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Development of the technique for independent dual focusing of contact type ultrasonic phased array transducer in two orthogonal planes

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ABSTRACT

Due to a low lateral resolution in elevation plane, the application of linear ultrasonic phased array transducers (ULPAT) is limited. The objective is to enhance the spatial resolution by means of spatial dual focusing technique of ULPAT in two orthogonal planes – azimuth and elevation.

A design of a special delay line possessing a convex cylindrical lens has been proposed. The lens enables fixed geometrical focusing of the excited beam in the elevation plane, while in the other, azimuth, plane the beam is electronically focused at an arbitrary point by the active aperture of the ULPAT. The simulation results demonstrate the extended possibilities of resolution enhancement. Experiments show that the undetectable defect is detected using the designed acoustic lens. In addition, the interfaces of the intermediate layer of metal composite were detected.

1. Introduction

Nowadays, the ultrasonic phased array (PA) technology is widely used in different sectors of industry and medicine [1–3]. This technology is attractive for its capability to provide the real time images of the internal structure of the specimen being analysed. These images are commonly used to detect volumetric or crack-like defects inside the specimen under investigation [4–7]. The most sophisticated ultrasonic scanners use linear arrays containing up to 256 piezo elements that may be electronically steered and focused via PA technique [8–10]. A linear array consists of piezoelectric elements separated by inter-element distances. By delaying the excitation signals of different elements of the array individually, different types of beam focusing and steering techniques are possible to be implemented [8]. The result of superposition of the excited ultrasonic fields by individual elements is the dynamically controllable focal spot in single plane only. The adjustment of this technique depends on the tasks of applications.

The advantage of using phased array technique in medical diagnostics is the ability to perform multiple examinations of the tissue properties without the need for reconfiguration. In many cases of industrial imaging for non-destructive testing linear arrays are used to produce two-dimensional (2D) cross-sectional images. Ultrasonic imaging of the internal subsurface defects of thin multi-layered samples is an extremely actual task for quality control, e.g. quality control of the metal composites. The possibility of separating the received ultrasonic signals depends on material properties of the object under investigation and properties of the adjacent layers. If a specimen under investigation has a thin layer to be inspected, the propagation distance in a particular medium is short [11]. The contact type linear ultrasonic phased array transducers (ULPAT) can be used for material characterization, quality control and fast detection of different types of internal defects located at different depths inside the sample. However, due to a low lateral resolution in the elevation plane not covered by electronically controlled beam as it is performed for the azimuth plane, application of ULPAT for quality control of multi-layered materials and detection of the internal non-homogeneities is quite limited (Fig. 1).

Applications of the fixed geometrical focusing of the excited ultrasonic beam using the concave lens and an intermediate immersion environment are widely used in medical diagnostic, NDT, material properties measurement and quality control [12–18]. The lens is placed over the elements of the array to provide some focusing in the elevation plane. The focal depth of the lens is determined by the radius of curvature of the lens and speed of sound in lens material. Those linear phased-array transducers can provide better resolution and do not require additional channels of the system beamformer [15,16]. Beam focusing for linear ULPAT is determined by two different dimensions: width of the elevation beam and width of the azimuth beam.

Unfortunately, there are some limitations to apply the immersion set-up due to specific geometry or spatial dimensions of the object under investigation, nonconformity of curved shapes of the lens and external surface of the sample. Therefore, due to possibility to perform

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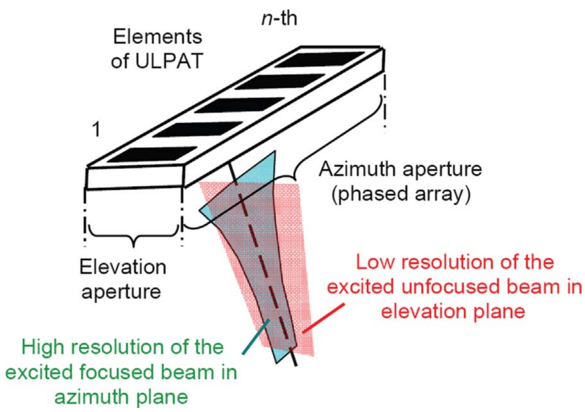

Fig. 1. Limitation of resolution of the conventional ULPAT in the elevation plane.

express testing (screening), also necessity to perform *on-site* investigation (e.g. inspection of aircraft components), the contact type configuration is being used as an alternative option. However, application of the focusing technique based on concave lens directly to a contact type testing and detection of defects in adjacent thin layers of multi-layered solid materials is not possible due to nonconformity of curved shapes of the concave lens and the planar surface of the sample under investigation. It does not ensure the focusing inside the sample and in the same way a stable coupling-based acoustic contact outside the water tank during the contact type testing. In addition, the contact type pulse-echo testing of thin multi-layered objects requires application of a delay line in order to avoid the overlapping of the reflections from the internal structure of the sample over the own reverberations of individual elements of transducer array. Therefore, a special delay line with focusing option is necessary to be developed.

