 | 32.4 | 13.398134 | 0.407753 | 0.407753 | -0.106561 | 0.106561 | 0.011355 |
| 26 | 32.9 | 13.505925 | 0.515544 | 0.515544 | 0.001230 | 0.001230 | 0.000002 |
| 27 | 33.3 | 13.365628 | 0.375247 | 0.375247 | -0.139068 | 0.139068 | 0.019340 |
| 28 | 33.8 | 13.469967 | 0.479586 | 0.479586 | -0.034728 | 0.034728 | 0.001206 |
| 29 | 34.3 | 13.573504 | 0.583123 | 0.583123 | 0.068809 | 0.068809 | 0.004735 |
| 30 | 34.7 | 13.419762 | 0.429381 | 0.429381 | -0.084934 | 0.084934 | 0.007214 |
| 31 | 35.2 | 13.519985 | 0.529604 | 0.529604 | 0.015290 | 0.015290 | 0.000234 |
| 32 | 35.6 | 13.355149 | 0.364768 | 0.364768 | -0.149546 | 0.149546 | 0.022364 |
| 33 | 36.1 | 13.452137 | 0.461756 | 0.461756 | -0.052558 | 0.052558 | 0.002762 |
| 34 | 36.5 | 13.275918 | 0.285537 | 0.285537 | -0.228777 | 0.228777 | 0.052339 |
| 35 | 37 | 13.369742 | 0.379361 | 0.379361 | -0.134953 | 0.134953 | 0.018212 |
| 36 | 37.5 | 13.462912 | 0.472531 | 0.472531 | -0.041783 | 0.041783 | 0.001746 |
| 37 | 38 | 13.555442 | 0.565061 | 0.565061 | 0.050747 | 0.050747 | 0.002575 |
| 38 | 38.5 | 13.647344 | 0.656963 | 0.656963 | 0.142649 | 0.142649 | 0.020349 |
| 39 | 39 | 13.738632 | 0.748251 | 0.748251 | 0.233937 | 0.233937 | 0.054726 |
| 40 | 39.5 | 13.829317 | 0.838936 | 0.838936 | 0.324622 | 0.324622 | 0.105379 |
| 42 | 40.4 | 13.717143 | 0.726762 | 0.726762 | 0.212447 | 0.212447 | 0.045134 |
| 45 | 41.8 | 13.674429 | 0.684048 | 0.684048 | 0.169734 | 0.169734 | 0.028809 |
| 47 | 42.7 | 13.529228 | 0.538847 | 0.538847 | 0.024533 | 0.024533 | 0.000602 |
| 50 | 44 | 13.114877 | 0.124496 | 0.124496 | -0.389818 | 0.389818 | 0.151958 |
| 55 | 46.5 | 13.490738 | 0.500357 | 0.500357 | -0.013958 | 0.013958 | 0.000195 |
| 60 | 49 | 13.856406 | 0.866025 | 0.866025 | 0.351711 | 0.351711 | 0.123701 |
| 65 | 51.3 | 13.469967 | 0.479586 | 0.479586 | -0.034728 | 0.034728 | 0.001206 |
| 70 | 53.8 | 13.800000 | 0.809619 | 0.809619 | 0.295305 | 0.295305 | 0.087205 |
| 75 | 56.2 | 13.718236 | 0.727855 | 0.727855 | 0.213541 | 0.213541 | 0.045600 |
| 80 | 58.6 | 13.600000 | 0.609619 | 0.609619 | 0.095305 | 0.095305 | 0.009083 |
| **Average Error [mm]:** | 0.514314 | **Variance [mm$^2$]:** | 0.030953 | **Standard Deviation [mm]:** | **0.175934** | | |

**Table A.45** Test Results of 30° Slits with 5 Mhz Compressional Wave Probes of 67°

| 10 (8.660254) mm Slit 30° | **Distance btw Probes:** 17.117046 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 25.593046 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 28.6 | 9.431861 | 0.771607 | 0.771607 | -0.229794 | 0.229794 | 0.052805 |
| 21 | 29 | 9.205976 | 0.545722 | 0.545722 | -0.455679 | 0.455679 | 0.207643 |
| 22 | 29.5 | 9.287088 | 0.626834 | 0.626834 | -0.374567 | 0.374567 | 0.140301 |
| 23 | 30 | 9.367497 | 0.707243 | 0.707243 | -0.294158 | 0.294158 | 0.086529 |
| 24 | 30.5 | 9.447222 | 0.786968 | 0.786968 | -0.214433 | 0.214433 | 0.045982 |
| 25 | 31 | 9.526279 | 0.866025 | 0.866025 | -0.135376 | 0.135376 | 0.018327 |
| 26 | 31.5 | 9.604686 | 0.944432 | 0.944432 | -0.056969 | 0.056969 | 0.003245 |
| 27 | 31.9 | 9.346657 | 0.686403 | 0.686403 | -0.314998 | 0.314998 | 0.099224 |
| 28 | 32.4 | 9.421253 | 0.760999 | 0.760999 | -0.240402 | 0.240402 | 0.057793 |
| 29 | 32.9 | 9.495262 | 0.835008 | 0.835008 | -0.166393 | 0.166393 | 0.027687 |
| 30 | 33.5 | 9.912114 | 1.251860 | 1.251860 | 0.250459 | 0.250459 | 0.062730 |
| 31 | 33.9 | 9.641577 | 0.981323 | 0.981323 | -0.020078 | 0.020078 | 0.000403 |
| 32 | 34.4 | 9.713908 | 1.053654 | 1.053654 | 0.052253 | 0.052253 | 0.002730 |
| 33 | 34.9 | 9.785704 | 1.125450 | 1.125450 | 0.124049 | 0.124049 | 0.015388 |
| 34 | 35.3 | 9.491575 | 0.831321 | 0.831321 | -0.170080 | 0.170080 | 0.028927 |
| 35 | 35.8 | 9.559812 | 0.899558 | 0.899558 | -0.101843 | 0.101843 | 0.010372 |
| 36 | 36.3 | 9.627565 | 0.967311 | 0.967311 | -0.034090 | 0.034090 | 0.001162 |
| 37 | 36.8 | 9.694844 | 1.034590 | 1.034590 | 0.033189 | 0.033189 | 0.001102 |
| 38 | 37.3 | 9.761660 | 1.101406 | 1.101406 | 0.100005 | 0.100005 | 0.010001 |
| 39 | 37.6 | 9.028289 | 0.368035 | 0.368035 | -0.633366 | 0.633366 | 0.401153 |
| 40 | 38.2 | 9.499474 | 0.839220 | 0.839220 | -0.162181 | 0.162181 | 0.026303 |
| 42 | 39.2 | 9.624968 | 0.964714 | 0.964714 | -0.036688 | 0.036688 | 0.001346 |
| 45 | 40.7 | 9.810199 | 1.149945 | 1.149945 | 0.148544 | 0.148544 | 0.022065 |
| 47 | 41.7 | 9.931767 | 1.271513 | 1.271513 | 0.270112 | 0.270112 | 0.072961 |
| 50 | 43.1 | 9.675226 | 1.014972 | 1.014972 | 0.013571 | 0.013571 | 0.000184 |
| 55 | 45.5 | 9.486833 | 0.826579 | 0.826579 | -0.174822 | 0.174822 | 0.030563 |
| 60 | 48.1 | 10.227903 | 1.567649 | 1.567649 | 0.566248 | 0.566248 | 0.320637 |
| 65 | 50.5 | 10.000000 | 1.339746 | 1.339746 | 0.338345 | 0.338345 | 0.114477 |
| 70 | 53 | 10.246951 | 1.586697 | 1.586697 | 0.585296 | 0.585296 | 0.342571 |
| 75 | 55.5 | 10.488088 | 1.827834 | 1.827834 | 0.826433 | 0.826433 | 0.682992 |
| 80 | 57.9 | 10.169071 | 1.508817 | 1.508817 | 0.507416 | 0.507416 | 0.257471 |
| **Average Error [mm]:** | 1.001401 | **Variance [mm$^2$]:** | 0.101454 | **Standard Deviation [mm]:** | **0.318518** | | |

