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StandardGuide for Planar Flaw Height Sizing by Ultrasonics[1]

This standard is issued under the fixed designation E2192; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides tutorial information and a description of the principles and ultrasonic examination techniques for measuring the height of planar flaws which are open to the surface. The practices and technology described in this standard guide are intended as a reference to be used when selecting a specific ultrasonic flaw sizing technique as well as establishing a means for instrument standardization.[2]

1.2 This standard guide does not provide or suggest accuracy or tolerances of the techniques described. Parameters such as search units, examination surface conditions, material composition, etc. can all have a bearing on the accuracy of results. It is recommended that users assess accuracy and tolerances applicable for each application.

1.3 This document does not purport to provide instruction to measure flaw length.

1.4 This standard guide does not provide, suggest, or specify acceptance standards. After flaw-sizing evaluation has been made, the results should be applied to an appropriate code or standard that specifies acceptance criteria.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]
E1316 Terminology for Nondestructive Examinations

3. Terminology

3.1 *Definitions*—Related terminology is defined in Terminology E1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *bi-modal*—ultrasonic examination method that utilizes both the longitudinal (L-wave) and shear (S-wave) modes of propagation in order to estimate or measure flaw height.

3.2.2 *corner reflector*—the reflected ultrasonic energy resulting from the interaction of ultrasound with the intersection of a flaw and the component surface at essentially 90 degrees.

3.2.3 *doublet*—two ultrasonic signals that appear on the screen simultaneously and move in unison as search unit is manipulated toward and away from the flaw. During tip-diffraction flaw sizing, the flaw tip signal and flaw base signal (corner reflector) will appear as a doublet.

3.2.4 *far-surface*—the surface of the examination piece opposite the surface on which the search unit is placed. (For example, when examining pipe from the outside surface the far-surface would be the inside pipe surface).

3.2.5 *focus*—the term as used in this document applies to dual crossed-beam search units that have been manufactured so that they have a maximum sensitivity at a predetermined depth or sound path in the component. Focusing effect may be obtained with the use of dual-element search units having both refracted and roof angles applied to each element.

3.2.6 *near-surface*—the surface of the examination piece on which the search unit is placed. (For example, when examining pipe from the outside surface the near-surface would be the outside pipe surface).

3.2.7 *sizing*—measurement of the through-wall height or depth dimension of a discontinuity or flaw.

3.2.8 *30-70-70*—term that is applied to the technique (and sometimes the search unit) using an incident angle that produces a nominal 70° L wave in the examination piece. Provided that a parallel far-surface exists, the 30° shear wave, produced simultaneously at the refracting interface, reflects as a 30° shear wave and generates a nominal 70° L wave as a result of mode conversion off the far-surface. The 70° L wave reflects off a planar flaw and is received by the search unit as a 70° L wave.

[1] This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.06 on Ultrasonic Method.

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[2] This Standard Guide is adapted from material supplied to ASTM Subcommittee E07.06 by the Electric Power Research Institute (EPRI).

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

4. Summary of Guide

4.1 This guide describes methods for the following flaw sizing techniques.

4.1.1 Far-surface creeping wave or mode conversion method,

4.1.2 Flaw-tip-diffraction method,

4.1.3 Dual element bi-modal method, and

4.1.4 Dual element, (focused) longitudinal wave or dual element, (focused) shear wave methods.

4.2 In this guide, ultrasonic sound paths are generally shown diagrammatically by single lines in one plane that represent the center of the ultrasonic energy.

4.3 Additional information on flaw sizing techniques may be found in the references listed in the Bibliography section.

5. Significance and Use

5.1 The practices referenced in this document are applicable to measuring the height of planar flaws open to the surface that originate on the far-surface or near-surface of the component. These practices are applicable to through-wall sizing of mechanical or thermal fatigue flaws, stress corrosion flaws, or any other surface-connected planar flaws.

5.2 The techniques outlined describe proven ultrasonic flaw sizing practices and their associated limitations, using refracted longitudinal wave and shear wave techniques as applied to ferritic or austenitic components. Other materials may be examined using this guide with appropriate standardization reference blocks. The practices described are applicable to both manual and automated examinations.

5.3 The techniques recommended in this standard guide use Time of Flight (TOF) or Delta Time of Flight (ΔTOF) methods to accurately measure the flaw size. This guide does not include the use of signal amplitude methods to determine flaw size.

5.4 Generally, with these sizing methods the volume of material (or component thickness) to be sized is divided into thirds; the inner ⅓, the middle ⅓ and the outer ⅓ . Using the far-surface Creeping Wave Method the user can qualitatively segregate the flaw into the approximate ⅓ zone.

5.5 The sizing methods are used in ⅓ zones to quantitatively size the crack, that is, Tip-diffraction for the inner ⅓, Bi-Modal method for the middle ⅓, and the Focused Longitudinal Wave or Focused Shear Wave Methods for the outer ⅓ . These ⅓ zones are generally applicable to most sizing applications, however, the various sizing methods have applications outside these ⅓ zones provided a proper reference block and technique is demonstrated.

6. Ultrasonic Flaw Sizing Methods

6.1 *30-70-70 Mode Conversion or Far-surface Creeping Wave Method*—The far-surface Creeping Wave or 30-70-70 Mode Conversion method (as illustrated in Fig. 1) provides qualitative additional depth sizing information. This method has considerable potential for use when approximating flaw size, or, determining that the flaw is far-surface connected.

