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CRITERIA FOR THE SELECTION OF FOCUSSING ULTRASONIC PROBES

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16. Abstract

The principles of operation employed in the focusing of a sound field are considered, taking into account the use of solid and liquid coupling media. The focusing limits for a given transducer are investigated. As a diffraction phenomenon, focusing is a function of the system dimensions, the frequency, and the sound velocity. The frequency and the material used for the lenses are in most cases determined in accordance with considerations regarding sound propagation. Changes in the focus are therefore effected mainly by the selection of transducer and lens dimensions. The functions of the focusing factor for a normal immersion probe and a direct contact angle probe are represented in graphs. The deviation of the appropriate parametric values for an ultrasonic probe is illustrated with the aid of examples.

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CRITERIA FOR THE SELECTION OF FOCUSSING ULTRASONIC PROBES

U. Schlengermann

1. Introduction /416*

Ultrasonic testing is viewed as a system designed to provide information on the state of a material or workpiece. The display, processing and evaluation of the data constitute the last link of the information chain and as such are meaningful only if the data has been obtained in an optimal manner. The goal of any attempt to optimize the testing system is always to modify the system so as to increase both the sensitivity of the test and the reliability of the data. One approach is the use of focused sound fields. They greatly improve the ratio of signal to noise, and the interaction between the sound field and reflector can be more easily judged if a sharply-defined sound beam is used.

This improvement has its limits, however. Because sound focusing is a diffraction phenomenon, there are limits both from above (no focusing) and from below (strongest focusing).

We shall present a quantitative description of these limits, and discuss the question of which focusing probes or focused sound fields are optimally suited for a given testing problem.

2. Focusing the Sound Field

The structure of a focused sound field is shown in Fig. 1.

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Here the field is generated by a circular transducer fitted with a spherical lens. The structure shown in Fig. 1 is valid in principle for all focusing systems, however:

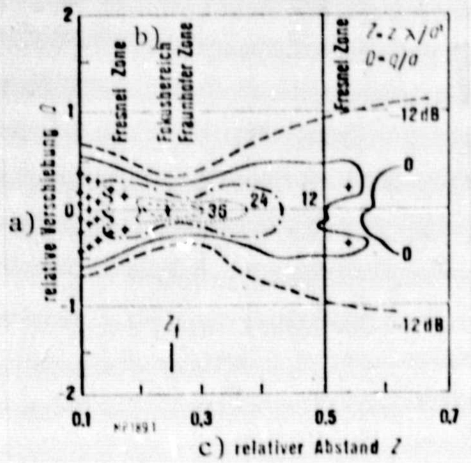

Fig. 1. Measured isobars in a focused sound field for Z_f = 0.25.
Key: a - Relative displacement; b - Focal region; c - Relative distance Z.

-- Close to the transducer is a near field (Fresnel zone) which corresponds to the near field of a nonfocusing probe, except that it is shortened by the focusing factor Z_f [1,2].

-- The focus, or point of highest acoustic pressure, is surrounded by a region which corresponds to the entire far field of the nonfocusing probe.

-- At greater distances from the transducer, another Fresnel zone forms which can be viewed as a mirror image of the near field. The stronger the focus (i.e., the smaller the focusing factor Z_f), the greater the size of this region [1,2].

For various reasons, the Fresnel zones of the sound field must generally be excluded during testing. Surrounding the focus is the working region of the sound field, called the focal region. It is usually defined as the region with a 6-dB loss of echo from a point reflector relative to the focus.

