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The Focusing of the Ultrasonic Phased Array in the Case of Non-contact NDE Methods

O. Tumsys[1], E. Jasiuniene[1]
[1]*Prof. K. Barsauskas Ultrasound Institute, Kaunas University of Technology,*
Studentu St. 50–137, LT-51368 Kaunas, Lithuania
olgirdas.tumsys@ktu.lt

***Abstract*—Ultrasonic phased arrays are currently very popular in medical diagnostics and are used more and more for non-destructive evaluation (NDE) of different materials. NDE methods using phased arrays are used to analyse material properties, to measure wall thickness, to detect hidden cracks and other defects affecting structural integrity. Ultrasonic phased arrays can be used for the detection of different types of defects at different depths. In many cases depth of the critical zone, where defects can appear, is known, so the signal of the phased array has to be focused at this depth. In some cases immersion methods are preferred. In this paper the algorithm for the calculation of the time delays of the phased array probe, when the beam has to be focused at the required focal depth in the test object, after passing through the water layer (in the case of the immersion testing), is presented. The time delays of the phased array probe where calculated using developed algorithm in MATLAB. The verification of the algorithm was performed using CIVA software – the focused ultrasonic fields at the given depth in the second media were calculated using the time delays, calculated using developed algorithm.**

***Index Terms*—Ultrasonic phased array, immersion testing, electronic steering, focal law.**

I. INTRODUCTION

Already for some time ultrasonic phased arrays are widely used for medical diagnostics [1]–[3]: they are used for gynaecology, obstetrics, encephalogy, ophthalmology, cardiology and etc. Nowadays the ultrasonic phased arrays are used more and more for non-destructive evaluation (NDE) of different materials as well [4]–[8]. In NDE phased arrays are used to analyse material properties, to measure wall thickness, to detect hidden cracks and other defects affecting structural integrity. Ultrasonic phased arrays are used in a wide variety of industries: aerospace, nuclear power, pipeline construction and etc. Different applications apply different ultrasonic beam patterns - phased arrays can implement many different inspection techniques [9]–[11].

The typical ultrasonic phased array system includes phased array probe, electronics for beam steering, acquisition and imaging modules. These systems allow high-speed electronic manipulation of the beam: phased arrays can scan, sweep, steer and focus the ultrasonic beam.

In most applications the ultrasonic arrays are used in the direct contact with the investigated specimen. However, in some cases immersion testing of the object has to be performed. This influences the design of the testing system and can cause some problems associated with that.

In this paper, the algorithm for the calculation of the time delays of the linear phased array probe is presented, when the beam has to be focused at the specified depth in the test object, inspected using the immersion testing.

II. PHASED ARRAY TECHNIQUE

The ultrasonic phased arrays are made from multiple ultrasonic elements. The time delays are used to steer the acoustic beam. Most popular are ultrasonic linear phased arrays. The typical linear ultrasonic phased array probe has up to 128 piezoelements. These elements can be excited in groups of 16, 32 or 64 elements with programmed time delays. This allows to change the angle of incidence, the depth of focusing of the ultrasonic beam and to scan the beam [9], [12]–[14]. There are three main beam scanning patterns: depth focussing, sectorial scanning and electronic scanning (Fig. 1).

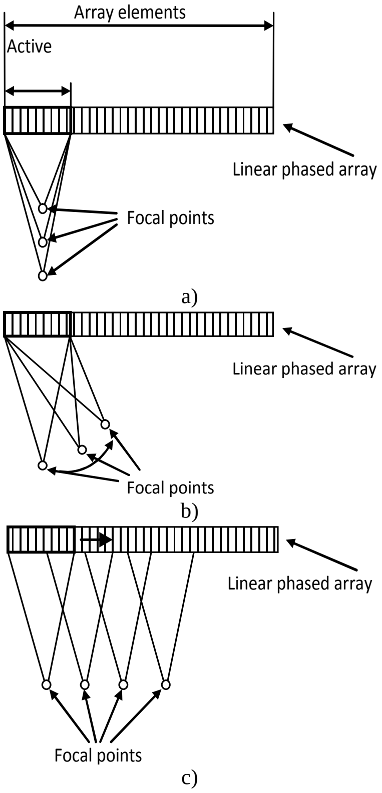

Fig. 1. The different beam scanning patterns: a) – depth focussing; b) – sectorial scanning; c) – electronic scanning.

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One of the most popular NDE inspection techniques is immersion testing of the specimen [15]. In this case the gap between the probe and the specimen is filled with water.

However, most often the phased arrays are used as contact probes. If to use them for immersion testing, some problems arise. One of the problems is determination of the delay laws of the phased array, taking into account that the ultrasonic wave travels through two mediums. If required focus depth in the material under the test is known, the time delays of the separate phased array elements have to be determined, taking into account the propagation differences in two media (i.e. different ultrasound velocities).