**Table A.46** Test Results of 30° Slits with 5 Mhz Compressional Wave Probes of 67°

| **5 (4.330127) mm Slit 30°** | **Distance btw Probes:** -6.441478 mm | | **Probe Delay:** 4.55 microseconds | | **Sound Travel Time Distance:** 12.796523 mm | | |
|---|---|---|---|---|---|---|---|
| **Distance btw Probes (2S) [mm]:** | **Measured Sound Travel Distance ($h_C$) [mm]:** | **Calculated Slit Depth (d) [mm]:** | **Calculated Error [mm]:** | **Absolute Error (xi) [mm]** | **(xi – Average Error) [mm]** | **Absolute (xi – Average Error) [mm]** | **(xi – Average Error)$^2$ [mm$^2$]** |
| 20 | 27.4 | 4.664762 | 0.334635 | 0.334635 | -0.269210 | 0.269210 | 0.072474 |
| 21 | 27.8 | 4.073082 | -0.257045 | 0.257045 | -0.346800 | 0.346800 | 0.120270 |
| 22 | 28.2 | 3.352611 | -0.977516 | 0.977516 | 0.373671 | 0.373671 | 0.139630 |
| 23 | 28.7 | 3.382307 | -0.947820 | 0.947820 | 0.343975 | 0.343975 | 0.118319 |
| 24 | 29.2 | 3.411744 | -0.918383 | 0.918383 | 0.314538 | 0.314538 | 0.098934 |
| 25 | 29.8 | 4.217819 | -0.112308 | 0.112308 | -0.491537 | 0.491537 | 0.241609 |
| 26 | 30.2 | 3.469870 | -0.860257 | 0.860257 | 0.256412 | 0.256412 | 0.065747 |
| 27 | 30.7 | 3.498571 | -0.831556 | 0.831556 | 0.227711 | 0.227711 | 0.051852 |
| 28 | 31.2 | 3.527038 | -0.803089 | 0.803089 | 0.199244 | 0.199244 | 0.039698 |
| 29 | 31.8 | 4.357752 | 0.027625 | 0.027625 | -0.576220 | 0.576220 | 0.332030 |
| 30 | 32.3 | 4.392038 | 0.061911 | 0.061911 | -0.541934 | 0.541934 | 0.293692 |
| 31 | 32.9 | 5.114685 | 0.784558 | 0.784558 | 0.180713 | 0.180713 | 0.032657 |
| 32 | 33.4 | 5.153639 | 0.823512 | 0.823512 | 0.219668 | 0.219668 | 0.048254 |
| 33 | 33.8 | 4.493328 | 0.163201 | 0.163201 | -0.440644 | 0.440644 | 0.194167 |
| 34 | 34.4 | 5.230679 | 0.900552 | 0.900552 | 0.296707 | 0.296707 | 0.088035 |
| 35 | 34.8 | 4.559605 | 0.229478 | 0.229478 | -0.374367 | 0.374367 | 0.140150 |
| 36 | 35.2 | 3.746999 | -0.583128 | 0.583128 | -0.020717 | 0.020717 | 0.000429 |
| 37 | 35.8 | 4.624932 | 0.294805 | 0.294805 | -0.309040 | 0.309040 | 0.095505 |
| 38 | 36.3 | 4.657252 | 0.327125 | 0.327125 | -0.276720 | 0.276720 | 0.076574 |
| 39 | 36.8 | 4.689350 | 0.359223 | 0.359223 | -0.244622 | 0.244622 | 0.059840 |
| 40 | 37.2 | 3.852272 | -0.477855 | 0.477855 | -0.125990 | 0.125990 | 0.015873 |
| 42 | 38.2 | 3.903844 | -0.426283 | 0.426283 | -0.177562 | 0.177562 | 0.031528 |
| 45 | 39.8 | 4.877499 | 0.547372 | 0.547372 | -0.056473 | 0.056473 | 0.003189 |
| 47 | 40.8 | 4.938623 | 0.608496 | 0.608496 | 0.004651 | 0.004651 | 0.000022 |
| 50 | 42.2 | 4.103657 | -0.226470 | 0.226470 | -0.377375 | 0.377375 | 0.142412 |
| 55 | 44.7 | 4.223742 | -0.106385 | 0.106385 | -0.497460 | 0.497460 | 0.247467 |
| 60 | 47.3 | 5.318834 | 0.988707 | 0.988707 | 0.384862 | 0.384862 | 0.148119 |
| 65 | 49.8 | 5.458022 | 1.127895 | 1.127895 | 0.524050 | 0.524050 | 0.274628 |
| 70 | 52.3 | 5.593747 | 1.263620 | 1.263620 | 0.659775 | 0.659775 | 0.435302 |
| 75 | 54.8 | 5.726255 | 1.396128 | 1.396128 | 0.792283 | 0.792283 | 0.627713 |
| 80 | 57.1 | 3.377869 | -0.952258 | 0.952258 | 0.348413 | 0.348413 | 0.121392 |
| **Average Error [mm]:** | 0.603845 | **Variance [mm$^2$]:** | 0.140565 | **Standard Deviation [mm]:** | **0.374920** | | |

# APPENDIX B

# TEST RESULTS OF REFLECTION OF SHEAR WAVE METHOD

**Table B.1** Test Results of Vertical Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 20 | 56.7 | 48.8 | 8.5 | 19.403806 | 20.596194 | 0.596194 | 0.161405 | 0.026052 |
| 20 | 56.7 | 70.9 | 15 | 20.414753 | 19.585247 | 0.414753 | 0.020037 | 0.000401 |
| 20 | 57.5 | 49.2 | 9 | 20.554813 | 19.445187 | 0.554813 | 0.120024 | 0.014406 |
| 20 | 57.5 | 72.7 | 16 | 20.173398 | 19.826602 | 0.173398 | 0.261392 | 0.068326 |
| **Average Error [mm]:** | 0.434789 | **Variance [mm$^2$]:** | 0.027296 | **Standard Deviation [mm]:** | **0.165215** | | | |

**Table B.2** Test Results of Vertical Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 15 | 76.8 | 62.8 | 15 | 24.913888 | 15.086112 | 0.086112 | 0.167249 | 0.027972 |
| 15 | 76.8 | 86.8 | 10.5 | 24.890271 | 15.109729 | 0.109729 | 0.143632 | 0.020630 |
| 15 | 72.2 | 62.5 | 10.5 | 25.706650 | 14.293350 | 0.706650 | 0.453289 | 0.205471 |
| 15 | 72.2 | 85 | 13.5 | 24.889047 | 15.110953 | 0.110953 | 0.142408 | 0.020280 |
| **Average Error [mm]:** | 0.253361 | **Variance [mm$^2$]:** | 0.068588 | **Standard Deviation [mm]:** | **0.261894** | | | |