In material testing, it is of interest to know:

-- the longitudinal and transverse dimensions of this region with respect to the acoustic axis, and how these quantities vary with the parameters of the transducer;

-- which sound source produces a focal region suitable for testing a given zone in the material. /417

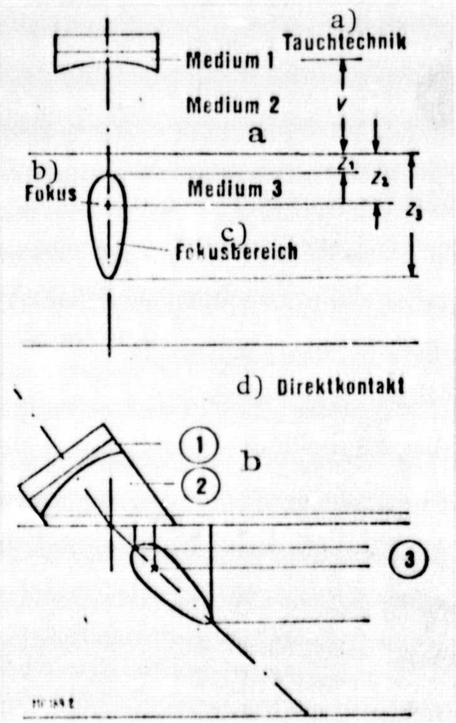

Fig. 2. Focusing with liquid and solid coupling paths.

The shape and position of the focal region (working region) are shown in Fig. 2 for two techniques of sound transmission:

Fig. 2a shows the probe for the immersion technique (here a normal probe), and Fig. 2b a probe for the direct contact method (here an angle probe). Three solid media are employed in direct contact testing, while medium 2 is a liquid in the immersion technique.

The advantage of the immersion method can be readily seen in Fig. 2: By varying the length of the coupling path v between lens and workpiece, the position of the focal region in the workpiece (medium 3) can be varied as desired within certain limits. The direct contact probe, however, can test only that zone for which is was designed.

3. Focusing Limits for a Given Transducer

These limits are best discussed in terms of the change in the focusing factor Z_f and normalized values [2].

The distances are normalized as

$$Z = z\lambda/a^2 \qquad R = r\lambda/a^2. \tag{1}$$

The half beam width b is normalized as

$$B = b/a, \tag{2}$$

where a is the transducer radius, r is the raidus of lens curvature, and λ is the wavelength.

Z_f expresses the degree to which the near field is shortened relative to the unfocused case. It also represents the relative focal distance and describes the beam width b at focal distance z_f:

$$z_f = Z_f a^2/\lambda, \tag{3}$$

$$2b = \text{const } aZ_f \tag{4}$$

(for a 6-dB echo loss, const = 0.514),

where

$$0 < Z_f \leq 1 \tag{5}$$

is always true [2].

In the case of the nonfocusing probe, the end of the near field is located at the distance $z = a^2/\lambda$; hence $Z_f = 1$ for the upper limit in the trivial case where the radius of lens curvature $r = \infty$.

As a diffraction phenomenon, sound focusing is dependent on the dimensions of the system, the frequency of the beam, and the sound velocity [1,2]:

$$Z_f = f(a, r, f, c_1, c_2, c_3). \quad (6)$$

For reasons of sound propagation, the frequency f is usually fixed, as are the materials used for the lens and workpiece. Focusing is then a function mainly of the transducer diameter 2a and the radius of lens curvature r.

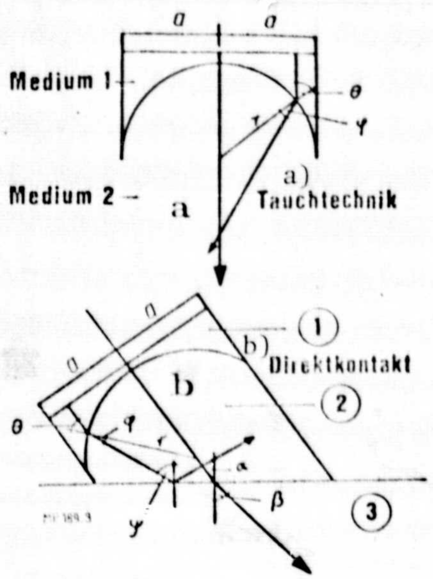

Fig. 3. Focusing limits for the immersion technique and direct contact.

Key: a - Immersion technique; b - Direct contact.