6.1.1 *Excitation of Creeping Waves*—The excitation of refracted longitudinal waves is always accompanied by refracted shear waves. In the vicinity of the excitation, the separation between these two wave modes is not significantly distinct. At the surface, a longitudinal wave cannot exist independently of a shear wave because neither mode can comply with the boundary conditions for the homogeneous wave equation at the free surface alone; consequently, the so-called headwave is formed. The headwave is always generated if a wave mode with higher velocity (the longitudinal wave) is coupled to a wave mode with lower velocity (the direct shear wave) at an interface. The longitudinal wave continuously energizes the shear wave. It can be concluded that the longitudinal wave, which in fact "creeps" along the surface, is completely attenuated a short distance from the location of the excitation. (See Fig. 2 for generation of the near-side creeping wave). With the propagation of the near-surface creeping wave and its continuous conversion process at each point it reaches, the energy converted to shear is directed into the material as shown in Fig. 3. Thus, the wave front of the headwave includes the head of the creeping wave, direct and indirect shear waves.

6.1.2 *Far-Surface Creeping Wave Generation*—When the headwave arrives at the far-surface of the component, the same wave modes will be generated which were responsible for generating the shear wave energy, due to the physical law of reciprocity. Thus, the indirect shear wave and part of the direct shear wave will convert into a far-surface creeping wave and a 70-degree longitudinal wave. The far-surface creeping wave will be extremely sensitive to small surface-breaking reflectors and the longitudinal wave will be engulfed in a bulk longitudinal beam created by beam spread. Additionally, these reflection mechanisms are responsible for a beam offset so that there

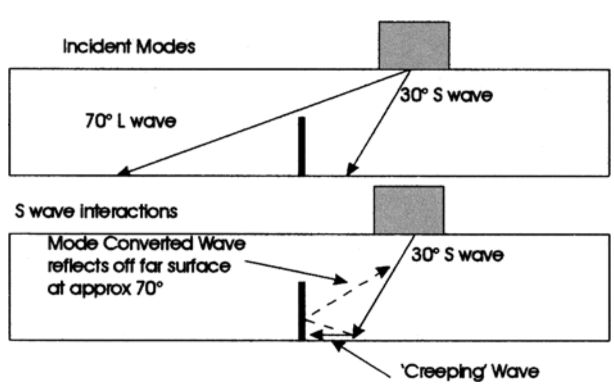


FIG. 1 Wave Generation for the Far-surface Creeping Wave/30-70-70 Mode-Conversion Search Unit

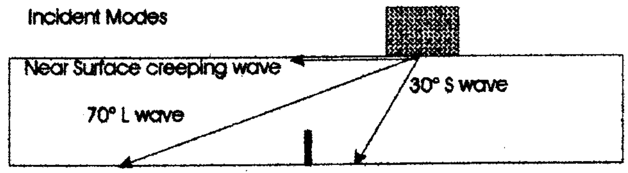


FIG. 2 Near-Surface Creeping Wave Occurs for a Short Distance in Association with the Incident Longitudinal Wave

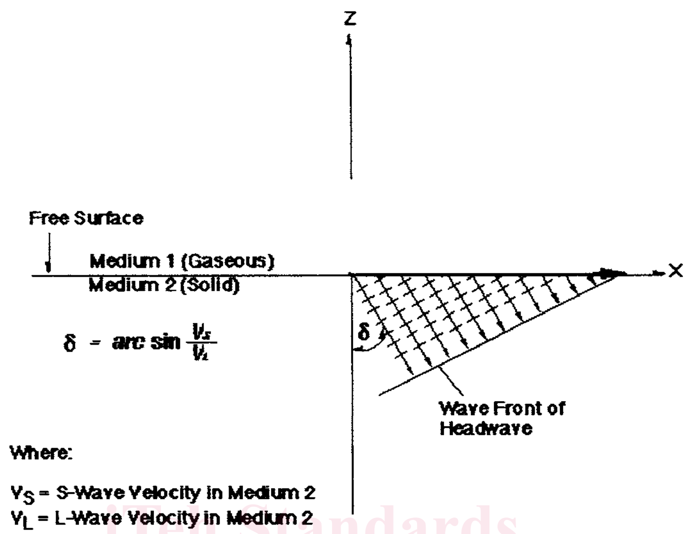


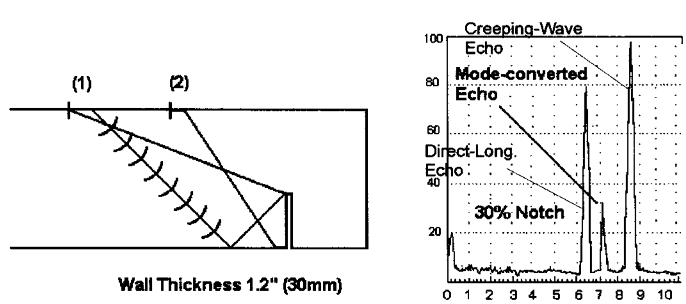
FIG. 3 Generation of S-Waves (Headwaves) by an L-Wave with Grazing Incidence

is a maximum far-surface creeping wave sensitivity at about 5 to 6 mm (0.20 to 0.24 in.) from the ideal conversion point on the far surface. The sensitivity range of the far-surface creeping wave extends from approximately 2 to 13 mm (0.080 to 0.52 in.) in front of the index point. The far-surface creeping wave, as reflected from the base of a far-surface notch or flaw, will convert its energy into a headwave since the same principles apply as established earlier for the near-surface creeping wave. The shear wave will continue to convert at multiple V-paths if the material has low attenuation and noise levels.

6.1.3 *Typical Echoes of the Far-Surface Creeping Wave/30-70-70 Mode Conversion Technique*—When the search unit approaches a far-surface connected reflector, three different signals will occur in sequence: (*1*) 70-degree longitudinal wave direct reflection; (*2*) 30-70-70 mode-converted signal; and (*3*) A far-surface creeping wave signal, as a result of mode conversion of the indirect shear wave.

