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Evaluating Image Precision of Acoustical Imaging Diffraction by Focused Ultrasound Beam

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Abstract: The paper concisely reveals an acoustic behavior - acoustic diffraction (scattering) phenomena, which arises between a spherical cavity of acoustic lens and the microstructure of an object in immersion. As the result, this phenomena cause some negative influence on acoustical imaging precision. As a certain condition is satisfied, the outline of microstructure in acoustic images become blurred, the image precision is somewhat corroded. The paper introduces a brief evaluation approach to this acoustic interaction, and provides some typical characteristics of this acoustic interaction in two-dimensional (2D) and three-dimensional (3D) acoustical images. The paper suggests the researcher should take into account this interaction behavior - diffraction, to avoid any misrepresentation as investigating microstructures and imaging characterization, promoting the accuracy for materials characterization through the acoustical images by scanning acoustic microscopy technology (SAM), in the application field of non-destructive Testing / Evaluation (NDT/E).

Keywords: Transducer, Acoustic lens, Scattering and diffraction, Time-of-flight (TOF), Signal aberration, Acoustical imaging, Scanning acoustic microscopy, Non-destructive testing / evaluation (NDT/E).

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1. Introduction

The technology of Scanning Acoustic Microscopy (SAM) is widely used in materials sciences. It was originally proposed by Quate and Lemons in 1974 [1]. In many modern high-tech industrial fields, the micro-sized internal defects inside a solid bulk material hide extreme risk in some applications. The microscopic inspection of internal defects for material characterization is prerequisite for some vital applications. SAM just provides the technology to detect this kind of internal defects in a non-destructed way in NDT/E field [2, 3]. In materials science SAM also provide powerful means to investigate the micro-sized internal structure and its characterization for bulk materials.

The mature two-dimensional (2D) imaging techniques, including A-(O-), B- and C-scan image by SAM, is used for evaluating the internal structures of non-transparent solid bulk specimen powerfully. Besides these 2D acoustical imaging techniques, based on isosurface technique a new approach to realize the three-dimensional (3D) acoustical imaging is proposed by Ding and He et al in 2013 [7, 8]. 3D scanning acoustic microscopy (3D SAM) will become a more attractive technology for the visualization of internal micro-sized structures in nondestructive testing/evaluation field [10].

Both two-dimensional acoustical imaging and three-dimensional acoustical imaging technology of SAM system, work based on a common platform, including same scanning system, electrical blocks, data conversion block, and database of computer. In any way, these two methods are both performed with the same kernel unit – acoustic lens. Acoustic lens is the key execute technology in the system [5].

The principle and process to produce acoustical image by acoustic lens are essentially based on the application of ultrasound wave behavior. Ultrasound wave is very sensitive to the varieties inside a local region - focal spot. The secondary acoustic response - waves arise from a serial of consecutive focal region on/inside the specimen. As the results, all acoustic interacted behavior - waves are collected from these regions, bringing all information of internal microstructures of the specimen. Variations of acoustic signal coming from diverse points of bulk material are displayed in the screen as a pixel of acoustical image. According to its own mechanism of acoustical contrast, all internal structures information is represented in acoustic images as each different pixel in a various degree of contrast.

In the application of scanning acoustic microscopy, various types of acoustic waves present their own appearance in acoustical image. The phenomena of scattering and diffraction as an adjunct acoustic behavior obviously contribute its influence on the final results of acoustic imaging [4, 6].

2. Evaluation

Acoustic lens is the ultrasound focusing system, which plays two roles in SAM - an actuator and a receiver. As an actuator, its native characteristics determine the basic resolution in acoustical imaging substantially. As a receiver, all ultrasound interaction and its various responses between the actuator and observation in immersion, including additional and even negative interaction which is inevitably collected, converted and involved into imaging process.

2.1. The Physical Structure of Acoustic Lens

Acoustic lens is an actuator, which consists of a disc-shaped plane piezoelectric transducer on the top of the waveguide, and a spherical cavity on the end side of the waveguide. See Fig. 1.