III. ALGORITHM FOR THE CALCULATION OF THE TIME DELAYS

Typically, the phased array instrumentation excites the individual channels with specified time delays in order to steer, focus or scan the beam [14]. The time-delayed wave fronts radiated by separate elements form the focused beam.

It should be noted that the phased array can be focused only in the near field of the probe. The near field of the array is given by [15]

$$N_0 = \frac{\left(A^2 + W^2\right)\cdot\left(0.78 - 0.27\frac{W}{A}\right) f}{\text{®} v_1}, \tag{1}$$

where A is probe active length (*active aperture*), W is the element length or probe width (*passive aperture*), f – ultrasound frequency, v_1 – velocity in medium (water).

Practical estimation of the near field is given by [9]

$$N_0 = \frac{A^2 f}{4 v_1}. \tag{2}$$

The focal depth F_1 in homogenous material (Fig. 2(a)) can be calculated as

$$F_1 = \frac{A}{2} tg\text{¥}. \tag{3}$$

According to (2) when $F_1 = N_0$ the angle is given

$$\text{¥} = arctg\left(\frac{Af}{2v_1}\right). \tag{4}$$

In immersion testing of the specimen the profile of the focused beam is changed in comparison with the beam focused in one media. The profile variation depends on the relationship between the longitudinal wave velocities in the water (v_1) and in investigated specimen (v_2) (Fig. 2(b)). The relationship can be described using Snell's law

$$\frac{\sin\text{~}}{\sin\ } = \frac{v_1}{v_2}, \tag{5}$$

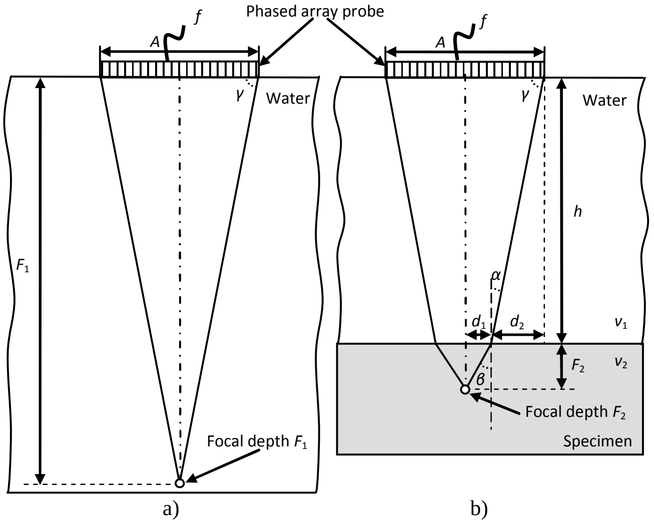
where $\text{~} = 90 - \text{¥}$ is angle of incidence, $= \arcsin\left(\frac{v_2 \cos\text{¥}}{v_1}\right)$ is angle of refraction.

The maximum possible depth of the focal point $F_{2\max}$ (Fig. 2(b)) in the specimen can be expressed as

$$F_{2\max} = \frac{d_1}{tg\ } = \frac{A^2 \cdot f - 4v_1 \cdot h_{\max}}{2A \cdot f \cdot tg\ }, \tag{6}$$

taking into account that:

$$\begin{cases} d_1 + d_2 = \dfrac{A}{2}, \\ d_2 = \dfrac{h}{tg\text{¥}}, \\ d_1 = F_2 \cdot tg\ \ . \end{cases} \tag{7}$$



a) b)

Fig. 2. Definition of the probe focussing in one a) focal point F_1 and two b) focal point F_2, mediums (water and specimen).

Equation (6) enables to calculate the maximum focal depth $F_{2\max}$ in specimen using known parameters of the phased array probe and water gap coupling height $h_{\max}$.

From a practical viewpoint, ultrasonic phased arrays can be used for the detection of different types of defects at different depths. In many cases depth of the critical zone, where defects can appear is known, so the signal of the phased array has to be focused at this depth. In the case of the immersion testing using phased array it is an inverse problem – how to calculate required water gap range, when the focal point depth in the test object is known.

According to (6) maximum water gap height for the used phased array probe can be calculated as

$$h_{\max} = \frac{Af}{4v_1}\left(A - 2F_2 \cdot tg\ \ \right), \tag{8}$$

where F_2 is the required focal depth in the investigated specimen.

The ultrasonic beam is focused at a given point by delaying the excitation of the elements located in the middle of array. The time delay Δt_k of each element can be calculated, when the distance l_n from the focal spot to each array element is known (Fig. 3). In Fig. 3 the group of n elements is shown. The active aperture length A of the group is given by [9]

$$A = n \cdot e + g \cdot (n-1), \tag{9}$$

where e is the width of a single element, g is the gap between two adjacent elements, n is number of elements.