**Table B.3** Test Results of Vertical Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error (x) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 10 | 83.2 | 72.6 | 11.5 | 30.128027 | 9.871973 | 0.128027 | 0.205585 | 0.042265 |
| 10 | 83.2 | 104.9 | 23 | 30.937503 | 9.062497 | 0.937503 | 0.603891 | 0.364684 |
| 10 | 83.5 | 73.8 | 10.5 | 30.044182 | 9.955818 | 0.044182 | 0.289430 | 0.083770 |
| 10 | 83.5 | 102.4 | 20 | 30.224736 | 9.775264 | 0.224736 | 0.108876 | 0.011854 |
| **Average Error [mm]:** | 0.333612 | **Variance [mm$^2$]:** | 0.125643 | **Standard Deviation [mm]:** | **0.354462** | | | |

**Table B.4** Test Results of Vertical Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error (x) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 5 | 100.7 | 89.5 | 12 | 34.073926 | 5.926074 | 0.926074 | 0.385018 | 0.148239 |
| 5 | 100.7 | 110.1 | 10 | 35.919302 | 4.080698 | 0.919302 | 0.378245 | 0.143069 |
| 5 | 93.1 | 102.9 | 10.5 | 35.132555 | 4.867445 | 0.132555 | 0.408502 | 0.166874 |
| 5 | 93.1 | 83 | 11 | 34.813704 | 5.186296 | 0.186296 | 0.354761 | 0.125855 |
| **Average Error [mm]:** | 0.541057 | **Variance [mm$^2$]:** | 0.146009 | **Standard Deviation [mm]:** | **0.382112** | | | |

**Table B.5** Test Results of Vertical Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 20 | 28.5 | 26.5 | 3 | 20.466775 | 19.533225 | 0.466775 | 0.103343 | 0.010680 |
| 20 | 28.5 | 30.3 | 2.5 | 20.384388 | 19.615612 | 0.384388 | 0.185730 | 0.034496 |
| 20 | 28.3 | 26 | 3.5 | 20.422192 | 19.577808 | 0.422192 | 0.147926 | 0.021882 |
| 20 | 28.3 | 30.2 | 2.5 | 18.992883 | 21.007117 | 1.007117 | 0.436999 | 0.190968 |
| **Average Error [mm]:** | 0.570118 | **Variance [mm$^2$]:** | 0.064506 | **Standard Deviation [mm]:** | **0.253981** | | | |

**Table B.6** Test Results of Vertical Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 15 | 35.5 | 37.3 | 2.5 | 25.245757 | 14.754243 | 0.245757 | 0.191841 | 0.036803 |
| 15 | 35.5 | 33.5 | 3 | 25.690465 | 14.309535 | 0.690465 | 0.252867 | 0.063942 |
| 15 | 35.3 | 33 | 3.5 | 25.707290 | 14.292710 | 0.707290 | 0.269692 | 0.072734 |
| 15 | 35.3 | 37.1 | 2.5 | 25.106880 | 14.893120 | 0.106880 | 0.330718 | 0.109375 |
| **Average Error [mm]:** | 0.437598 | **Variance [mm$^2$]:** | 0.070713 | **Standard Deviation [mm]:** | **0.265920** | | | |

**Table B.7** Test Results of Vertical Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 10 | 42.2 | 39.8 | 3.5 | 29.815507 | 10.184493 | 0.184493 | 0.267411 | 0.071508 |
| 10 | 42.2 | 44.8 | 3.5 | 29.097499 | 10.902501 | 0.902501 | 0.450597 | 0.203038 |
| 10 | 42.2 | 40.2 | 3 | 30.688308 | 9.311692 | 0.688308 | 0.236404 | 0.055887 |
| 10 | 42.2 | 45.1 | 4 | 30.032314 | 9.967686 | 0.032314 | 0.419590 | 0.176056 |
| **Average Error [mm]:** | 0.451904 | **Variance [mm$^2$]:** | 0.126622 | **Standard Deviation [mm]:** | **0.355840** | | | |

**Table B.8** Test Results of Vertical Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 5 | 48.4 | 45.9 | 4 | 36.773330 | 3.226670 | 1.773330 | 0.920328 | 0.847003 |
| 5 | 48.4 | 51.3 | 4 | 34.306487 | 5.693513 | 0.693513 | 0.159489 | 0.025437 |
| 5 | 48.9 | 51.7 | 4 | 35.892978 | 4.107022 | 0.892978 | 0.039977 | 0.001598 |
| 5 | 48.9 | 46.2 | 4 | 35.052186 | 4.947814 | 0.052186 | 0.800816 | 0.641306 |
| **Average Error [mm]:** | 0.853002 | **Variance [mm$^2$]:** | 0.378836 | **Standard Deviation [mm]:** | **0.615497** | | | |

**Table B.9** Test Results of Vertical Slits with 2 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – $x_i$) [mm]:** | **(Average Error – $x_i$)$^2$ [mm$^2$]:** |
| 20 | 29 | 25.6 | 5 | 19.932584 | 20.067416 | 0.067416 | 0.250321 | 0.062661 |
| 20 | 29 | 32.1 | 4 | 19.264999 | 20.735001 | 0.735001 | 0.417264 | 0.174109 |
| 20 | 30 | 27.2 | 4 | 20.374484 | 19.625516 | 0.374484 | 0.056747 | 0.003220 |
| 20 | 30 | 33.5 | 4.5 | 19.905952 | 20.094048 | 0.094048 | 0.223689 | 0.050037 |
| **Average Error [mm]:** | 0.317737 | **Variance [mm$^2$]:** | 0.072507 | **Standard Deviation [mm]:** | **0.269271** | | | |

**Table B.10** Test Results of Vertical Slits with 2 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – $x_i$) [mm]:** | **(Average Error – $x_i$)$^2$ [mm$^2$]:** |
| 15 | 35.4 | 39.1 | 5 | 24.998115 | 15.001885 | 0.001885 | 0.303864 | 0.092333 |
| 15 | 35.4 | 32.1 | 5 | 25.285557 | 14.714443 | 0.285557 | 0.020192 | 0.000408 |
| 15 | 35.9 | 33.2 | 4 | 25.448857 | 14.551143 | 0.448857 | 0.143108 | 0.020480 |
| 15 | 35.9 | 39.7 | 5 | 24.513303 | 15.486697 | 0.486697 | 0.180948 | 0.032742 |
| **Average Error [mm]:** | 0.305749 | **Variance [mm$^2$]:** | 0.036491 | **Standard Deviation [mm]:** | **0.191026** | | | |

**Table B.11** Test Results of Vertical Slits with 2 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 10 | 44.1 | 39.8 | 6 | 29.181687 | 10.818313 | 0.818313 | 0.408890 | 0.167191 |
| 10 | 44.1 | 49.3 | 7 | 31.175387 | 8.824613 | 0.113319 | 0.296103 | 0.087677 |
| 10 | 43.7 | 38.4 | 8 | 30.602663 | 9.397337 | 0.602663 | 0.193241 | 0.037342 |
| 10 | 43.7 | 48.2 | 6 | 30.328223 | 9.671777 | 0.103394 | 0.306029 | 0.093653 |
| **Average Error [mm]:** | 0.409422 | **Variance [mm$^2$]:** | 0.096466 | **Standard Deviation [mm]:** | **0.310590** | | | |