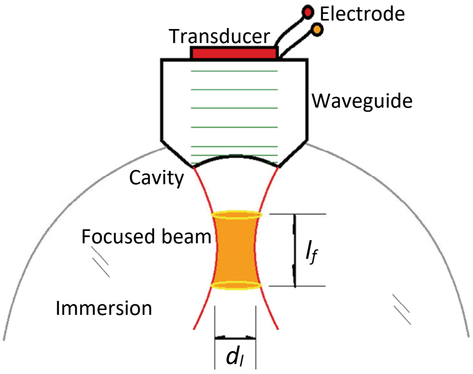


Fig. 1. A plane transducer and a spherical cavity located on two ends of the waveguide of an acoustic lens.

Based on the piezoelectric effect, the electrical generator excites a fast electric shock to the disc-shaped transducer, producing an acoustic ultra-short wave (pulse) at the boundary between the transducer and the waveguide of acoustic lens. This ultra-short wave propagates in a type of plane wave inside the waveguide of acoustic lens, towards the cavity on the other side of waveguide [9]. As this plane wave arrives at the spherical interface between the cavity in waveguide and the immersion (water), in term of Snell law - the spherical cavity of acoustic lens produces a convergent ultrasound probe beam into the immersion.

This convergent probe beam forms a caustic zone in water immersion. The structure and its parameters of this focused beam are determined by two factors - the frequency of transducer and the physical characteristics of the spherical cavity embedded in the end side of waveguide.

The variant l_f and d_l is the length and diameter of this focused beam produced by acoustic lens. See Equation (1) and (2). These two characters are determined by two parameters - λ and θ_m.

$$l_f = \frac{2\lambda}{1 - Cos\ \theta_m} \approx \frac{4\lambda}{\theta_m^2} \tag{1}$$

and

$$d_l = \frac{0.61\lambda}{Sin\ \theta_m} \approx \frac{0.6\lambda}{\theta_m} \tag{2}$$

The parameter λ is the wavelength of this plane wave, θ_m is the maximal half angle of the cavity drilled inside the end side of waveguide of acoustic lens. These two parameters exhibit the native essential character of an acoustic lens, which are the key factor for an scanning acoustic microscope intrinsically, to contribute the basic resolution in acoustical imaging.

In the application of acoustic lens for SAM, the higher frequency value f of the transducer provides the more less value of l_f and d_l - the smaller sizes of the focal zone (spot) inside immersion and specimen.

Practically in the field of SAM, for a high resolution acoustical imaging, usually a high working frequency of the transducer is employed, usually fabricated from 20 MHz up to 3000 MHz to obtain a small caustic-shaped focused probe beam in immersion, with the diameter of this focal spot being in tens of micrometers.

For the same purpose, the bigger value θ_m of the cavity of acoustic lens provides the smaller value of l_f and d_l, which also means the smaller sizes of this focal zone (spot) and higher resolution are realized for the acoustic lens and SAM system.

On the contrary, in most application of SAM, acoustic lens is also being a receiver while the system only employs a unique acoustic lens in a SAM. The cavity of acoustic lens has the capability to collect the echo ultrasound waves from the specimen in immersion; also, in term of Snell law the spherical cavity of acoustic lens transfer all these collected ultrasound responses through the bulk of waveguide to the transducer on the top of waveguide. According to converse piezoelectric effect, the transducer receives and transforms all various ultrasound waves into a serial of electric ultrasound signals in an echo signal pattern. In this process, some natural, additional, and faint hidden acoustic behavior is also carried among these signal sequences in echo signal patterns.

2.2. Acoustic Scattering Behavior

In the procedure of acoustical imaging, the native character and parameters of acoustic lens in a SAM determine the basic resolution of images. At the same time, all ultrasound interactions received by acoustic lens also contribute their comprehensive influences on the precision of acoustical images.

All acoustic responses received by acoustic lens are a sensitive way to exhibit in acoustic images, including all kinds of faint interactions from the micro interface on/inside the observation object. Scattering phenomena is such a usual acoustic interaction in nature, while an acoustic wave meets with a spatial spot in a wave field.