6.1.3.1 *Direct Longitudinal Wave Signal*—If the flaw extends to within approximately 0.375 to 0.625 in. (9.5 to 15.9 mm) of the scanning surface (near surface), the direct longitudinal wave will reflect from the upper extremity of the flaw face, which is very similar to the high-angle longitudinal wave sizing method discussed later.

6.1.3.2 *Mode Converted Signal*—If the flaw exceeds a height of 10 to 20 % of the wall thickness, an indication from the mode converted signal will occur at a typical wall thickness-related position. This mode converted signal results from the headwave or direct shear wave, which mode converts the 70-degree longitudinal wave that impinges on the reflector at its highest part; it is reflected as a 70-degree longitudinal wave back to the search unit as depicted by position 1 in Fig. 4. The presence of the mode-converted echo is a strong indication of a flaw with a height greater than 10 to 20 % of the wall thickness. In the case of smooth or at least open flaws,



1—Mode-Converted Signal
2—Far-Surface Creeping-Wave Signal

FIG. 4 Search Unit Index Point Position

amplitude versus height function curves can give a coarse estimate of flaw height.

6.1.3.3 *Far-Surface Creeping Wave Signal*—If a far-surface connected reflector is within the range of sensitivity (as described above), the far-surface creeping wave will be reflected and mode converted into the headwave or shear wave directed to the search unit (Fig. 5). Since the far-surface creeping wave is not a surface wave, it will not interact with weld root convexity and will not produce an indication from the root as shown by position 1 in Fig. 6. However, if the search unit is moved too far toward the weld centerline, the direct shear wave beam could result in a root signal, but there is at least 5 mm (0.2 in.) difference in positioning as shown in Fig. 6. The far-surface creeping wave signal is a clear, sharp signal with a larger amplitude than the mode converted signal. It does not have as smooth an echo-dynamic behavior as does the mode converted signal, and it cannot be observed over as long a distance as shown in Fig. 7.

6.2 *Tip-Diffraction Method*—Ultrasonic diffraction is a phenomenon where ultrasound tends to bend around sharp corners or ends of an object placed in its path, as illustrated in Fig. 8. While the flaw tends to cast a shadow, diffraction occurs at the flaw tips and ultrasonic energy is bent to fill part of the shadow region. Sharp edges are diffraction centers tending to radiate spherical or cylindrical wave fronts as though they were actually ultrasonic point or line sources. If the screen signals correlating to these diffraction centers are identified, it is possible to determine their positions relative to the thickness of the component. The tip-diffraction method relies on this principle. Although the tip-diffraction concept sounds simple, there are many other signals that may complicate screen interpretation. This is due to the fact that the ultrasound/planar flaw interaction is very complex. When ultrasound strikes a flaw, specular reflection from the main plane of the flaw and texture reflections from flaw surface facets occur in addition to diffraction and mode conversions. There are two standardization and measuring techniques for tip-diffraction sizing: (*1*) The Time of Flight (TOF) technique that measures the arrival time of the tip-diffracted signal from the top of the flaw and locates the top of the flaw with respect to the near surface; and (*2*) The Delta Time of Flight (ΔTOF) technique that measures the difference in arrival time of the tip-diffracted signal and the corner reflector signal at the far surface.

6.2.1 *Time of Flight (TOF) Sizing Technique*—The TOF sizing technique is a tip-diffraction technique that takes advantage of uniquely locating the flaw tip. The signal from the flaw tip is peaked (maximized), and its arrival time or sound path is measured without regard to the arrival time of other signals. This time of flight or sound path is then a direct measurement of the remaining ligament (material) above the flaw, or the distance from the flaw tip to the examination surface. This technique is illustrated in Fig. 9. Note that here the second half-V path is possible also. When the search unit is moved away from the flaw, the tip echo may again be obtained after the tip-diffracted signal reflects off the opposite surface of the component. With the second half-V path technique, the tip signal will occur later in time than the signal from the flaw corner reflector.

NOTE 1—It is very important that the user be extremely conscious of the weld geometry when using the second half-V path since, for example, the counterbore can exaggerate flaw height.

NOTE 2—Longitudinal waves should not be applied when practicing the second half-V path technique as this can cause mode conversions that may interfere with the ability to interpret the instrument display.

6.2.2 *Delta Time of Flight (ΔTOF) Technique*—The ΔTOF Technique is applied by observing the arrival time difference between the flaw corner reflector signal and the diffracted signal from the flaw tip while both are simultaneously present on the ultrasonic instrument display. While using this technique, the ultrasonic beam diameter must be greater than the projected height of the flaw (actual height multiplied by the sine of the refracted beam angle) and the flaw must be essentially perpendicular to the examination surface. In this situation, the tip-diffracted signal will occur earlier in time due

