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3D High-Quality Ultrasonic Imaging

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1. Introduction

Methods of direct quasioptical vision and holography can be used in systems of ultrasonic vision to form high-quality images of objects (V. A. Zvereva, I. N. Stepanova, 1979). The formation of images in the ultrasonic wavelength bands has certain specific features, namely: the sizes of the image-forming systems and of the objects of observation are comparable with wavelength, so that the diffraction nature of the image must be taken into account in calculating the structure of the image.

Both in the ultrasonic and optical wave bands, dielectric lenses and mirror antennas are used to format images of objects (Zelkin E. T., Petrova R. A., 1974). The application of these focusing elements does not solve the problem completely since objective lenses with very large apertures – on the order of several meters – are needed to obtain high-quality ultrasonic images. Fabrication of such lenses involves considerable technological problems because the more practical ones are lenses with a small refractive coefficient and focal length equal to the aperture (Minin I.V., Minin O.V., 1992).

The thickness of the lens is several tens of percent of aperture size. Therefore the mass of such a ultrasonic objective is considerable. Energy losses connected with absorption of the transmitted radiation in the lens material are high. Using mirrors to generate ultrasound images is constrained by the fact that the object and the image area on the same side of the focusing system.

Promising analogues of lenses in the ultrasonic band are objectives based on diffractive elements (Minin I.V., Minin O.V., 1992. Minin I. V., Minin O. V. , 1988. Minin I. V., Minin O. V., 1989).

When building a real system for generating ultrasonic images of objects with the resolution depth greater than given by a conventional image, one must scan the object in three coordinates. For instance, using a mechanical scanning into the depth of the object makes it difficult, and sometimes impossible, to obtain the entire radio image of the object in real time.

A realistic system of visualization of three-dimensional objects in the ultrasound wave band must provide scanning of a volume of space of at least $(10^5 - 10^8)\lambda^3$, and it is required that objects whose characteristic sizes come to several wavelength must be reliably identified in this volume. Therefore, the system of visualization must provide resolving power in the object space of about 5-6 mm. In classical systems of image generation, that is, in systems that use lenses and mirrors as image formatting elements, high transversal resolution (relative to the optical axis of the objective lens) is achieved at high values of numerical aperture. However, as the resolution on the object increases, the resolution depth of the lens (and therefore, the longitudinal resolution) decreases, and if we take into account that

$$\delta_{longit} \sim 2\lambda(F/D)^2 \quad \text{and} \quad \delta_{transv} \sim 1.22\lambda(F/D),$$

it is not difficult to arrive at the following estimate:

$$\delta_{longit} \sim 1.3\delta^2_{transv}/\lambda \ .$$

A contradiction thus arises: trying to increase resolution on the object in the transverse direction, the resolution depth of the image-formatting systems decreases following square law, that is, the problem of generating a ultrasonic image of a three-dimensional object whose extension in the longitudinal direction is several tens of wavelengths, becomes practically unresolvable in this approach because of the high spatial resolution.

Generation of quasioptical ultrasonic images of objects

We shall consider now how to obtain images of objects with resolution depth greater than that provided by the quasioptical system.

The problem may be solved in this case by applying the so-called layer-by-layer scanning of the object. The essence of this technique is that at each given moment of time a flat two-dimensional radio image is constructed of one layer of the object or of an individual point within the resolution depth of the transmitting lens with high transversal resolution. The total image of a three-dimensional object is then reconstructed by summing up individual layer images with assigned weight coefficients. A layer-by-layer scanning of a three-dimensional object can be implemented, for instance, using the method pointed to in (Pat. FRG 1762, 406, 2301800, 26555257).

For instance, three-dimensional information is reconstructed in several spatial zones arranged stepwise into 3D space. The zones are then displayed sequentially one after another for a short interval on the controlling video device. Therefore, the observer is offered not only the general view of an object observed in a single plane of image – as we have in cinema or television – but also information on spatial depth which is used as additional information by quantizing over depth. It is expedient to choose the time sequence of the displayed two-dimensional flat images in such a way that the observer (owing to the inertia of eye vision) perceives the sequence as one total image.

In a continuous process of creating a large number of images with various positions of layers, an object is created and poorly defined details are suppressed by filtering through a filter with predominantly high-frequency characteristics. By adding up these filtered signals, the total image of a three-dimensional object is created and the corresponding non-filtered image is added to the filtered one. Filtration here can be implemented with a filter with a linearly growing frequency curve – because it is assumed that in continuous focusing and summation (integration). For instance, if a distribution of intensity of light dots over black background is processed and then this image is integrated, a pointlike image with a wide halo appears.

A change in the focal distance of the quasi-optical system that uses diffractive elements is implemented by changing the frequency of radiation emitted by the irradiator. To implement spatial selection of the signal reflection by the object and the signal sent by the irradiator, and for automatic "tracing" of the region of focusing along one of the coordinates, for instance, along the optical axis, it is advisable to use either off-axis diffractive elements or diffractive elements with off-axis position of the focusing region. The former option is preferable for the radio vision because diffractive elements then retain their focusing ability in a wider frequency band than elements with off-axis position of the focal point.