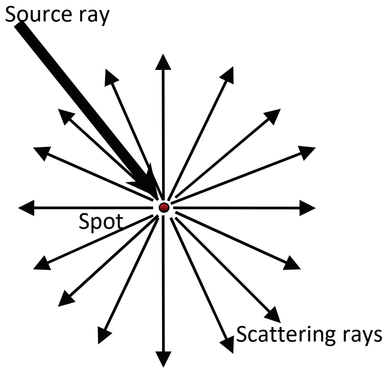


Fig. 2. An acoustic source ray meets with a particle and produces a plenty of scattering rays around this particle.

Fig. 2 shows a pattern about the acoustic scattering phenomena. The figure demonstrates an acoustic scattering behavior takes place around an individual particle (spot) in a field.

As a main acoustic wave (source ray) propagates to a spatial central spot – a particle, the source ray meets with this particle and interact each other, then the acoustic wave scatters out around this particle. Some of scattering is reflected in an opposite direction along the original route, but most of scattering are reflected in any arbitrary angle to any other directions. Generally, the scattering rays transmit outside from the central spot, spreading out in a disperse direction. This transmitting behavior is not only limited inside a two-dimensional plane, but in a kind of three-dimensional full directions around the central spot. In this case, for a receiver or a sensor located at any arbitrary position from any arbitrary direction, it is only small amount of these scattering rays can be collected and contribute their influence.

2.3. Acoustic Edge Diffraction

Once a serial of individual particles (spots) are placed next to each other in a spatial, and extend along one dimensional direction as an edge (line), where a wave resource radiate and excite, all scattering behavior from every particles in the edge present a comprehensive diffraction formation around this edge.

Edge diffraction takes place around the angular elements, such as corner, edge, wedge, etc. [4] See Fig. 3. The figure shows and interprets a typical behavior of edge diffraction.

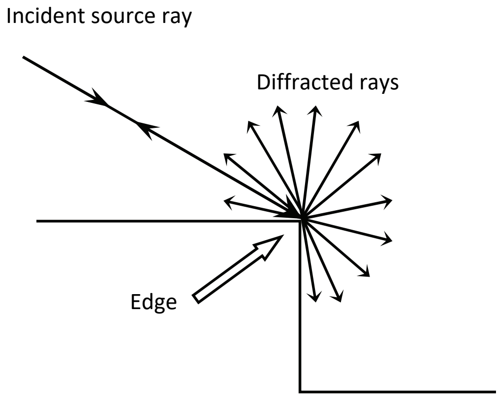


Fig. 3. Schematic of edge diffraction - acoustic interaction between an incident ray and an edge.

As the incident rays interact with the edge, there are two kinds of interaction possibilities:

1) As an incident ray excites the edge in a normal plane, which is perpendicular to the edge, the diffracted rays arise from the incidental spot, and the diffraction spread out limited inside the same perpendicular normal plane.

2) Once the incident ray excites this edge along an arbitrary direction with an angle, all diffracted rays disperse out with the same angle but in an opposite side from the incidental spot, forming a crossed pyramidal tract.

In these cases, once an observation object in a shape of particle (spot) or outline (sharp edge), which is placed under an ultrasound wave field, scattering and its integral behavior - edge diffraction will release its acoustic response.

3. Experimental

Based on Raster principle, driven by a mechanical scanning system, acoustic lens moves along the scanning route in *x, y, z* coordinately - point by point, and line by line over a specimen in immersion. According to the spatial positions of acoustic lens, and the relevant digital ultrasound signals in echo signal pattern at each position, which is depicted by the intensity for every pixel in a two-dimensional image (B-, C-Scan). In this experiment a small aperture acoustic lens is employed with $\theta_m \approx 6^0$ and focus time delay is 27.5 µs.

3.1. Edge Diffraction in Acoustical Imaging

For this evaluation, a thin plate specimen is used whose outline is with a sharp edge. As the acoustic lens is driven by the mechanical scanning system in a unidirectional (*x* or *y*), a transversal topography inside specimen – B-Scan image is obtained; in a cross-direction (*x* and *y*) a lateral topography (cross-section) - C-Scan image showing at different level inside specimen is realized. Under this imaging technology, the formation of edge diffraction is introduced by Ding and Levin et al in 2011 [6]. See Fig. 4.