For the desired focusing to be achieved, it is necessary that the entire surface of the transducer emit sound into the workpiece. For conventional immersion probes, this is usually the case if $r \geq a$, as Fig. 3 shows. For direct contact probes, however (Fig. 3b), a total reflection takes place on the workpiece surface below certain values of r, with a consequent indirect decrease in the size of the emitting transducer surface and the occurrence of interfering echos from the lens.

3.1. Immersion Technique

If $c_1 > c_2$, as is the case for conventional lenses, all lens curvatures $r \geq a$ are allowable. The smallest radius is $r_{min} = a$ (Fig. 3a). According to eqn. (1), we thus have

$$R_{min} = \lambda/a \quad (7)$$

for the relative radius R.

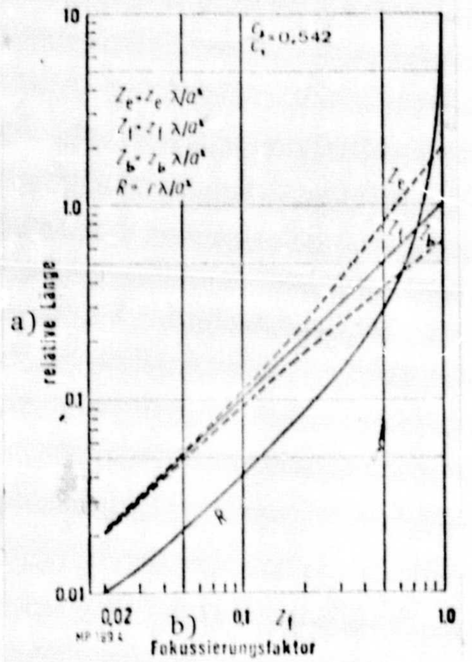

Fig. 4. Functions of the focusing factor Z_f for an immersion probe.

Key: a - Relative length; b - Focusing factor.

The corresponding focusing factor Z_{fmin} can be plotted in a generally valid graph for a constant index of refraction c_2/c_1 for immersion probes, as shown in Fig. 4. The graph also gives the relative distances Z_b for the beginning of the focal region and Z_e for the end of this region as a function of the focusing factor Z_f (calculations after [1]). The width 2b of the sound beam at the focus can also be determined from eqn. (2) with the factor Z_f. The calculation of the upper and lower limits for the length of the working region and the beam width is illustrated in Example 1 (see Appendix).

3.2. Direct Contact Technique

Depending on the media employed (Fig. 3b), the waves from the edge of the transducer in direct contact probes may be unable to penetrate into the workpiece. This must be prevented. The condition for the minimum allowable radius r_{min} is as follows:

$$r_{min} = a/\sin\Theta, \tag{8}$$

where the angle Θ (Fig. 3b) must satisfy the condition:

$$\theta = \frac{c_2}{c_3}\sin\beta \left[\sqrt{1-(\sin\theta)^2}\sqrt{1-\left(\frac{c_2}{c_1}\sin\theta\right)^2} + \frac{c_2}{c_1}(\sin\theta)^2\right] + \sqrt{1-\left(\frac{c_2}{c_3}\sin\beta\right)^2}\left[\sin\theta\sqrt{1-\left(\frac{c_2}{c_1}\sin\theta\right)^2} - \frac{c_2}{c_1}\sin\theta\sqrt{1-(\sin\theta)^2}\right], \tag{9}$$

/418

where β is the incident beam angle in the workpiece.

After normalization, eqn. (8) leads to

$$R_{min} = (1/\sin\theta)\cdot(\lambda/a). \qquad (10)$$

The minimum focusing factor Z_{fmin} for this normalized radius R_{min} can again be determined graphically.