**Table B.12** Test Results of Vertical Slits with 2 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 5 | 50.4 | 46.5 | 6 | 36.748162 | 3.251838 | 1.748162 | 0.922267 | 0.850577 |
| 5 | 50.4 | 57.2 | 9 | 35.120049 | 4.879951 | 0.120049 | 0.705846 | 0.498219 |
| 5 | 48.9 | 54.7 | 8 | 35.570662 | 4.429338 | 0.570662 | 0.255234 | 0.065144 |
| 5 | 48.9 | 44.8 | 6 | 34.135292 | 5.864708 | 0.864708 | 0.038813 | 0.001506 |
| **Average Error [mm]:** | 0.825895 | **Variance [mm$^2$]:** | 0.353862 | **Standard Deviation [mm]:** | **0.594863** | | | |

Table B.13 Test Results of 15° Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 20 | 61.7 | 49.6 | 13 | 20.206779 | 19.793221 | 0.474705 | 0.014211 | 0.000202 |
| 20 | 61.7 | 75 | 14 | 21.230060 | 18.769940 | 0.548576 | 0.088082 | 0.007758 |
| 20 | 58.4 | 48.3 | 11 | 21.022483 | 18.977517 | 0.340999 | 0.119496 | 0.014279 |
| 20 | 58.4 | 74.5 | 17 | 21.159182 | 18.840818 | 0.477698 | 0.017203 | 0.000296 |
| **Average Error [mm]:** | 0.460494 | **Variance [mm$^2$]:** | 0.005634 | **Standard Deviation [mm]:** | **0.075059** | | | |

Table B.14 Test Results of 15° Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 15 | 72.7 | 91.7 | 20 | 25.476301 | 14.523699 | 0.034812 | 0.515800 | 0.266049 |
| 15 | 72.7 | 64.3 | 9 | 24.539130 | 15.460870 | 0.971983 | 0.421371 | 0.177554 |
| 15 | 76.3 | 62.3 | 15 | 24.733330 | 15.266670 | 0.777783 | 0.227171 | 0.051607 |
| 15 | 76.3 | 90.6 | 15 | 25.093244 | 14.906756 | 0.417869 | 0.132743 | 0.017621 |
| **Average Error [mm]:** | 0.550612 | **Variance [mm$^2$]:** | 0.128208 | **Standard Deviation [mm]:** | **0.358061** | | | |

**Table B.15** Test Results of 15° Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 10 | 83.4 | 112.5 | 30.5 | 28.977658 | 11.022342 | 1.363084 | 0.763292 | 0.582615 |
| 10 | 83.4 | 76 | 8 | 30.245214 | 9.754786 | 0.095528 | 0.504265 | 0.254283 |
| 10 | 86.2 | 79.2 | 7.5 | 29.659669 | 10.340331 | 0.681073 | 0.081280 | 0.006606 |
| 10 | 86.2 | 111.9 | 27 | 30.081257 | 9.918743 | 0.259485 | 0.340307 | 0.115809 |
| **Average Error [mm]:** | 0.599792 | **Variance [mm$^2$]:** | 0.239828 | **Standard Deviation [mm]:** | **0.489723** | | | |

**Table B.16** Test Results of 15° Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 5 | 95.7 | 87.9 | 8.5 | 36.441870 | 3.558130 | 1.271499 | 0.210374 | 0.044257 |
| 5 | 95.7 | 111.8 | 17 | 33.198006 | 6.801994 | 1.972365 | 0.911240 | 0.830359 |
| 5 | 94.5 | 117.1 | 24 | 35.376902 | 4.623098 | 0.206531 | 0.854594 | 0.730331 |
| 5 | 94.5 | 86.7 | 8.5 | 35.964476 | 4.035524 | 0.794105 | 0.267020 | 0.071300 |
| **Average Error [mm]:** | 1.061125 | **Variance [mm$^2$]:** | 0.419062 | **Standard Deviation [mm]:** | **0.647350** | | | |

**Table B.17** Test Results of 15° Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 20 | 28.2 | 26.2 | 3 | 20.242831 | 19.757169 | 0.438653 | 0.246302 | 0.060665 |
| 20 | 28.2 | 29.6 | 2 | 20.626369 | 19.373631 | 0.055115 | 0.137235 | 0.018834 |
| 20 | 28.3 | 26 | 3.5 | 20.422192 | 19.577808 | 0.259292 | 0.066942 | 0.004481 |
| 20 | 28.3 | 29.7 | 2 | 20.697826 | 19.302174 | 0.016342 | 0.176008 | 0.030979 |
| **Average Error [mm]:** | 0.192350 | **Variance [mm$^2$]:** | 0.028740 | **Standard Deviation [mm]:** | **0.169528** | | | |

**Table B.18** Test Results of 15° Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 15 | 35.7 | 37.5 | 2.5 | 25.384633 | 14.615367 | 0.126480 | 0.446143 | 0.199044 |
| 15 | 35.7 | 33.7 | 3 | 25.839677 | 14.160323 | 0.328564 | 0.244060 | 0.059565 |
| 15 | 35.5 | 33.4 | 3 | 24.578889 | 15.421111 | 0.932224 | 0.359601 | 0.129313 |
| 15 | 35.5 | 38.1 | 3.5 | 24.607887 | 15.392113 | 0.903226 | 0.330602 | 0.109298 |
| **Average Error [mm]:** | 0.572623 | **Variance [mm$^2$]:** | 0.124305 | **Standard Deviation [mm]:** | **0.352569** | | | |

**Table B.19** Test Results of 15° Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 10 | 43.7 | 41.6 | 3 | 30.439349 | 9.560651 | 0.098607 | 0.442422 | 0.195737 |
| 10 | 43.7 | 46.6 | 4 | 31.066487 | 8.933513 | 0.725745 | 0.184716 | 0.034120 |
| 10 | 43.3 | 41.3 | 3 | 31.508729 | 8.491271 | 1.167987 | 0.626958 | 0.393076 |
| 10 | 43.3 | 45.5 | 3 | 30.168964 | 9.831036 | 0.171778 | 0.369251 | 0.136347 |
| **Average Error [mm]:** | 0.541029 | **Variance [mm$^2$]:** | 0.189820 | **Standard Deviation [mm]:** | **0.435683** | | | |

**Table B.20** Test Results of 15° Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 5 | 48.9 | 46.8 | 3 | 34.154941 | 5.845059 | 1.015430 | 0.097612 | 0.009528 |
| 5 | 48.9 | 52.3 | 5 | 37.055223 | 2.944777 | 1.884852 | 0.967034 | 0.935155 |
| 5 | 49.8 | 53.1 | 4.5 | 34.945809 | 5.054191 | 0.224562 | 0.693256 | 0.480604 |
| 5 | 49.8 | 47.1 | 4 | 35.716799 | 4.283201 | 0.546428 | 0.371390 | 0.137930 |
| **Average Error [mm]:** | 0.917818 | **Variance [mm$^2$]:** | 0.390804 | **Standard Deviation [mm]:** | **0.625143** | | | |

**Table B.21** Test Results of 15º Slits with 2 MHz Shear Wave Probe of 45º

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 20 | 28.4 | 25.4 | 4.5 | 19.979816 | 20.020184 | 0.701668 | 0.487330 | 0.237490 |
| 20 | 28.4 | 30.9 | 3.5 | 20.714502 | 19.285498 | 0.033018 | 0.181319 | 0.032877 |
| 20 | 28.7 | 25.8 | 4.5 | 20.765594 | 19.234406 | 0.084110 | 0.130228 | 0.016959 |
| 20 | 28.7 | 31.6 | 4 | 20.720040 | 19.279960 | 0.038556 | 0.175782 | 0.030899 |
| **Average Error [mm]:** | 0.214338 | **Variance [mm$^2$]:** | 0.079556 | **Standard Deviation [mm]:** | **0.282058** | | | |