As the focus of convergent ultrasound probe beam by acoustic lens is located below the surface of a plate specimen, while the acoustic lens moves in unidirectional *x*, a transversal 2D image - B-scan image is obtained in picture a) of Fig. 4. A parabolic line opens upward from the point on the edge of this plate specimen, almost in a symmetrical shape occurs around at this point of the edge in B-scan image.

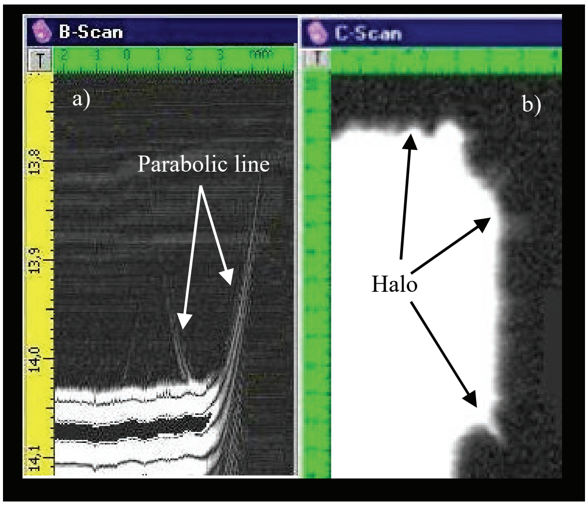
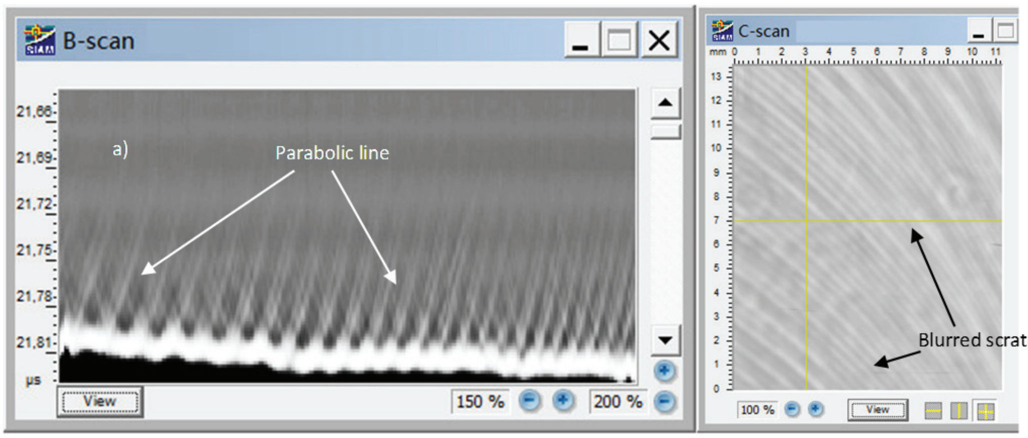


Fig. 4. Edge diffraction and its formation exhibited in B-Scan and C-Scan image.

On the other hand, while the acoustic lens moves along *x* and *y* direction, and, by setting the width of electrical gate at the depth on the surface in echo signal pattern, a cross-section image is obtained in the picture b) of Fig. 4 - C-scan image, displaying the surface of this plate specimen. The picture b) exhibits a plenty of halo rim around the outline of this plate specimen obviously. Just this plenty of halo rim results in a blurry outline of specimen in C-Scan image. The appearance size (area) of this specimen in C-Scan image is enlarged than its native size.

The diffraction formation in two pictures a) and b) of Fig. 4 is a couple of relevant view each other for the same outline of the specimen. For the reason of edge diffraction, different formation in two kinds of images makes the imaging characterization becomes more complicated for investigators.



(a) (b)

Fig. 5. Edge diffraction and its influence on 2D acoustical imaging for a surface evaluation.

3.2. Surface Characterization in Acoustic Image

A metallic machining parts is polished, and still remained with many mechanical scratches on its surface. The picture a) in Fig. 5 is the surface of it in a transversal B-Scan image. While the focus of convergent ultrasound beam is below the surface of this specimen, many parabolic lines arise upward at every minim burr on the surface of machining parts in B-Scan image.