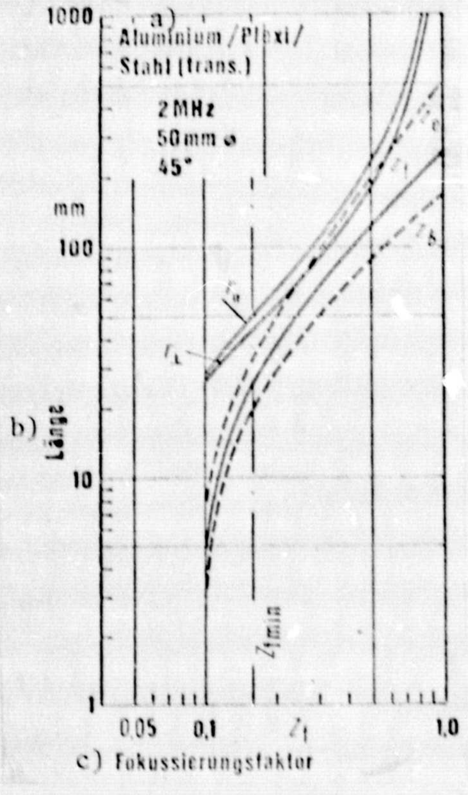

Fig. 5. Functions of the focusing factor Z_f for a direct contact angle probe.

Key: a - Aluminum/Plexiglas/steel (transverse); b - Length; c - Focusing factor.

For direct contact probes, normalization of the graphs is less helpful because the coupling path in the wedge has various relative values depending on the probe and the angle of incidence. In this case it is better to use special graphs like that shown in Fig. 5 for a 2-MHz transverse-wave probe with 2a = 50 mm and β = 45°. This graph was calculated using programs of the BAM [3] for the calculation of direct contact probes. Due to the oblique incidence of the beam, the lens must have different curvatures perpendicular ($\perp$) and parallel ($\|$) to the plane of incidence so that a beam of approximately circular cross-section will be produced in the focal region [3]. The beginning (Z_b) and end (Z_e) of the focal region in the steel are indicated in the graph as projected distances (Fig. 2b), thus making it easier to determine the depth zone tested. The lower focusing limit Z_{fmin} according to eqn. (8)-(10) is also shown.

The factors $1/\sin\Theta$, which are important for judging the focusing of direct contact probes, are given in Table 1 for several 2-MHz probes (0° long. incidence, 45° trans. incidence) currently on the market. The lens material is aluminum/Plexiglas.

Table 1. Important Factors for Judging the Focusing of Direct Contact Probes

a) Schwinger-dmr. $2a$ mm	b) Einschall-winkel β°	$1/\sin\theta$	r_{min} mm	$Z_{f\,min}$
34	0	1,40327	23,86	0,167
	45	1,73712	29,53	0,204
50	0	1,40327	35,08	0,116
	45	1,73712	43,43	0,142
75	0	1,40327	52,62	0,078
	45	1,73712	65,14	0,096
100	0	1,40327	70,16	0,059
	45	1,73712	86,86	0,072

Key: a. Transducer diameter 2a, mm
b. Angle of incidence β°
(Commas in tabulated material are equivalent to decimal points.)

The focusing limits of a direct contact probe are determined in Example 2 (see Appendix).

4. Matching the Focus to the Testing Problem

The graphs in Fig. 4 and 5 for immersion and contact probes make it possible to derive the parameters of the focal region or determine the focusing limits for any probe if the quantities a, r, ξ, c_1, c_2, c_3 are known, eqn. (3), (4) and (6). The problem is more difficult if a suitable focusing probe must be found for a given workpiece, i.e. for a given zone in the object under test or given reflector dimensions.

Often a probe is sought which will just cover a given test zone, in which case secondary conditions are usually made for the coupling distance v or for the transducer diameter 2a or near field length a^2/λ. The zone is covered by the focal region if the beginning of the region Z_b coincides with the beginning of the test zone at distance z_1, and the end of the focal region Z_e is at z_3 (Fig. 6). The parameters on which the value of v or a^2/λ should depend are expressed in generalized form as p and q. We thus obtain the following equation system:

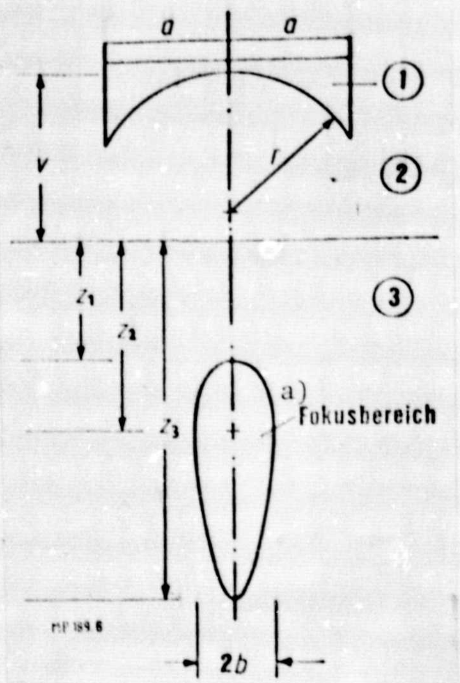

Fig. 6. Matching the focusing to the test problem.

Key: a - Focal region.

$$Z_a N_2 - r = (c_3/c_2) z_1, \tag{11}$$

$$Z_e N_2 - r = (c_3/c_2) z_3, \tag{12}$$

$$N_2 = f(p_1), \tag{13}$$

$$r = g(q_1). \tag{14}$$

This system of four equations can be solved for the two unknowns N and r only if eqn. (15) and (16) are both satisfied:

$$(c_3/c_2)(z_3 - z_1) = f(p_1)(Z_e - Z_a), \tag{15}$$

$$(c_3/c_2)(z_3 Z_a - z_1 Z_e) = g(q_1)(Z_e - Z_a). \tag{16}$$

All quantities necessary for using the focused probe can be derived from these solutions. All the quantities associated with the transducer diameter 2a can be derived from eqn. (15), and the coupling distance v from eqn. (16).

4.1. The Prevention of Interfering Multiple Echos from the Coupling Path

This secondary condition is made in almost every immersion testing problem:

$v > (c_2/c_3)z_3$.

Thus, there should be no interfering echos from the coupling path over the testing region from z_1 to z_3. With eqn. (14) and (17), we obtain the solution: /419

$$\frac{Z_e}{Z_a} < \frac{z_3[1+(c_2/c_3)^2]}{z_1+(c_2/c_3)^2 z_3}. \tag{18}$$

Thus we see that only those factors Z_f are allowed for which Z_e/Z_b satisfies the condition of eqn. (18). Since the function Z_e/Z_b is limited, as Fig. 7 shows, there will be no solution to the problem in certain cases. The necessary transducer radius a is obtained from eqn. (15) with eqn. (13).

$$N_2 = a^2/\lambda_2 = \frac{c_3}{c_2}\left(\frac{z_3 - z_1}{Z_e - Z_a}\right). \tag{19}$$

With eqn. (16) and (14), we obtain the corresponding coupling distance v as:

$$v = \frac{c_3}{c_2}\left(\frac{z_3 Z_a - z_1 Z_e}{Z_e - Z_a}\right). \tag{20}$$

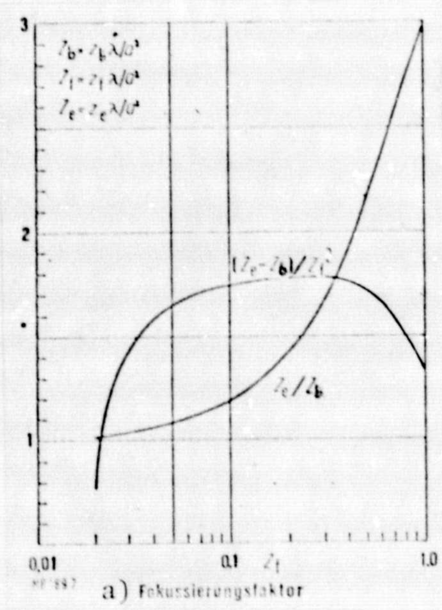

Fig. 7. Functions of the focusing factor Z_f for the immersion technique.
Key: a - Focusing factor.

It is desirable in every case to choose the smallest possible transducer size or the shortest possible coupling path, and thus to select a focusing factor Z_f whose quotient Z_e/Z_b satisfies eqn. (18) with approximate equality. See Example 3 for illustration (Appendix).