**Table B.22** Test Results of 15º Slits with 2 MHz Shear Wave Probe of 45º

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 15 | 36.2 | 39.2 | 4 | 24.901092 | 15.098908 | 0.610021 | 0.150315 | 0.022595 |
| 15 | 36.2 | 32.3 | 5.5 | 24.072288 | 15.927712 | 1.438825 | 0.678489 | 0.460347 |
| 15 | 38.1 | 36.6 | 2 | 24.695847 | 15.304153 | 0.815266 | 0.054930 | 0.003017 |
| 15 | 38.1 | 39.6 | 2 | 25.688345 | 14.311655 | 0.177232 | 0.583104 | 0.340010 |
| **Average Error [mm]:** | 0.760336 | **Variance [mm$^2$]:** | 0.206492 | **Standard Deviation [mm]:** | **0.454414** | | | |

Table B.23 Test Results of 15º Slits with 2 MHz Shear Wave Probe of 45º

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 10 | 44.6 | 37.3 | 11 | 30.355312 | 9.644688 | 0.014570 | 0.800217 | 0.640348 |
| 10 | 44.6 | 53 | 11 | 31.306803 | 8.693197 | 0.966061 | 0.151273 | 0.022884 |
| 10 | 42.5 | 39 | 5 | 29.046504 | 10.953496 | 1.294238 | 0.479451 | 0.229873 |
| 10 | 42.5 | 48.6 | 8 | 29.356462 | 10.643538 | 0.984280 | 0.169493 | 0.028728 |
| **Average Error [mm]:** | 0.814787 | **Variance [mm$^2$]:** | 0.230458 | **Standard Deviation [mm]:** | **0.480061** | | | |

Table B.24 Test Results of 15º Slits with 2 MHz Shear Wave Probe of 45º

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 5 | 49.4 | 46 | 5 | 34.926149 | 5.073851 | 0.244222 | 0.728363 | 0.530513 |
| 5 | 49.4 | 55 | 8 | 37.168648 | 2.831352 | 1.998277 | 1.025692 | 1.052044 |
| 5 | 48.9 | 55.7 | 9 | 34.133867 | 5.866133 | 1.036504 | 0.063919 | 0.004086 |
| 5 | 48.9 | 45.5 | 5 | 34.559033 | 5.440967 | 0.611338 | 0.361247 | 0.130500 |
| **Average Error [mm]:** | 0.972585 | **Variance [mm$^2$]:** | 0.429286 | **Standard Deviation [mm]:** | **0.655199** | | | |

**Table B.25** Test Results of 30° Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 20 | 56.3 | 52.7 | 4 | 23.739998 | 16.260002 | 1.060506 | 0.180833 | 0.032701 |
| 20 | 56.3 | 60.4 | 4.5 | 24.031698 | 15.968302 | 1.352206 | 0.472533 | 0.223287 |
| 20 | 55.8 | 51.7 | 4.5 | 22.134226 | 17.865774 | 0.545266 | 0.334406 | 0.111828 |
| 20 | 55.8 | 59 | 3.5 | 23.240204 | 16.759796 | 0.560712 | 0.318960 | 0.101736 |
| **Average Error [mm]:** | 0.879673 | **Variance [mm$^2$]:** | 0.117388 | **Standard Deviation [mm]:** | **0.342619** | | | |

**Table B.26** Test Results of 30° Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 15 | 65 | 67.3 | 2.5 | 25.920770 | 14.079230 | 1.088849 | 0.070797 | 0.005012 |
| 15 | 65 | 60.9 | 4.5 | 25.928945 | 14.071055 | 1.080674 | 0.078972 | 0.006237 |
| 15 | 65.5 | 61 | 5 | 27.548491 | 12.451509 | 0.538872 | 0.620773 | 0.385359 |
| 15 | 65.5 | 67.3 | 2 | 28.939806 | 11.060194 | 1.930187 | 0.770542 | 0.593735 |
| **Average Error [mm]:** | 1.159646 | **Variance [mm$^2$]:** | 0.247586 | **Standard Deviation [mm]:** | **0.497580** | | | |

**Table B.27** Test Results of 30° Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – $x_i$) [mm]:** | **(Average Error – $x_i$)$^2$ [mm$^2$]:** |
| 10 | 74.6 | 70.1 | 5 | 31.517801 | 8.482199 | 0.178055 | 0.837570 | 0.701524 |
| 10 | 74.6 | 90.2 | 17 | 32.570772 | 7.429228 | 1.231026 | 0.215401 | 0.046398 |
| 10 | 75.1 | 70.1 | 5.5 | 30.223294 | 9.776706 | 1.116452 | 0.100827 | 0.010166 |
| 10 | 75.1 | 91.9 | 18 | 29.802778 | 10.197222 | 1.536968 | 0.521343 | 0.271798 |
| **Average Error [mm]:** | 1.015625 | **Variance [mm$^2$]:** | 0.257472 | **Standard Deviation [mm]:** | **0.507417** | | | |

**Table B.28** Test Results of 30° Slits with 4 MHz Shear Wave Probe of 70°

| **Real Probe Angle:** 68.632527° | | **Probe Delay:** 6.50 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 109.8 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – $x_i$) [mm]:** | **(Average Error – $x_i$)$^2$ [mm$^2$]:** |
| 5 | 101.7 | 95.1 | 7 | 32.765863 | 7.234137 | 2.904010 | 1.259942 | 1.587454 |
| 5 | 101.7 | 120.7 | 20 | 34.581504 | 5.418496 | 1.088369 | 0.555699 | 0.308801 |
| 5 | 101.2 | 115.9 | 15.5 | 34.334987 | 5.665013 | 1.334886 | 0.309182 | 0.095594 |
| 5 | 101.2 | 96.1 | 5.5 | 36.918880 | 3.081120 | 1.249007 | 0.395061 | 0.156073 |
| **Average Error [mm]:** | 1.644068 | **Variance [mm$^2$]:** | 0.536981 | **Standard Deviation [mm]:** | **0.732790** | | | |

**Table B.29** Test Results of 30° Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 20 | 32.9 | 31 | 2.5 | 20.749144 | 19.250856 | 1.930348 | 0.640319 | 0.410009 |
| 20 | 32.9 | 35 | 3 | 24.221473 | 15.778527 | 1.541981 | 0.251953 | 0.063480 |
| 20 | 32.8 | 30.8 | 3 | 23.675937 | 16.324063 | 0.996445 | 0.293584 | 0.086191 |
| 20 | 32.8 | 34.6 | 2.5 | 23.370832 | 16.629168 | 0.691340 | 0.598688 | 0.358428 |
| **Average Error [mm]:** | 1.290029 | **Variance [mm$^2$]:** | 0.229527 | **Standard Deviation [mm]:** | **0.479090** | | | |

**Table B.30** Test Results of 30° Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 15 | 38.2 | 40.5 | 3 | 25.246122 | 14.753878 | 1.763497 | 0.274273 | 0.075226 |
| 15 | 38.2 | 36.3 | 3 | 28.803615 | 11.196385 | 1.793996 | 0.304772 | 0.092886 |
| 15 | 38.2 | 36 | 3 | 25.202525 | 14.797475 | 1.807094 | 0.317869 | 0.101041 |
| 15 | 38.2 | 40.8 | 3.5 | 26.417309 | 13.582691 | 0.592310 | 0.896915 | 0.804456 |
| **Average Error [mm]:** | 1.489224 | **Variance [mm$^2$]:** | 0.268402 | **Standard Deviation [mm]:** | **0.518075** | | | |