Correspondingly in the picture 2) in Fig. 5 - C-Scan image, these mechanical scratches are observed with many curves tightly distributed on its surface. This C-Scan image provides scratches distribution on the surface qualitatively. All scratches on the surface are blurred in C-Scan image. The outlines or edges of all scratches cannot be distinguished explicitly. The imaging precision is damaged by edge diffraction.

3.3. Internal Structure in Acoustic Image

SAM is a convenient technology to investigate internal microstructure for bulk materials. Fig. 5 gives an acoustical imaging for the characterization of a piece of bulk materials with an internal laminated structure within a local area.

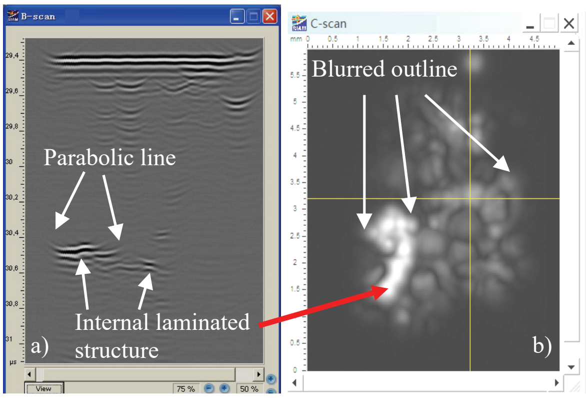


Fig. 6. Visualization of internal microstructure in 2D acoustical imaging and its appearances.

The picture a) and b) in Fig. 6 exhibit two 2D images - B- and C-scan image, showing the profile of some internal structure inside a solid bulk specimen. The ripples with some parabolic lines are the internal laminated microstructure in B-Scan image. The C-Scan image (the picture b) gives a bright area relevant to the ripples areas in picture a).

The brightness of local area with a different contrast represents some internal local area – laminated internal interface and its distribution in a horizontal level along x and y in C-Scan image.

It also obviously shows that the bright areas are surrounded by their own blurred rim. It also provide unclear outline of internal microstructures in the image, and the areas size of internal local microstructures are enlarged too.

3.4. Internal Structure in 3D Acoustic Image

Three-Dimensional acoustical imaging for bulk specimen by SAM is proposed and realized. The method - isosurface technique and square column model which is employed in 3D SAM, which is sensitive to catch the weak signal variance, and exhibit the variance in a full direction way for a bulk materials [7, 8, 10].

Therefore, as the convergent beam reaches and excites the micro edge of internal structures or big particles inside a specimen, phenomena of scattering and diffraction is more sensitive and evident displayed in 3D acoustical imaging than in 2D acoustical imaging.

The picture a) in Fig. 7 shows some internal microstructure (void, defect or inclusion) inside a piece of bulk materials in 3D acoustical imaging. The arrows point out the minim rim surrounding its kernel - internal microstructure in picture a). By the procedure to adjust the signal process for 3D imaging, the investigator may more conveniently find the involving regularity to catch the kernel - the real internal microstructure for characterization using 3D acoustical imaging technology.

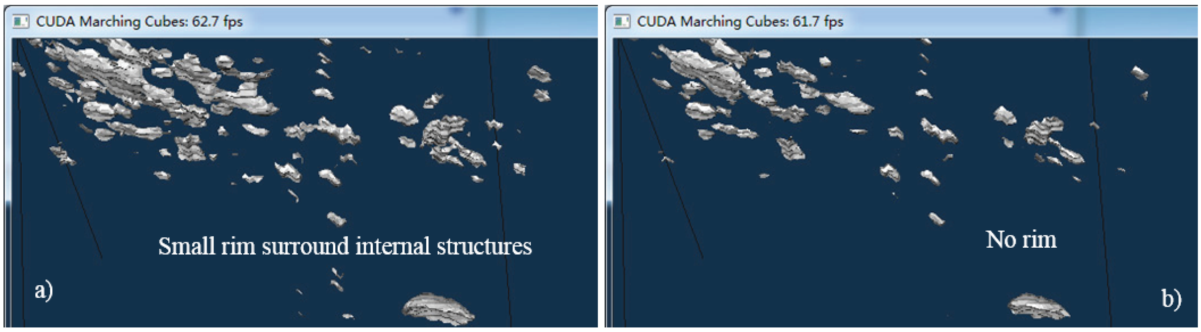


Fig. 7. 3D visualization of internal microstructure and the influence by phenomena - Scattering and diffraction in three-dimensional acoustical imaging.