In case of homogeneous material if the distance between the middle of the phased array probe and focal point F_1 is l_0, then the distances l_k between the individual elements k and focal point can be written as

$$l_k^2 = l_0^2 + \left(\frac{g+e}{2} + \left(\frac{n}{2} - k \right) p \right)^2, \tag{10}$$

where $k \le \frac{n}{2}$.

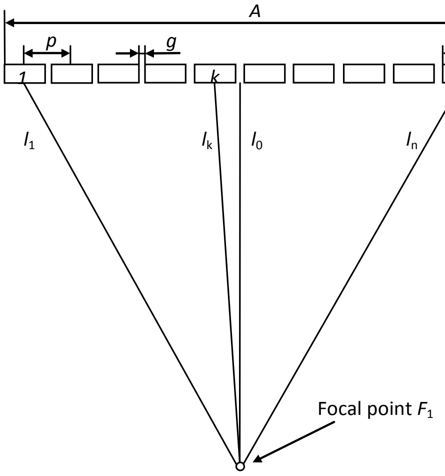


Fig. 3. The principle of the delay law calculation.

If the distance between the centres of two adjacent elements is $p = e + g = \frac{A-e}{n-1}$ (*elementary pitch*) then the distances l_k can be written as

$$l_k = \sqrt{l_0^2 + \left(\frac{(n-2k+1)(A-e)}{2(n-1)} \right)^2}, \tag{11}$$

where $k \le \frac{n}{2}$.

The time shifted delays Δt_k in homogenous material for individual piezoelements 1 ÷ k in sequence can be calculated as

$$\Delta t_k = \frac{\sqrt{l_0^2 + \frac{(A-e)^2}{4}} - \sqrt{l_0^2 + \left((A-e) \frac{|n-2k+1|}{2(n-1)} \right)^2}}{v_1}. \tag{12}$$

In case of homogeneous material $l_0 = F_1$. In case of the immersion testing l_0 in (12) is calculated taking into account (3) and (7)

$$l_0 = \frac{h}{1 - \frac{2F_2}{A} tg}. \tag{13}$$

If piezoelements of the phased array are excited using time delays calculated using (12), the beam will be focused at the required depth.

IV. SIMULATED RESULTS

The objective of the simulation was to calculate the ultrasonic field of the phased array probe focused at a given distance in the case of the immersion testing. The time delays Δt_k of the phased array probe were calculated using MATLAB. Then, the calculated time delays were used in CIVA [16] for modelling of the ultrasonic field transmitted by a phased array probe. The modelling was performed according the following algorithm:

– The maximum possible focal depth F_{2max} (6) for the given setup was calculated;

– The maximum water gap height h_{max} (8) was calculated;

– The water gap height h ($h \le h_{max}$) was chosen taking into account the required focal depth F_2 ($F_2 \le F_{2max}$);

– The focal depth F_1 of the given phased array probe in water (13) was determined;

– The time delays Δt_k for individual piezoelements (12) were calculated;

– The calculated time delay laws were used in CIVA for the setup of the phased array;

– The ultrasonic fields of the phased array were modelled using CIVA software.