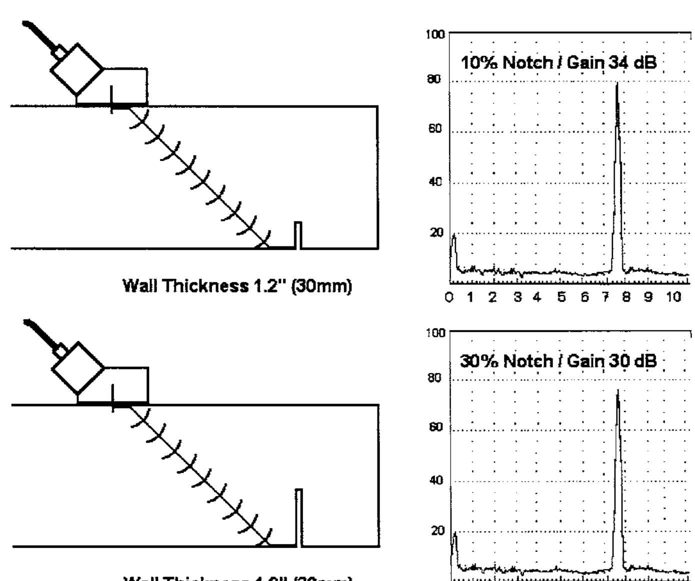
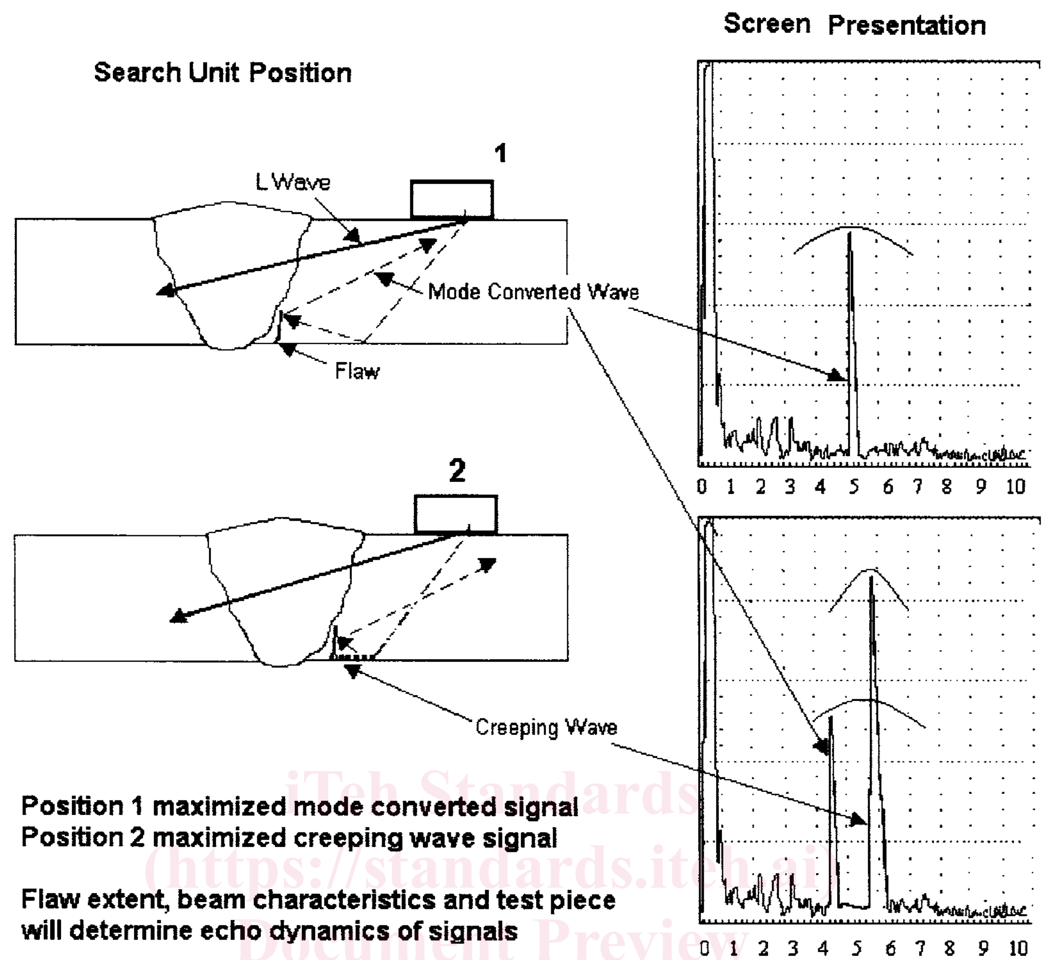


FIG. 5 Generation of Far-Surface Creeping Wave Signal



1—Flaw indication maximized for mode-converted wave signal
2—Flaw indication maximized for creeping-wave signal

FIG. 6 Far-Surface Creeping Wave Search Unit Position Related to Index Point

to its shorter sound path. The tip signal amplitude is very small in comparison to the flaw corner reflector signal; and the flaw tip and corner signals are out of phase due to one signal being diffracted and the other reflected twice. To measure flaw height, it is necessary to note the difference in the time of arrival between the two signals, then apply the following formula:

$$h = \frac{v(\delta t)}{2cos\theta}$$

where:

h = flaw height,
v = ultrasonic velocity in the material,
δt = difference in arrival time, and
θ = refracted beam angle.

Alternately, the ultrasonic instrument may be standardized to read directly in flaw height. This standardization method will be addressed in the standardization section. Separation between the doublets should remain constant as the signals move across the screen. The echo dynamic of the doublet is asynchronous; however, since it is the fixed interval between the doublet arrival times that is measured, it is not necessary to maximize the response from either signal. This technique allows measurement when the weld crown is wide, preventing maximization of the tip signal. It may also be possible to note a tip signal after reflection from the back surface (second half-V path). The principles are the same as for the first half-V path except that the tip signal will appear later in time than the corner reflector signal. Whether using the first or second half-V path, accuracy of the height measurement depends on the flaw orientation. If the flaw is vertical, then the measurement is accurate. If the flaw is oriented toward the search unit, the first half-V path measurement will overestimate the height and the second half-V path measurement will underestimate the height. The opposite occurs for flaws oriented away from the search unit.