So, the picture b) presents the internal microstructures in 3D image, by reducing the influence from acoustic scattering and edge diffraction. Comparing two pictures between picture a) and b), the volume of all internal microstructures with their own rims in picture a), are bigger than the volume of all same particles in picture b). Phenomena - scattering and edge diffraction also enlarge the volume size than its real volume of internal microstructures for evaluation and characterization in 3D acoustical imaging.

4. Calculation

The above experimental results show that, in immersion as a particle or an edge is placed within a field of convergent ultrasound beam, the particle rise up an acoustic response - scattering or edge diffraction responding to this source radiation.

Fig. 8 provides the physical interaction model which interprets the acoustic interaction, between an arbitrary spatial particle in a field of convergent ultrasound beam and a spherical cavity of an acoustic lens. In the focusing system, the spherical cavity of acoustic lens produces its physical focus in immersion - symbol *O*. In fact, the virtual focus by a spherical cavity in water is deeper than its physical focus. In this paper, the authors use a physical focus model to investigate this interaction.

The line *A'A* is the symmetry line of the acoustic lens pass through its focal position - focus, which is perpendicular to the interface of cavity; the line *B'B* is the one pass through the arbitrary position *B* and focal position, which is also the one perpendicular to the cavity; the angle between these two lines is an angle θ; the parameter θ_m is the maximal half angle of the cavity of acoustic lens; parameter c is the sound velocity in water.

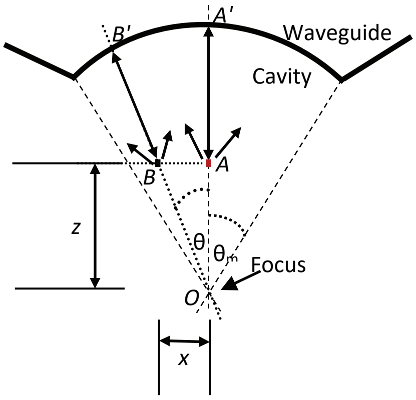


Fig. 8. The schematic about a scattering (diffraction) interaction between a particle (edge) and a spherical cavity.

An arbitrary particle is placed on a horizontal plane in water inside a convergent beam, where its vertical displacement from the focus is variant z; on its horizontal plane this particle shifts from position *B* to *A*. The horizontal displacement from position *B* to *A* is variant x. Position *A* is just located on the central symmetry line of acoustic lens.

In this convergent ultrasound field in water, the perpendicular distance to the cavity from the position *A* and *B* is different individually. The distance – *A'* to *A* is bigger (longer) than the distance - *B'* to *B*. The time interval (difference) between the cavity and two position of particle - position - *A* and -*B* is induced in equation (3) [6].

$$\tau_{\mathrm{D}} = \pm \frac{\sqrt{z^2 + x^2} - |z|}{c}, \quad x \le |z| \cdot tg\,\theta_{\mathrm{m}} \qquad (3)$$

The value of variant τ_D is the time interval between the position *A* - equivalent to the main reflected signal from the surface of a specimen, and the position *B* - equivalent to the diffracted signal from the particle or edge of a specimen. The equation (3) reveals that diffraction is tightly relative to Time-Of-Flight (TOF), which depends on the direction and the route of acoustic wave propagation.

The sign of equation (3) reveals the time interval changed as the focus of acoustic lens cavity is below or up than the front face of plate specimen. The branches and its open direction of a parabolic line in B-Scan image, are directed upward or downward as the focus of acoustic lens is below or over than an observation object.

5. Discussion

Comparing to the diffraction model above, the formation of edge diffraction in an echo signal pattern is shown in Fig. 9. The picture shows two signal formation difference as an edge of a plate specimen shift from position *A* to *B* under a convergent ultrasound beam.