**Table B.31** Test Results of 30° Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error (x) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 10 | 44.6 | 42 | 3.5 | 28.963500 | 11.036500 | 2.376246 | 0.863526 | 0.745677 |
| 10 | 44.6 | 47.4 | 4 | 32.819506 | 7.180494 | 1.479760 | 0.032960 | 0.001086 |
| 10 | 44.3 | 41.7 | 4 | 32.641806 | 7.358194 | 1.302060 | 0.210660 | 0.044378 |
| 10 | 44.3 | 47.5 | 4.5 | 32.232560 | 7.767440 | 0.892814 | 0.619906 | 0.384284 |
| **Average Error [mm]:** | 1.512720 | **Variance [mm$^2$]:** | 0.293856 | **Standard Deviation [mm]:** | **0.542085** | | | |

**Table B.32** Test Results of 30° Slits with 4 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 4.70 microseconds | | **Probe Index:** 14 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error (x) [mm]:** | **Absolute (Average Error − x) [mm]:** | **(Average Error − x)$^2$ [mm$^2$]:** |
| 5 | 50.2 | 47.6 | 3.5 | 32.715134 | 7.284866 | 2.954739 | 1.215982 | 1.478613 |
| 5 | 50.2 | 52.8 | 3.5 | 34.456763 | 5.543237 | 1.213110 | 0.525647 | 0.276305 |
| 5 | 50.3 | 53.3 | 4 | 34.236932 | 5.763068 | 1.432941 | 0.305816 | 0.093523 |
| 5 | 50.3 | 48 | 3.5 | 37.024111 | 2.975889 | 1.354238 | 0.384519 | 0.147855 |
| **Average Error [mm]:** | 1.738757 | **Variance [mm$^2$]:** | 0.499074 | **Standard Deviation [mm]:** | **0.706452** | | | |

**Table B.33** Test Results of 30° Slits with 2 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 20 | 33 | 29.5 | 5 | 22.245435 | 17.754565 | 0.434057 | 0.780687 | 0.609472 |
| 20 | 33 | 37.7 | 6 | 21.894354 | 18.105646 | 0.785138 | 0.429606 | 0.184562 |
| 20 | 34.4 | 31.7 | 4 | 24.340186 | 15.659814 | 1.660694 | 0.445950 | 0.198872 |
| 20 | 34.4 | 39.6 | 7 | 24.658579 | 15.341421 | 1.979087 | 0.764343 | 0.584220 |
| **Average Error [mm]:** | 1.214744 | **Variance [mm$^2$]:** | 0.394281 | **Standard Deviation [mm]:** | **0.627918** | | | |

**Table B.34** Test Results of 30° Slits with 2 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error – x) [mm]:** | **(Average Error – x)$^2$ [mm$^2$]:** |
| 15 | 38.9 | 43.9 | 6.5 | 26.371765 | 13.628235 | 0.637854 | 0.722670 | 0.522252 |
| 15 | 38.9 | 35 | 5.5 | 25.981818 | 14.018182 | 1.027801 | 0.332723 | 0.110705 |
| 15 | 39.6 | 35.6 | 5.5 | 25.737591 | 14.262409 | 1.272028 | 0.088497 | 0.007832 |
| 15 | 39.6 | 44.2 | 6.5 | 29.514033 | 10.485967 | 2.504414 | 1.143890 | 1.308484 |
| **Average Error [mm]:** | 1.360524 | **Variance [mm$^2$]:** | 0.487318 | **Standard Deviation [mm]:** | **0.698082** | | | |

**Table B.35** Test Results of 30° Slits with 2 MHz Shear Wave Probe of 45°

| **Real Probe Angle:** 44.488288° | | **Probe Delay:** 5.60 microseconds | | **Probe Index:** 13 mm | | **Measured Backwall Echo Sound Travel Distance:** 56.1 mm | | |
|---|---|---|---|---|---|---|---|---|
| **Slit Length [mm]** | **Measured Sound Travel Distance (%80 SH) ($h_{s1}$) [mm]:** | **Measured Sound Travel Distance (%40 SH) ($h_{s2}$) [mm]:** | **Distance btw Measurement Points (S) [mm]:** | **Calculated Depth [mm]:** | **Calculated Slit Height (d) [mm]:** | **Calculated Error ($x_i$) [mm]:** | **Absolute (Average Error − $x_i$) [mm]:** | **(Average Error − $x_i$)$^2$ [mm$^2$]:** |
| 10 | 45.8 | 41.4 | 6 | 29.572047 | 10.427953 | 1.767699 | 0.098629 | 0.009728 |
| 10 | 45.8 | 52.3 | 8 | 28.499007 | 11.500993 | 2.840739 | 1.171669 | 1.372808 |
| 10 | 45 | 41.1 | 5.5 | 30.293293 | 9.706707 | 1.046453 | 0.622617 | 0.387652 |
| 10 | 45 | 51.6 | 8.5 | 30.318357 | 9.681643 | 1.021389 | 0.647681 | 0.419491 |
| **Average Error [mm]:** | 1.669070 | **Variance [mm$^2$]:** | 0.547420 | **Standard Deviation [mm]:** | **0.739878** | | | |