6.2.3 *Application Considerations*—For all of the physics involved in tip diffraction, the method relies on the user's ability to uniquely identify the location of the flaw tip. The signal need not originate singly from diffraction, since reflection can also occur very near the flaw tip. In fact, reflection is the mechanism that will primarily be observed when using notched reference blocks. It is reasonable to expect some reflection to occur at an actual flaw tip. The associated rough texture will often act as a good scattering center. It should be noted, however, that this may not be true in every case and the

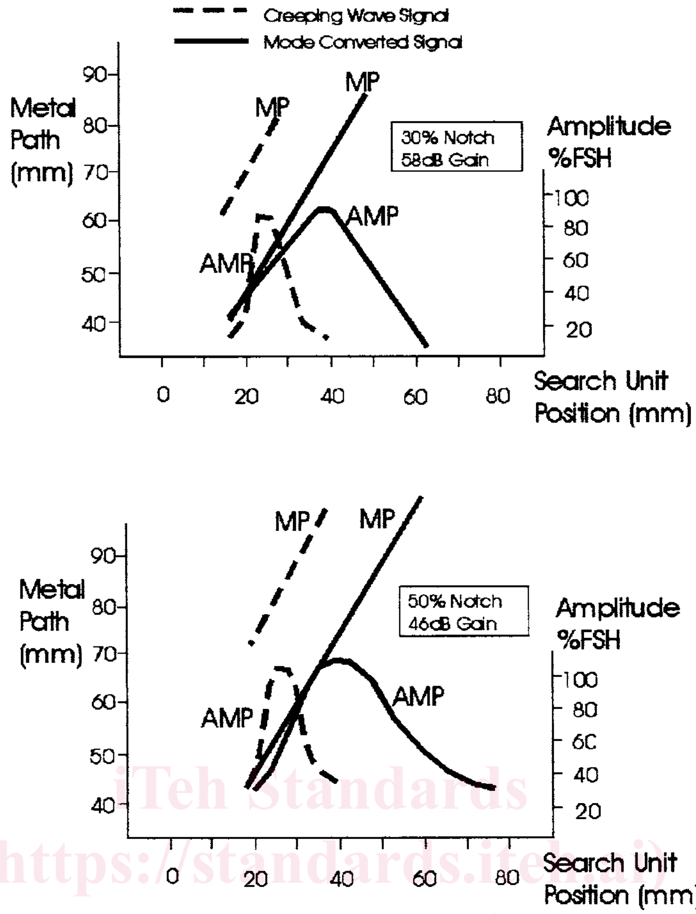


FIG. 7 Echo-Dynamic Behavior of Mode-Converted Echo Signal and Far-Surface Creeping-Wave Signal

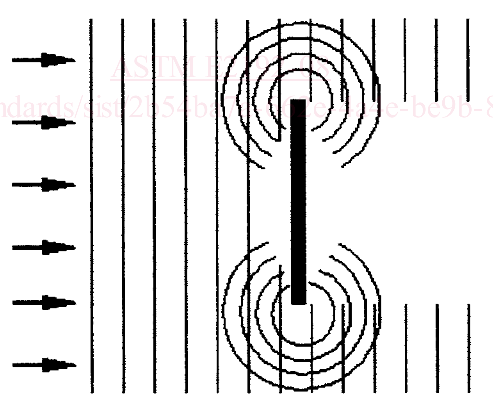


FIG. 8 Corners or Ends of Reflectors are Diffraction Centers and Tend to Radiate Spherical or Cylindrical Waves

amplitudes of the signals received may be 20-30 dB below the flaw corner-reflector signal amplitude. Each component and material type examined should be considered as a separate examination problem. The flawed area should be adequately scanned so that all signals, which occur in the region, can be identified. Care should be taken to define the tip signal since some geometries or weld flaws produce signals that can be readily confused with the true tip signal. Some flaws produce multiple tip signals that must be resolved. The ability of the operator to distinguish between tip and corner signals can be compromised if several cracks are clustered in the same area. In areas of clustered cracks, corner reflections will dominate and mask tip signals. In cases of clustered cracks, the depth of the peaked signal may be the only reliable means to distinguish the tip signals from the corner signals. The tip-diffraction methods can be valid for a wide range of flaw heights. The prerequisites are that the tip of the flaw and the tip signal be distinguishable from other signals. For very shallow flaws, the tip signal may be masked by the flaw corner-reflector signal due to poor resolution. A search unit with a shorter pulse duration will improve this limitation. Broadband search units have been noted for their short pulse durations; however, due to dispersion in austenitic stainless steel weld metal, it may be beneficial to select a narrow-band search unit with greater

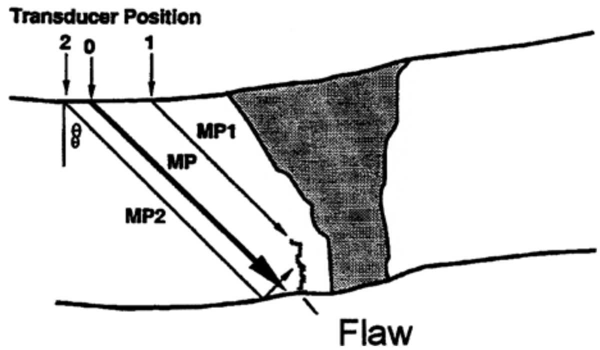
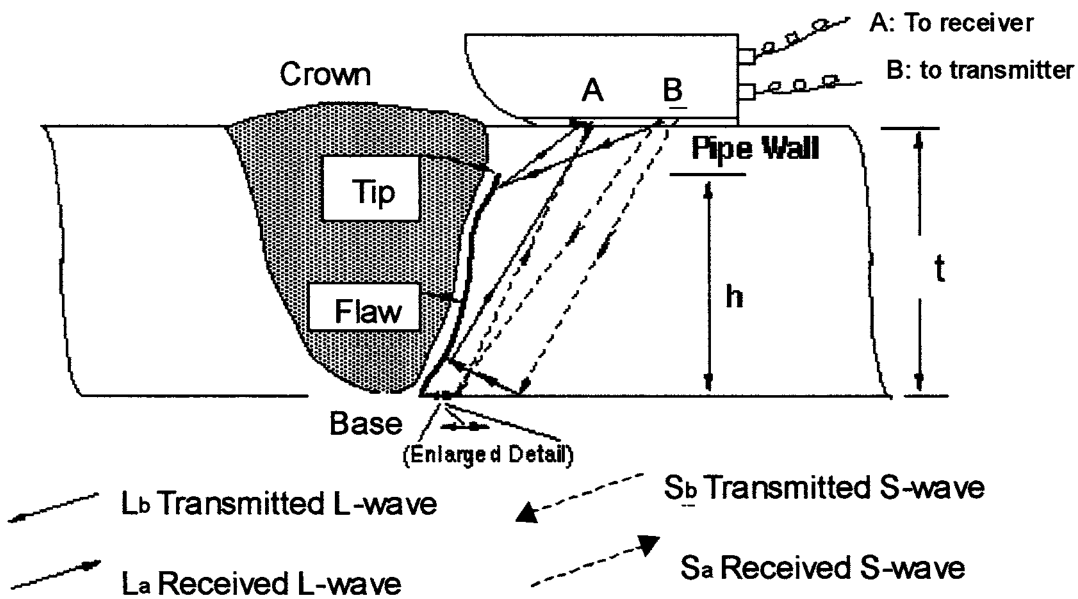