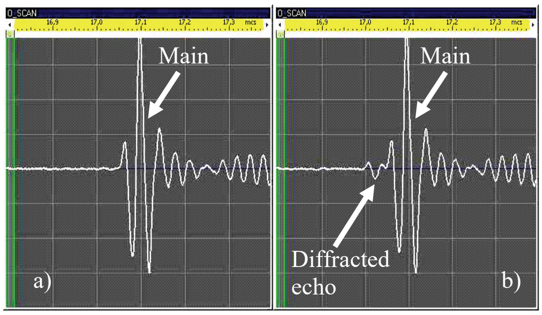


Fig. 9. The formation of a diffracted echo pulse in echo signal pattern as the edge located at two positions.

The formation in the picture a) is relevant to signal response as the surface of plate specimen occupying the position *A*, showing a typical reflected main pulse signal; and the picture b) is relevant to the moment, which the edge of specimen shifts to the position *B*, at this moment a diffracted echo signal respond, with a signal aberration appears in echo signal pattern.

Theoretically, the equation (3) gives the explanation that, once the object is located at a defocus condition inside a convergent ultrasound beam, all these formations by the diffracted echo pulse take part into the imaging process, impacting on one-, two- and three- dimensional images:

1) In A- (O) -Scan imaging, also in echo signal pattern, a diffracted echo pulse signal from the edge , is attached and even merges with the main reflected pulse (signal) which is from the specimen surface;

2) In B-Scan imaging, as the outline (sharp edge) of a microstructure located on the surface or inside the bulk specimen, a symmetrical parabolic line is opened upward or downward at its end position of edge. The open degree of parabolic line is determined by the variant – the value of horizontal and vertical displacement from the focus;

3) In C-Scan imaging, as the outline (sharp edge) of microstructure located on the surface or inside the bulk specimen, a plenty of halo rim surrounds all microstructures. It blurs the outline and enlarges the area size of microstructures in image, and results in the image worse precision for visualization and its characterization. The blurry degree is also determined by the variant - the value of horizontal and vertical displacement from the focus;

4) In 3D imaging, all halo rims caused by scattering or diffraction expand in full direction. It makes the visualization and characterization complicated. The volume of microstructure in image is enlarged too;

5) The model in Fig. 8 and equation (3) induces that, as the focus of convergent beam is just concentrated on a horizontal level, at which the surface of a microstructure (object) is located, the phenomena diffraction can be lessen maximally. Only at this moment and in this way, it is possible to obtain a high precision imaging with all these acoustic images for testing and evaluation using SAM technology.

5. Conclusion

Scanning Acoustic Microscopy is a sensitive technology to investigate internal microstructure for a nontransparent bulk material. Its imaging precision is a basic consideration for some new potential applications. The authors concisely point that, the imaging precision of SAM technology is not only determined by the native properties (frequency and maximal half angle) of acoustic lens, the external possible element - high precision mechanical scanning system is also a necessary operative condition. Indeed, the authors emphasize that acoustical imaging precision is also determined and influenced by an external additional acoustic interacted behavior – scattering and diffraction phenomena.

Phenomena scattering and diffraction is widely exit in nature. The authors introduce that, in the application of SAM edge diffraction arises as a specific condition satisfied – the defocusing in a convergent ultrasound field, the acoustic interaction between a spherical cavity of acoustic lens and the micro interface (particle, edge, sharp outline) of an object in immersion.

The authors emphasize that the phenomena diffraction is an inevitable behavior taking part in the imaging process of SAM. The paper presents all representative formation in 2D acoustical imaging (A-(O-), B- and C-Scan) and 3D acoustical imaging: a parabolic line around the particle of edge of a structure in B-Scan image, a blurred outline and its enlarged area of a microstructure in C-Scan image, and its enlarged volume of a microstructure in 3D acoustical image.

The authors interpret its essential reason in physics about this acoustic interaction. It gives a clue that, to realize a high precision acoustical imaging employing SAM, the key is to arrange the focus of acoustic lens concentrated on the structures which the investigator are interest on/inside a specimen. Finally, the authors remind that the investigators should take into account edge diffraction and its influence while evaluation and characterization process, to promote the evaluating accuracy in NDT/E field by using Scanning Acoustic Microscopy.

Acknowledgements

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