The objective of this work was to enhance the spatial resolution by means of independent dual focusing technique of ULPAT in two orthogonal planes: in active (covered by phased array) and passive (elevation) apertures. The particular tasks were to achieve the narrow, symmetrical and elongated focus of the excited ultrasonic beam in both orthogonal planes, and to perform the contact non-destructive testing of specially manufactured sample with flat bottom holes (FBH) and sample of multi-layered metal composite.

In this work, directivities of the excited ultrasonic beam and detection of artificial defects were simulated in the case of focusing the ultrasonic field excited by ULPAT in the azimuth (active aperture) and elevation (passive aperture) planes. In order to focus the beam in elevation plane, the special delay line with a convex type lens (internally implemented) is proposed to be applied in the case of the contact type testing of the thin specimens with internal defects. Simulation of the ultrasonic field distributions and defect detection has been performed to demonstrate the valuable effect of the proposed delay line with convex lens.

2. Analysis of focusing of ultrasonic beam in elevation plane

Typically, to control the thickness of multi-layered materials and detect the internal defects, the linear phased-array transducers with different configurations are used as an alternative to immersion testing [7]. A linear array consists of piezoelectric elements separated by inter-element distances. The excited ultrasonic field can be steered and dynamically focused by sequentially exciting the elements by appropriate focal law [8]. The result of superposition of the excited ultrasonic fields by individual elements is the dynamically controllable focal spot in single plane only. However, in the elevation plane focusing cannot be achieved (Fig. 1) and this limits the spatial resolution during detection of the internal non-homogeneities or defects.

In medical ultrasonic imaging for improvement of resolution in the azimuth and elevation planes the mechanical lens with a fixed focus has been proposed [12–18]. The lens is placed over the elements of the array to provide some focusing in the elevation plane. Those linear phased-array transducers can provide better resolution and do not require additional channels of the system beamformer [15,16]. Unfortunately, to apply this technique directly to contact type testing and detection of defects in adjacent thin layers of the multi-layered solid materials is not possible due to nonconformity of curved shapes of the lens and external surface of the sample.

In the field of ultrasonic NDT of austenitic weld inspection the principle of beams overlapping of the transmitting and receiving phased arrays (similar to configuration of Transmitter Receiver Longitudinal (TRL) probes) is being used in order to increase the resolution and avoid the lateral beam steering [19,20]. However, the sharp focusing was not achieved and the resolution in elevation plane is limited to width of the excited and geometrically unfocused ultrasonic beams. In the case of two-dimensional (2D) TRL arrays are being used the possibility of skewing of overlapped beams exists. However, in the case of limited number of array elements in elevation plane the performance of beam skewing is limited as well.

In order to improve the performance of testing and defect characterization, a non-conventional concept of special delay line for ultrasonic contact phased array transducer is necessary to be proposed. Therefore, the modified concept of ultrasonic contact type phased-array transducer with focusing in the elevation plane by convex lens was proposed (Fig. 2). The convex lens was realized by implementing of milled curved surface within the delay line and filling this gap with coupling liquid.

The position of the focal point F in the analysed specimen depends on geometric dimensions of the delay line, radius of convex lens and ultrasound velocities in the neighbouring mediums, i.e. the delay line, filler of the lens (liquid) and the specimen. According to the Fig. 2 the incidence (α) and refracted (β) angles of propagating ultrasonic rays can be calculated as:

$$\sin\alpha = \frac{s_0}{R}, \quad \sin\beta = \frac{c_2 \cdot \sin\alpha}{c_1} = \frac{c_2 \cdot s_0}{c_1 \cdot R} \leq 1, \tag{1}$$

where R is the radius of curvature of the lens surface, s_0 is the lateral distance between the axis of symmetry of the lens and the refraction point of ultrasonic ray at boundary filler of the lens and the delay line, c_1 and c_2 are the ultrasound velocities in the filler - water (space between the radiating surface of the phased-array transducer and the delay line) and Plexiglas (material of the delay line) respectively. Eq. (1) defines the conditions to be met in order to perform focusing of the ultrasonic beams excited by the elements of the phased array along the

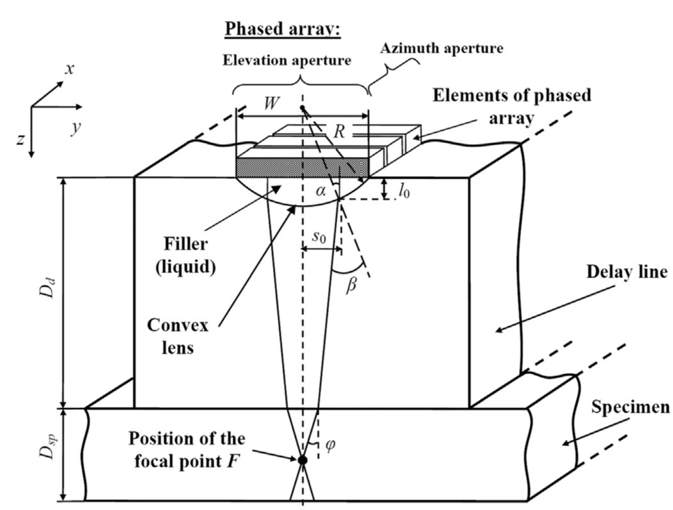

Fig. 2. Focusing in elevation plane of ULPAT using the delay line with convex lens.

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