FIG. 9 Various Metal Paths (MP) from Different Search Unit Positions Used in the TOF Technique

penetrating characteristics. This argument holds true for very deep flaws also. When the flaw is located in the weld region or very near the weld region, longitudinal waves may be considered for the tip-diffraction method. Longitudinal waves may help locate weak tip-diffracted signals in highly attenuative stainless steel but reflection from the component far surface should be avoided due to mode conversion. A very important factor in the sizing of planar flaws using the tip-diffraction method is signal pattern recognition. To size with this method, the user must be able to identify two signals: (*1*) a signal that is diffracted from the flaw tip and (*2*) a second signal that is reflected from the base of the flaw. The task of identifying the two signals is complicated by the high-amplitude noise signals and geometric signals from the component surface. Some ultrasonic instruments allow the user the option of using the un-rectified or rectified display (RF display) signals. In many cases, an RF display facilitates in distinguishing the tip signal from noise signals by identifying the phase of the signals. The signal from the tip of the flaw must always peak when the search unit is moved forward from the point where the corner signal is maximized (for first half-V path) or backed up from the point where the corner signal is maximized (for second half-V path). This distance traveled is directly related to flaw height. The examiner must become accustomed to the search unit movement as it relates to flaw height by becoming familiar with the characteristics observed when sizing notches of known heights.

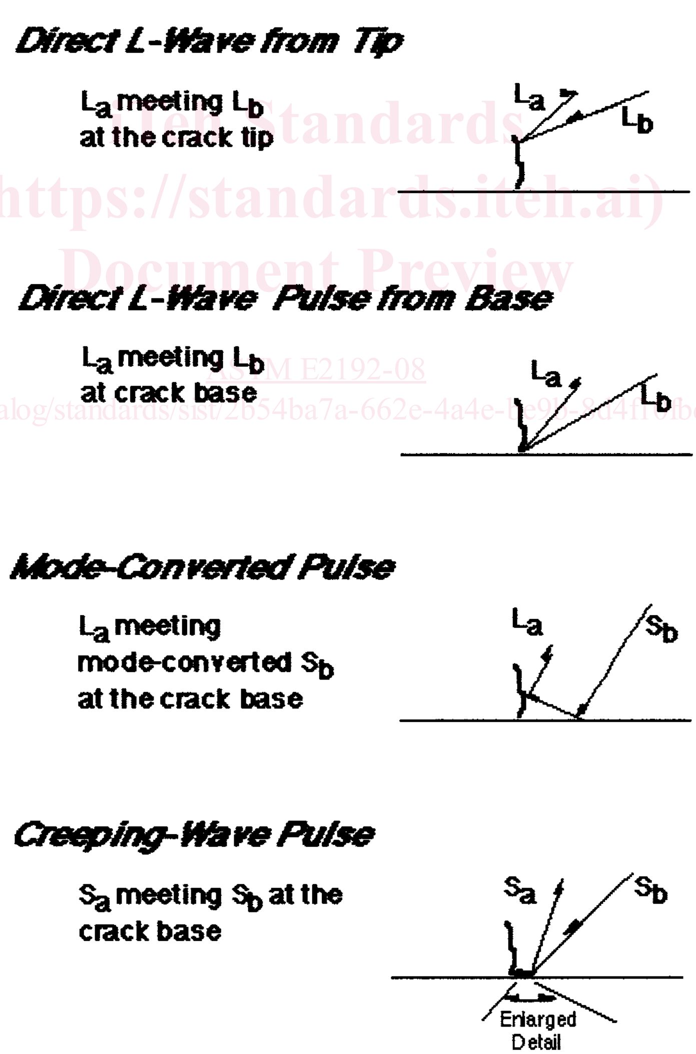
6.3 *Dual-Element Bi-Modal Method*—The Bi-Modal Sizing Method is based on the use of a dual-element search unit. This dual-element search unit is designed to insonify the entire wall thickness by transmitting and receiving high-angle refracted longitudinal waves as well as low-angle shear waves. For this reason, the Bi-Modal sizing methods that feature the dual-element search unit are applicable to far-surface connected planar flaws from 10 to 90 % through-wall. The TOF technique requires that the first signal, the longitudinal wave, be maximized or peaked and the peaked first signal is measured along the instrument time base which is standardized in through-wall depth. The ΔTOF technique is particularly useful because the flaw height-related separation between the direct longitudinal wave and mode-converted signal can be measured before the search unit is restricted by the weld crown. For the ΔTOF technique, both measurements are independent of signal amplitudes. A20 % far-surface notch and an 80 % far-surface notch are sufficient to standardize the time base for components in the thickness range of 10 to 40 mm (0.4 to 1.6 in.). Flaw height may then be read directly on the screen in percent of wall thickness. The extent of the flaw is indicated by the signals that are observed in the left half of the instrument screen. The further the direct longitudinal wave is peaked, or the greater the separation of the signals from the mode-converted signal, or peaks from mid-screen, the deeper the flaw. Signals originating from the interaction of shear waves with the base of the flaw, with or without mode conversion, are confined to the right half of the instrument screen and merely indicate that the flaw is far-surface connected.