# APPENDIX C

# TECHNICAL DRAWING OF TEST BLOCKS

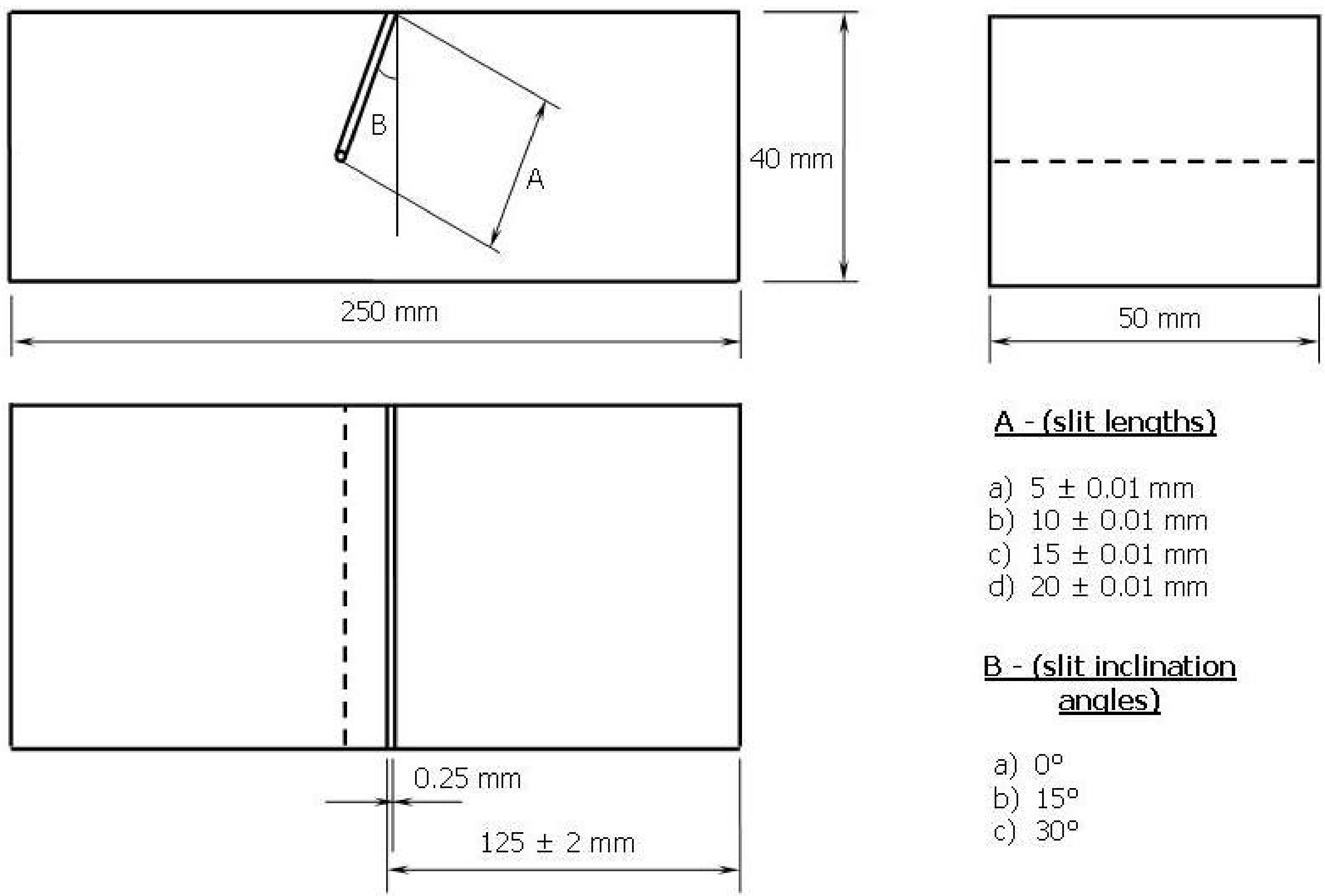


**Figure C.1** Technical Drawing of Test Blocks

# APPENDIX D

# TECHNICAL DRAWINGS OF PLEXIGLAS WEDGES

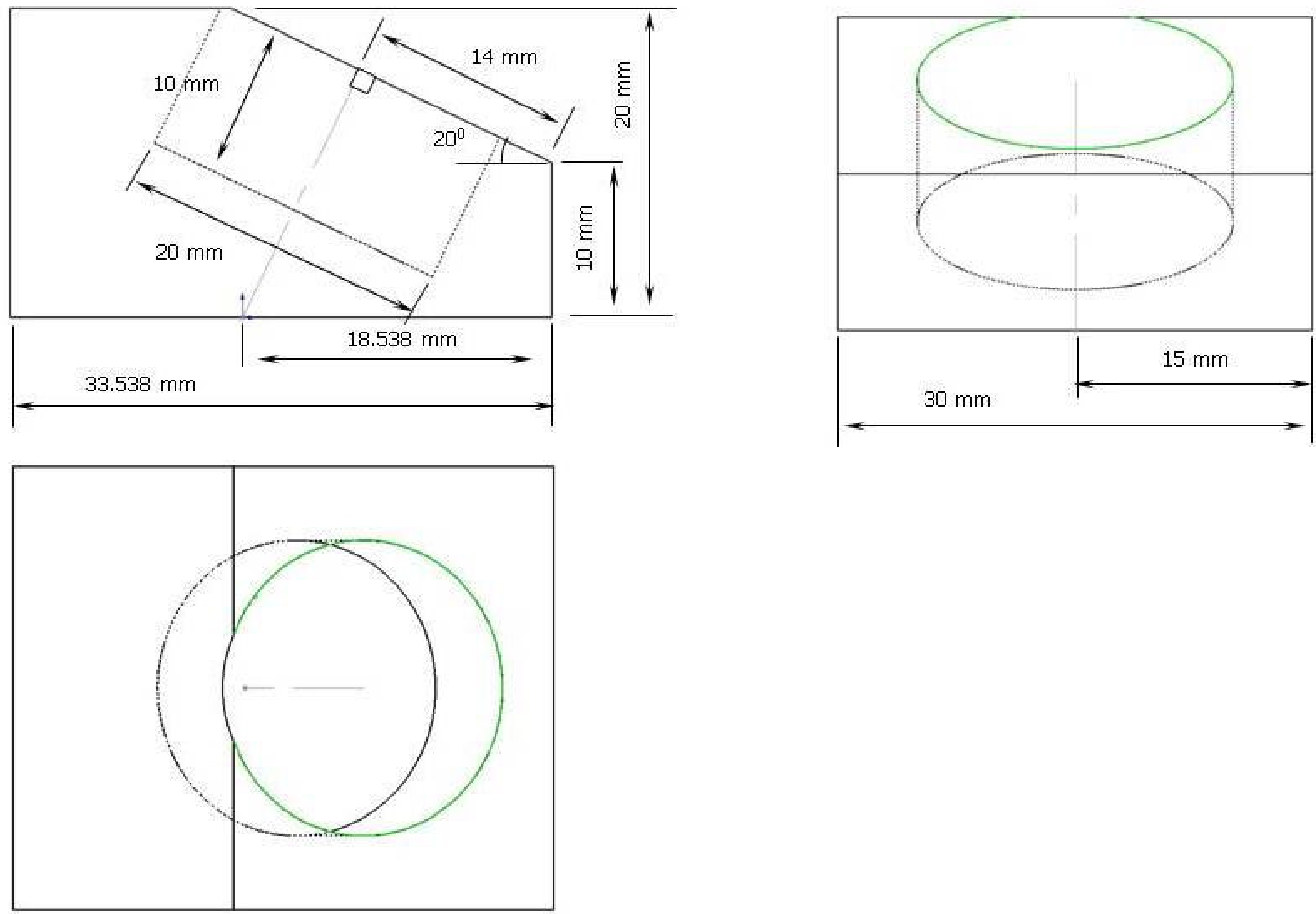


**Figure D.1** Technical Drawing of 45° Plexiglas wedge

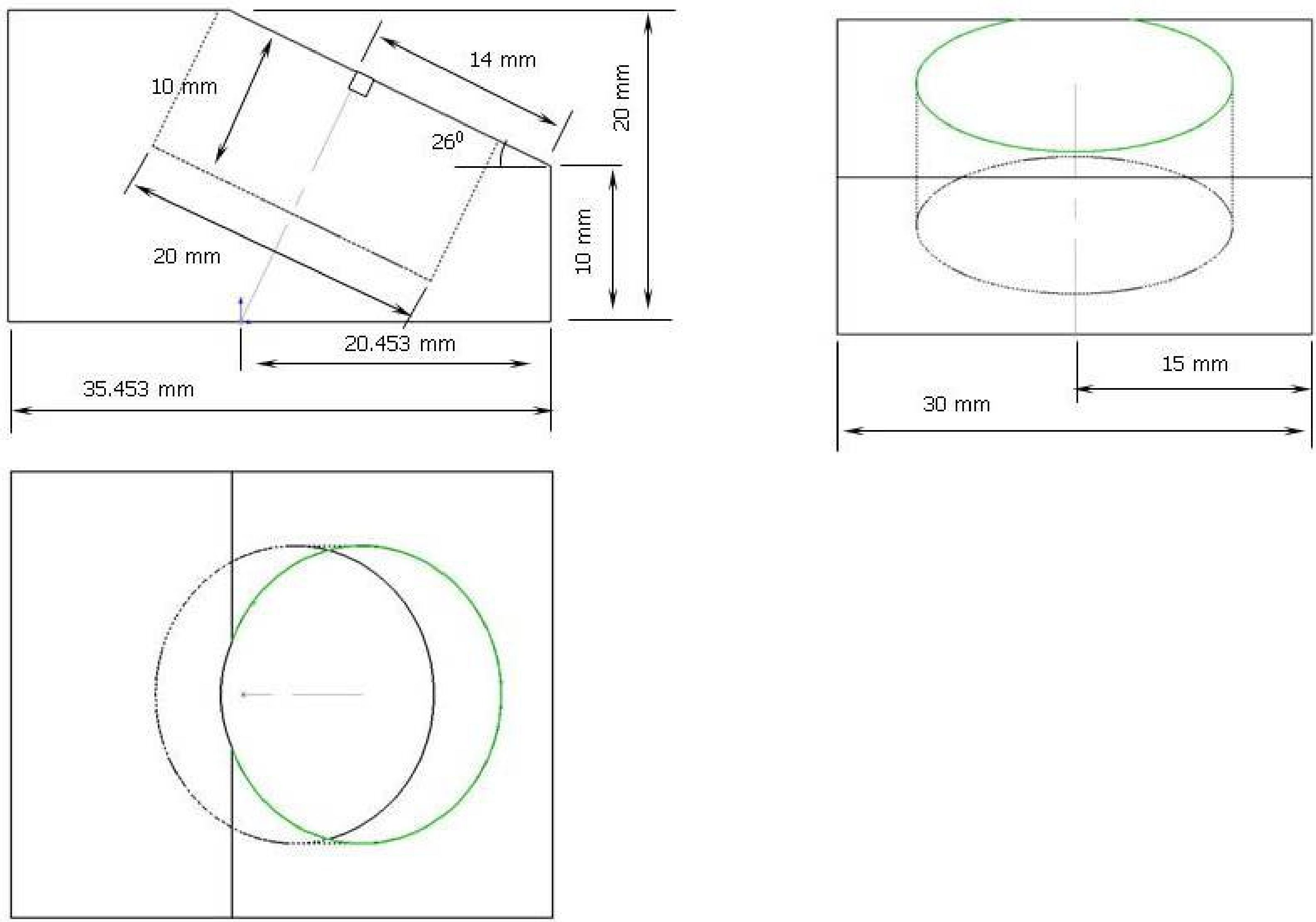


**Figure D.2** Technical Drawing of 70º Plexiglas wedge

## REFERENCES


[1] Charlesworth, J.P., Temple, J.A.G., *Engineering Applications of Ultrasonic Time of Flight Diffraction*, 2nd ed., Research Studies Press Ltd., Baldock, Hertfordshire, England, 2001

[2] Halmshaw, R., *Non-Destructive Testing*, 2nd ed.,

[3] K.J. Marsh, R.A. Smith, R.O. Ritchie, *Fatigue Crack Measurement, Techniques and Applications*

[4] Lamble, J.H., *Principles and Practice of Non-Destructive Testing*

[5] Sharpe, R.S., *Research Techniques in Non-Destructive Testing*

[6] Doyum, B., ME 450 Class notes

[7] Kavrak, M.A., *Ucak Bakiminda Tahribatsiz Kontrol Yontemleri*

[8] Serensen, S.V., Garf, M.E., Kuz'menko, V.A., *The Dynamics of a Fatigue-Testing Machine*

[9] Lawson, S., *Ultrasonic Testing and Image Processing for in-progress weld inspection,*http://www.surrey.ac.uk/eng/research/mechatronics/robots/People/mes3sl/UTpaper/paper.html

[10] Sanford, R.J., Principles of Fracture Mechanics, Pearson Education, Inc., NJ, USA, 2003

[11] Baby, S., Balasubramanian, T., Pardikar, R.J., *Estimation of the height of surface breaking cracks using ultrasonic timing methods,* In: The 6th International Conference of the Slovenian Society for Non-Destructive Testing, September 13-15, 2001, Portoroz, Slovenia

[12] Silk, M.G., Lidington, B.H., *The Potential of scattered or diffracted ultrasound in the determination of crack depth,* Journal of Non-Destructive Testing, pp.146-151, June 1975

[13] Date, K., Shimada, H., Ikenaga, N., *Crack height measurement – an evaluation of the accuracy of ultrasonic timing methods,* Journal of NDT International, pp.315-318, December 1982

[14] British Standard: Guide to Calibration and setting-up of the ultrasonic time of flight diffraction (TOFD) technique for the detection, location and sizing of flaws, BS 7706:1993

[15] Wüstenberg, H., Erhard, A., *Matching of ultrasonic flaw sizing methods to the defect type and location,* Journal of Nuclear Engineering and Design, Vol.81, pp.315-323, 1984

[16] Lidington, B.H., Saunderson, D.H., Silk, M.G., *Interference effects in the reflection of ultrasound from shallow slits,* Journal of Non-Destructive Testing, pp. 185-190, August 1975