4.2. Necessary Beam Width 2b

If the sound field must have a certain lateral resolving power, there is a certain maximum beam width 2b at the focus which must not be exceeded. From eqn. (3) and (4), we thus have

$$N_2 = a^2/\lambda_2 = \frac{4b^2}{k^2 Z_f^2 \lambda_2} \tag{21}$$

for the fall of echo amplitude, where k is a constant.

Using eqn. (15) and (13), we obtain the solution

$$\left(\frac{Z_e - Z_b}{Z_f^2}\right) = \frac{k^2 c_3 (z_3 - z_1)}{4 b^2 f} \tag{22}$$

(for -6dB, k = 0.514).

The function $(Z_e - Z_b)/Z_f{}^2$ is also plotted over Z_f in Fig. 7. This function, too, is limited. The problem at hand can be solved only if a solution to eqn. (22) is possible within this range of values. If there is a solution, it is unique in a and v. These quantities are determined from eqn. (13) through (16) analogously to the case in 4.1. See Example 4 for illustration (Appendix).

4.3. Probe with Minimum Beam Width or Coupling Distance

In section 4.1 it was determined which probes are suitable for covering a specified zone in the workpiece. But it is important to know which of these possible solutions yields the smallest beam width at the focus (and thus the best resolving power) or can be employed with the shortest coupling path possible.

As eqn. (22) shows, the beam width is minimal when the value of $(Z_e - Z_b)/Z_f^2$ is maximal. However, the coupling distance v is minimal according to eqn. (16) when Z_e/Z_b is maximal. Since the latter quantity increases monotonically with Z_f, the coupling distance can be kept small by employing as weak a focus as possible, or in other words by making Z_f as large as possible.

The beam width 2b does not increase monotonically with Z_f, as Fig. 7 shows. The value of $(Z_e - Z_b)/Z_f^2$ is maximal at a focusing factor of 0.3. If the solution $Z_f = 0.3$ is allowed by eqn. (18), this probe will yield the smallest possible beam width which will still cover the zone to be tested.

Thus, from all the solutions which satisfy eqn. (18), one can always select one solution which yields either a small beam width (usually with a large coupling distance) or a small coupling distance (usually with a larger beam width). This is illustrated in Example 5 (see Appendix).

5. Summary

As a diffraction phenomenon, acoustic focusing is dependent on the diameter of the transducer relative to the wavelength. Since only the Fraunhofer region is generally employed for ultrasonic testing, the dimensions that can be achieved for the focal region are a function of the transducer dimensions and the wavelength, or to be more precise, the ratio a/λ. In general, a stronger focus can be achieved with immersion probes than with direct contact probes for the same transducer and frequency.

Matching the focused sound field to the testing problem imposes conditions on the coupling distance v and transducer size 2a which must always be satisfied simultaneously. Graphs like those in Fig. 4 and 7 are a useful aid in finding the solution.

In testing practice, it would naturally be desirable to work with the smallest transducer dimensions and shortest coupling path possible. Some trade-offs must be made, however, and the weakest focus possible (maximum value of Z_f) offers the most favorable solution in practice.

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APPENDIX

Example 1

Given:
f = 5.00 MHz, 2a = 20.00 mm, c_1 = 2.73 km/s (Plexiglas), c_2 = 1.48 km/s (water);

Without focusing:
Z_{fmax} = 1.000, Z_{emax} = 2.000, Z_{bmax} = 0.670 (Fig. 4), z_{amax} = 676.00 mm, z_{bmax} = 226.00 mm eqn. (1), $(z_e - z_b)_{max}$ = 450.00 mm, $2b_{max}$ = 5.14 mm eqn. (4);

Strongest focusing:
R_{min} = 0.0296 eqn. (7), Z_{fmin} = 0.0712, Z_{emin} = 0.0763, Z_{bmin} = 0.0669 (Fig. 4), z_{emin} = 25.78 mm, z_{bmin} = 22.60 mm eqn. (1), $(z_e - z_b)_{min}$ = 3.18 mm, $2b_{min}$ = 0.370 mm eqn. (4).