6.3.1 *Wave Propagation Through the Material*—It is acknowledged that shear waves cannot interact effectively with the upper extremities of tight and branched, medium to large flaws that are located near the sound-scattering fusion lines of austenitic welds. These may not produce readily recognizable tip-diffracted signals for flaw sizing purposes. The Bi-Modal search unit is designed specifically for austenitic weld examination, however, this is also applicable to carbon steel materials. As shown in Fig. 10, the Bi-Modal search unit transmits one longitudinal wave, and two shear waves and receives two longitudinal waves (one from the tip of the flaw and one from the base of the flaw), one mode-converted signal from the flaw face, and one far-surface Creeping wave signal from the base of the flaw when the search unit is operated in its normal dual element mode. Depending upon search unit design, either element can be used as the transmitter or the receiver. The directivity patterns of the Bi-Modal search units are quite broad due to the relatively small active element size and low operating frequency in the region of 3 MHz. Therefore, the high-angle longitudinal waves and the low-angle shear waves insonify the entire component wall thickness. Four associated signals that move together on the instrument screen can be expected when the search unit is scanned over a far-surface connected flaw with broad back-and-forth movements, (Fig. 11). This follows from the premise that while the longitudinal waves interact effectively with both extremities of the flaw (the tip and the base), the shear waves interact only with the flaw base. The first signal originates from the upper tip of the flaw. If each element were a transmitter, the longitudinal wave energy from the two elements would converge to this area. The usually weak tip-diffracted signal is enhanced while the background of irrelevant indications is



Subscript 'a' denotes travel to the receiver and subscript 'b' denotes travel from the transmitter. Enlarged detail note refers to Fig. 11.

FIG. 10 Bi-Modal Search Unit Longitudinal Wave and Shear Wave Signals



Subscripts as in Fig. 10.

FIG. 11 Interaction of the Incident L-Wave and S-Wave from a Bi-Modal Search Unit with a far-surface Connected Flaw Resulting in Four Associated Signals

suppressed by restricting the longitudinal wave beams to the upper flaw tip area. The next signal can sometimes be observed from a flaw and is usually observed from a far-surface notch as a result of the longitudinal wave from the transmitter reflecting at the flaw base and being received as a longitudinal wave by the receiver. The third signal is usually the strongest because it results from the mode-converted shear wave from the face of the flaw. The reflection of the incident shear wave at the flaw opening results in the fourth signal which is analogous to the far-surface creeping wave signal. The echo-dynamic curve is broadest for the longitudinal wave signal and narrowest for the creeping wave signal as shown in Fig. 12. The mode-converted signal peaks shortly after the flaw is insonified. It follows from geometrical considerations that the echo-dynamic curves for the longitudinal wave signal and the far-surface creeping wave signal are nearly synchronous for a large flaw (that is, the rise in the amplitude of one signal is in unison with the amplitude rise of the other). When the center of the incident longitudinal wave beam is directed toward the flaw tip, the center of the incident shear wave beam is directed toward the flaw base, and the amplitude of the longitudinal wave signal, as well as that of the far-surface creeping wave signal, is maximized. Upon moving the search unit closer to the flaw, the longitudinal wave signal will again recede into the background of irrelevant indications. To determine the arrival time of this signal, the user typically moves the search unit toward the flaw until the amplitude drops.

6.3.2 *Principles of Bi-Modal TOF Technique*—Weld crown permitting, the search unit may be moved toward the weld far enough to peak the longitudinal wave signal. Fig. 13 shows that the relationship between the signal arrival time in screen divisions and the flaw height in percent of wall thickness is very nearly linear and independent of wall thickness.

6.3.3 *Principles of the ΔTOF Technique*—The longitudinal wave signal may be considered as a satellite of the mode-converted signal since their separation, measured in screen divisions, is practically independent of the axial coordinate of the search unit relative to that of the flaw. Figs. 14 and 15 illustrate the nearly linear relationship between normalized flaw height and this signal separation. The most useful feature of the Bi-Modal sizing method is that the flaw height can be measured anywhere along the length of the flaw as long as both the longitudinal wave and the mode-converted signals are seen moving in unison on the screen, allowing height measurements to be made even when a wide weld crown is present. A second ΔTOF measurement may sometimes be used to confirm the flaw height. This second measurement is obtained by noting the difference in arrival time of the longitudinal wave signal and the longitudinal wave signal reflected from the flaw base. These two signals also move in unison and form a linear relationship when the flaw is oriented vertically.