[17] Silk, M.G., Lidington, D.H., *A preliminary study of the effect of defect shape and roughness on ultrasonic size estimation,* Journal of Non-Destructive Testing, pp. 27-31, February 1975

[18] Silk, M.G., Lidington, D.H., *An evaluation of single probe bulk-wave time-delay techniques in sizing cracks in steel*, Journal of NDT International, pp.129-134, June 1977

[19] Klanke, H.P., Wüstenberg, H., *Long term surveillance of turbine shafts by ultrasonics*, Journal of Nuclear Engineering and Design, Vol.130, pp. 333-338, 1991

[20] Pohl, R., Erhard, A., Montag, H. – J., Thomas, H. – M., Wüstenberg, H., *NDT Techniques for railroad wheel and gauge corner inspection,* Journal of NDT&E International, Vol.37, pp.89-94, 2004

[21] Lidington, B.H., Silk, M.G., *A Reappraisal of the variability of ultrasonic transducers,* Journal of Non-Destructive Testing, pp. 204-208, August 1974

[22] Brekow, G., Wüstenberg, H., *Non-Destructive inspection of nozzle inner corner at boiling water reactor pressure vessels with ultrasonic flaw detection and crack depth determination,* Journal of Nuclear Engineering and Design, Vol.87, pp.175-184, 1985

[23] Möhrle, W., Schulz, E., *Phased array concept for the ultrasonic inservice inspection of the spherical bottom of BWR-Pressure vessels*, Journal of Nuclear Engineering and Design, Vol.112, pp. 105-114, 1989

[24] Erhard, A., Wüstenberg, H., Schenk, G., Möhrus, W., *Calculation and construction of phased array UT probes,* Journal of Nuclear Engineering and Design, Vol.94, pp. 375-385, 1986

[25] Wüstenberg, H., Schulz, E., Erhard, A., *Fundamental influences on the ultrasonic inspection at cladded nuclear components,* Journal of Nuclear Engineering and Design, Vol.88, pp. 35-47, 1985

[26] Bray, D.E., Stanley, R.K., *Non Destructive Evaluation – A tool for design, manufacture and Service*

[27] Hanstock, R.F., *Non Destructive Testing – Views, Reviews, Previews*

[28] Mahmutyazicioglu, N., *2000'li yillara girerken tahribatsiz muayene faaliyetlerinin ulkemizde ve dunyadaki durumu*, 1st International NDT Symposium & Exhibition, ANKARA, 1999

[29] Doyum, B., Ankara, O.A., Gur, C.H., *ODTU – Kaynak Teknolojisi ve Tahribatsiz Muayene Merkezi'ndeki Uygulamalar, Egitim ve Sinav Faaliyetleri*, 1st International NDT Symposium & Exhibition, ANKARA, 1999

[30] Larsen, Allison, *Small Crack Test Methods*

[31] Höller, P. *New Procedures in NDT*