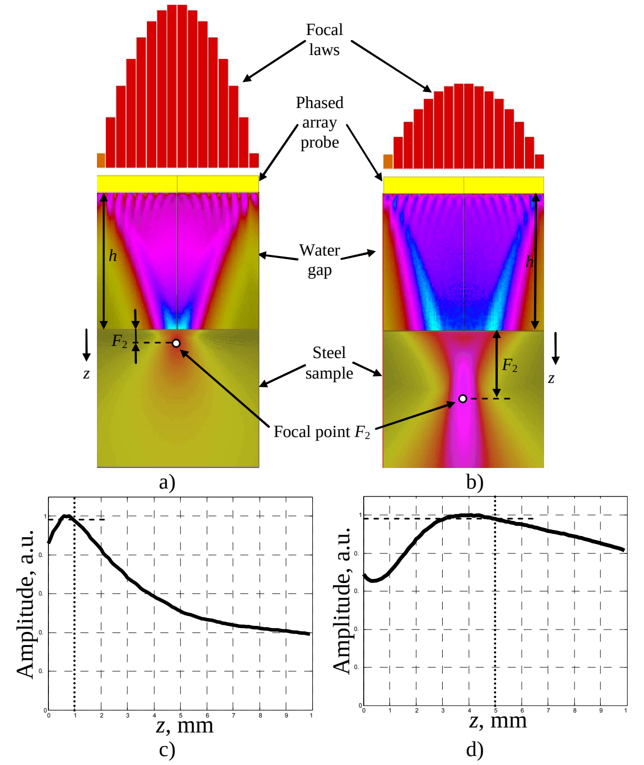
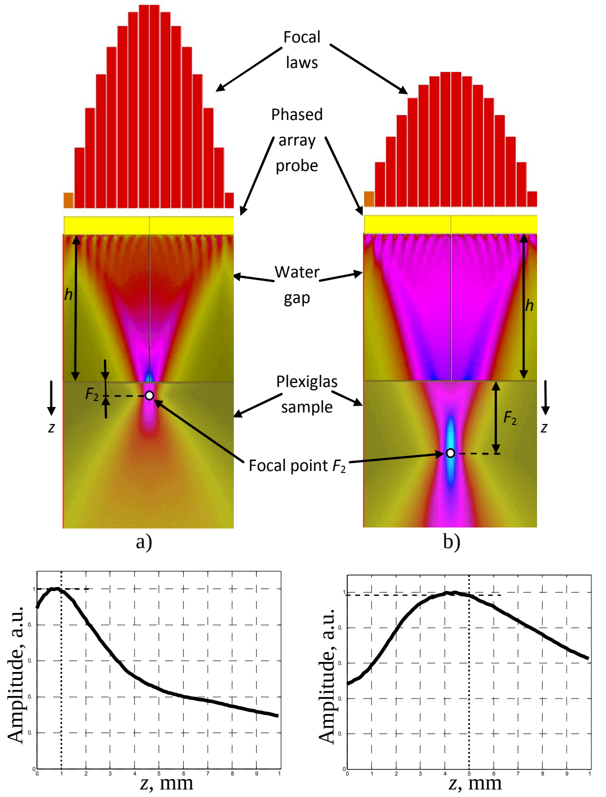


Fig. 4. The modelled ultrasonic field in steel when F_2 = 1 mm (a), and F_2 = 5 mm (b). Amplitude distribution in steel on the transducer axis when F_2 = 1 mm (c) and F_2 = 5 mm (d).

The modelling was performed for a linear phased array probe with 16 elements. The centre frequency of the probe was 2.25 MHz. The probe parameters: elements width e = 0.651 mm, gap between elements g = 0.1 mm, incident dimension A = 11.916 mm, orthogonal dimension W = 12 mm. The ultrasonic immersion method (water, v_1 = 1470A m/s) for the investigation of the steel (v_2 = 6000 m/s) and plexiglas (v_2 = 2680 m/s) samples was used. The water gap was 10 mm. The required focal point was at F_2 = 1 mm and F_2 = 5 mm distance from the surface.

The modelled ultrasonic field in steel when required focal point was F_2 = 1 mm is presented in Fig. 4(a) and when F_2 = 5 mm in Fig. 4(b). The amplitude distribution in steel along transducer axis in case of F_2 = 1 mm is shown in Fig. 4(c), in case of F_2 = 5 mm is shown in Fig. 4(d).

The modelled ultrasonic field in plexiglas when required focal point was F_2 = 1 mm is presented in Fig. 5(a) and when F_2 = 5 mm in Fig. 5(b). The amplitude distribution in plexiglas along transducer axis in case of F_2 = 1 mm is shown in Fig. 5(c), in case of F_2 = 5 mm is shown in Fig. 5(d).



a) b)

c) d)

Fig. 5. The modelled ultrasonic field in plexiglas when F_2 = 1 mm (a), and F_2 = 5 mm (b). Amplitude distribution in plexiglas on the transducer axis when F_2 = 1 mm (c), and F_2 = 5 mm (d).

The results of the modelling show that the proposed algorithm for the calculation of the focal laws of the phased array probe gives good results. In case of steel when the required focal point was 1 mm, obtained field maximum is at 0.9 mm. Amplitude drop at 1 mm is less than 0,1 dB from obtained maximum. When the required focal point was 5 mm, obtained field maximum is at 4.2 mm. Amplitude drop at 5 mm is less than 0,2 dB from obtained maximum. In case of plexiglas when the required focal point was 1 mm, obtained field maximum is at 1 mm. When the required focal point was 5 mm, obtained field maximum is at 4.5 mm. Amplitude drop at 5 mm is less than 0,1 dB from obtained maximum. The maximum values of the calculated ultrasonic beam fields are well consistent with real focal points.

V. CONCLUSIONS

In this paper, the algorithm for the calculation of the time delays of the phased array probe is presented, when the focus depth in the specimen is given and the specimen is inspected using the immersion testing. The proposed algorithm for the calculation of the focal laws of the phased array probe enables to calculate the required time delays of the separate phased array elements, when phased array has to be focused at a given distance in the test object in the case of the immersion testing. The simulated ultrasonic beam fields using the time delays determined by developed algorithm are well consistent with real focal points.

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