Example 2

Given:
f = 2.00 MHz, 2a = 50.00 mm, β = 45.00°, c_1 = 6.32 km/s (aluminum), c_2 = 2.73 km/s (Plexiglas), c_3 = 3.25 km/s (steel, trans.);

Without focusing:
Z_{fmax} = 1.0000;

Projected depth level:
z_{emax} = 516.00 mm, z_{bmax} = 168.00 mm, steel, Fig. 5, $(z_e - z_b)_{max}$ = 348.00 mm, $2b_{max}$ = 12.84 mm, eqn. (4);

Strongest focusing:
R_{min} = 0.0948 eqn. (10), r_{min} = 43.43 mm eqn. (1), Z_{fmin} = 0.1420 Fig. 5;

Projected depth level:
z_{emin} = 25.73 mm, z_{bmin} = 15.40 mm steel, Fig. 5, $(z_e - z_b)_{min}$ = 10.33 mm, $2b_{min}$ = 1.824 mm eqn. (4).

Example 3

Given:

f = 2.00 MHz, c_1 = 2.73 km/s (Plexiglas), c_2 = 1.48 km/s (water), c_3 = 5.92 km/s (steel, long.), z_1 = 50.00 mm, z_3 = 80.00 steel;

Calculated:

$Z_e/Z_b < 1.5455$ eqn. (18), $Z_f < 0.2547$ Fig. 7;

Selected:

$Z_f = 0.200 < 0.2547$, $Z_e = 0.244$, $Z_b = 0.171$ Fig. 4, a^2/λ_2 = 1644.00 mm eqn. (15) and (13), a = 34.88 mm, 2a ≈ 70 mm, v = 81 mm eqn. (16) and (14), 2b = 3.58 mm eqn. (4).

Example 4

Given:

f = 2.00 MHz, c_1 = 2.73 km/s (Plexiglas), c_2 = 1.48 km/s (water), c_3 = 5.92 km/s (steel, long.), z_1 = 50.00 mm, z_3 = 80.00 steel;

Required:

2b = 3.64 mm;

Calculated:

$Z_e - Z_b/Z_f^2 = 1.771$ eqn. (22), $Z_{f1} = 0.1908$, $Z_{f2} = 0.3606$ Fig. 7.

Since it is required by Example 3 that $Z_f < 0.2547$, Z_{f2} is not a solution to the present problem. If the testing zone is covered, it is true that the required beam width 2b is present. But the coupling distance v needed for complete coverage is so short that multiple interfering echos arise.

$Z_{e1} = 0.2306$, $Z_{b1} = 0.1644$ Fig. 4, a^2/λ_2 = 1813.00 mm eqn. (15) and (13), a = 36.62 mm, 2a ≈ 74 mm, v = 98.00 mm eqn. (16) and (14), 2b = 3.59 mm eqn. (4).

Example 5

Given:

= 2.00 MHz, c_1 = 2.73 km/s (Plexiglas), c_2 = 1.48 km/s (water), c_3 = 5.92 km/s (steel, long.), z_1 = 50.00 mm, z_3 = 110.00 mm steel;

Calculated:

$Z_e/Z_b < 2.0549$ eqn. (18), $Z_f < 0.4566$ Fig. 7;

Selected:

$Z_{f_1} = 0.4500 < 0.4566$, $Z_{f_2} = 0.3000 < 0.4566$;

Calculated:

$z_{e_1} = 0.6935$, $z_{b_1} = 0.3401$, $z_{e_2} = 0.4031$, $z_{b_2} = 0.2428$, Fig. 4; a_2^2/λ_2 = 679.0000 mm, a_2^2/λ_2 = 1497.0000 mm, eqn. (15) and (13), a_1 = 22.42 mm, a_2 = 33.29 mm, $2a_1 \approx 45$ mm, $2a_2 \approx 67$ mm, v_1 = 31.00 mm, v_2 = 164.00 mm, eqn. (16) and (14), $2b_1$ = 5.19 mm, $2b_2$ = 5.13 mm, eqn. (4).