6.4 *Focused Longitudinal Wave or Dual-Elements Focused Shear Wave Methods*—The dual-element focused longitudinal or dual-element focused shear wave flaw sizing techniques are essentially the TOF or sound-path measurement techniques with the use of focused longitudinal or shear wave search units, generally greater than 50 % from the far surface in depth. These techniques are particularly suitable for sizing flaws which are mid-wall to very deep. The use of high beam angles results in this technique being the most accurate for very deep flaws. As with the tip-diffraction method, the signal from the flaw tip is maximized or peaked and its time of flight or sound path is recorded without regard to the arrival time of other signals. The focused longitudinal wave and focused shear wave sizing techniques are used to measure the remaining ligament of good material between the flaw and the scanning surface. Actual flaw height is obtained by subtracting the remaining ligament from the local wall thickness. Occasionally, the signal associated with the upper extreme of a flaw is due to beam

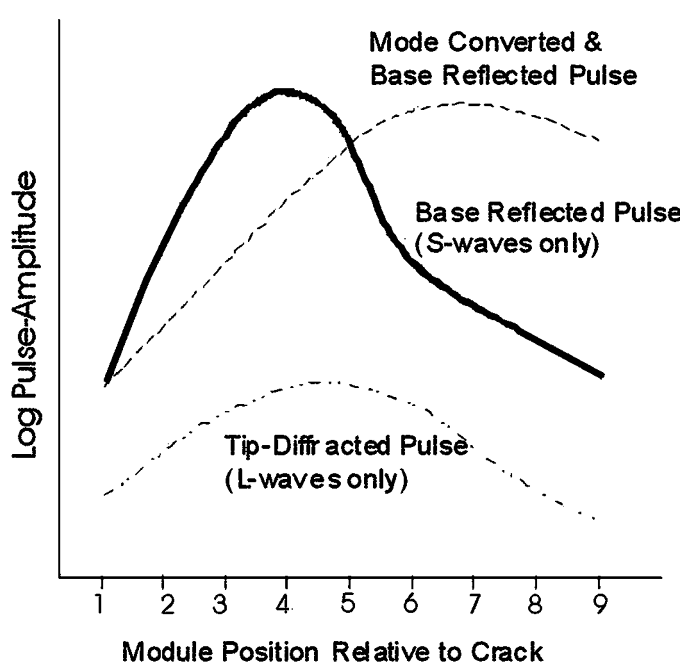


FIG. 12 Asynchronous Echo-Dynamic Curves for a 50 % Deep far-surface Notch

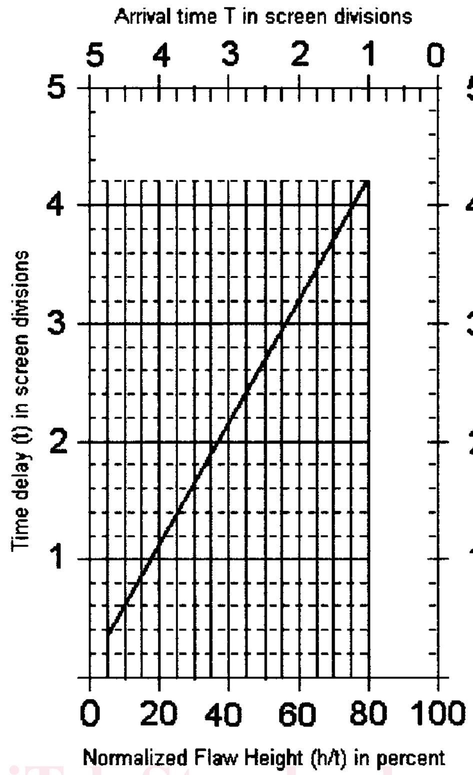


FIG. 13 Correlation of Normalized Flaw Height With Time Delay, τ, Obtained by the Bi-Modal Time of Flight Technique

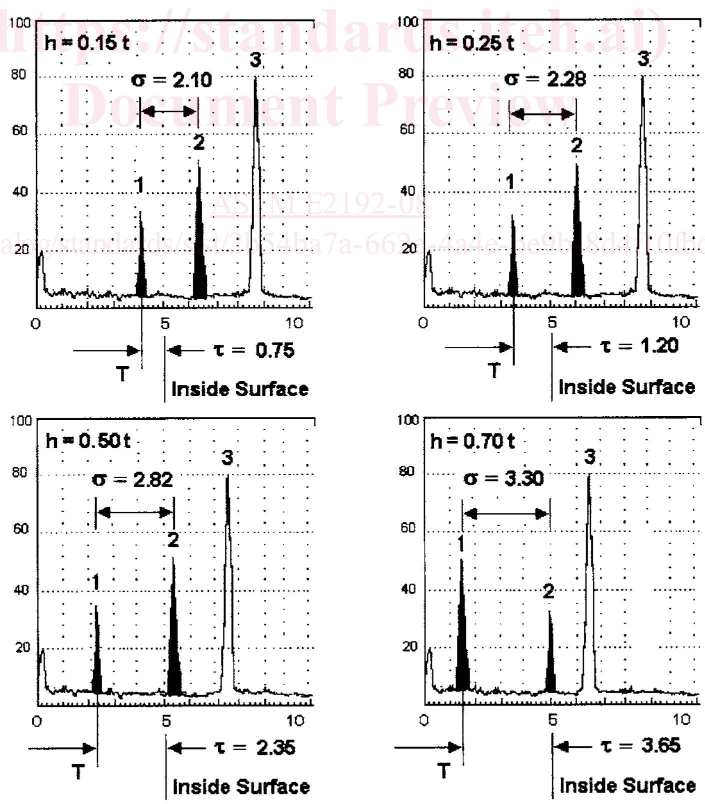


FIG. 14 Relationships Among Normalized Flaw Height, *h/t*, Doublet Separation, σ and Time Delay, τ

reflection rather than diffraction. This is most prevalent when a flaw follows the weld fusion line toward the outside surface of the weld and is oriented away from the weld and the search unit is placed on the weld reinforcement and directed at the flaw. In this case instead of a diffracted wave returning to the search unit, the upper extreme of the flaw face reflects ultrasonic