Formation of images using partially coherent radiation

We will consider the problem of suppressing interference fringes in the optical system for formatting the image, with the irradiator being a small-size thermal source of quasi-monochromatic radiation $\Delta\nu/\nu << 1$, where $\Delta\nu$ and ν are the effective frequency and the irradiator's frequency band, respectively.
According to (Perina J., 1972. Tarlykov V. A., Magurin V. G., 2002) we can observe here interference fringes, provided

$$\Delta\nu\Delta a < \bar{\lambda},$$

where $\bar{\lambda} = c/\bar{\nu}$ is the effective wavelength, c is the velocity of light and Δa is the size of the source (Kaliteevskii N. I., 1971).
If a thermal source of quasi-harmonic radiation is used as irradiator, the interference fringes on the image is removed if the ratio of numerical apertures of the source and the receiver $\rho_s/\rho_0 >> 1$ and the resulting resolution corresponds to the diffraction limit of receiver optics with non-coherent illumination.
When an object with specularly reflecting surface is observed, its image contains sparkling that suppresses the fine structure of the image. At the same time sparkling from external sources are superimposed onto the original images.
It is possible to remove this distorting noise without changes in illuminating sources, for instance, by placing in front of a flat object a nonuniform transparent scattering (refracting) plate. The possibility of removing the sparkling is determined by the scattering diagram of the plate and by the optical power of noise.
The illumination of the object in systems of direct vision in the ultrasound band is done with coherent radiation. The image of the object is constructed in reflected radiation using special high-aperture objectives (lenses). An interference image is formed when layer images are added up. Furthermore, most objects have specular surface in this wavelength band. This occurs because the wavelength λ_0 at which vision systems work is much longer than the visible light wavelength λ_c used to visualize an object $\lambda_0/\lambda_c \sim 10^4$. Therefore the surface structure of visualized objects is smoother (more specular) with respect to ultrasonic than it is for light by a factor of (λ_0/λ_c); hence, an interpretation of the resulting image becomes ambiguous. For instance, the image of a sphere is a point.
Method of isotropic construction of images of three-dimensional objects (Minin I. V., Minin O. V., 1998)
As it well known reflection coefficients of objects for ultrasound waves are generally random complex value. Hence the conventional coherent imaging systems have suffered to some extent from speckle noise. Speckle occurs when scattered radiation from objects or rough surfaces randomly destructively interferes and degrades image smoothness. So speckle noise and weak edges make the image difficult to identify the object in the ultrasound image. And the analysis of ultrasound image is more challenging one. But if we can generate at each point on the object sufficient large number of sample wave fields with the same magnitude and random phases and the image of the average intensity of the field can be derived, then a desired imaging which is free from speckle noises must be realized (Takayoshi Yokota, Takuso Sato, and Makoto Hirama, 1985).

The “spaced-apart reception” techniques can be used to suppress interference noise in ultrasonic images.
Let us consider an object model consisting of two pointlike reflectors. With two-frequency illumination, the best suppression of interference noise is achieved if

$$\Delta\lambda/\lambda \sim 1/2m,$$

where $m = d/\lambda$ and d is the distance between the reflectors.
In the case where there is only one wavelength and we have two receivers whose signals are added up, the following condition can be obtained for the angular separation Ω between two receivers:

$$\Omega = \arctan[(4m - 1)^{1/2}/(2m - 1)] . \quad (1)$$

Similarly, we can derive for n-frequencies illumination and a string of n receivers the formulas

$$\Delta\lambda/\lambda = (n - 1)/mn,$$

$$\Omega_\kappa = \arctan[(2mn\kappa - \kappa^2)/(mn - \kappa)], \quad n = 2, \dots ,$$

$$\kappa = 0, \dots , (n - 1).$$

The interval $\Delta\lambda$ corresponds to the difference between the maximum and the minimum of wavelengths of n-frequencies irradiation and Ω_κ corresponds to the angular separation between the first and the Kth receiver of the linear string.
Consider the placement of several receivers optimized for suppressing interference noise in a finite field of view.
To suppress interference noise in a finite field of view we distribute n receivers in such a way that for each point there would be two receivers whose signals are in antiphase. We define the number of receivers as the ratio of the solid angle covering the system of receivers to the solid angle of a single receiver.
In order to maximally suppress interference effects at a point A on the axis (fig. 1) it is necessary to place the second receiver 2 at a distance given by formula (1). To suppress interference effects at the edge of the field of view at points BB′ it is necessary to install receivers 3 and 4 at such a distance from receiver 1 that the difference between the optical path lengths between receivers 3 and 4 and the point B equal 1/2 of the wavelength of the radiation used.

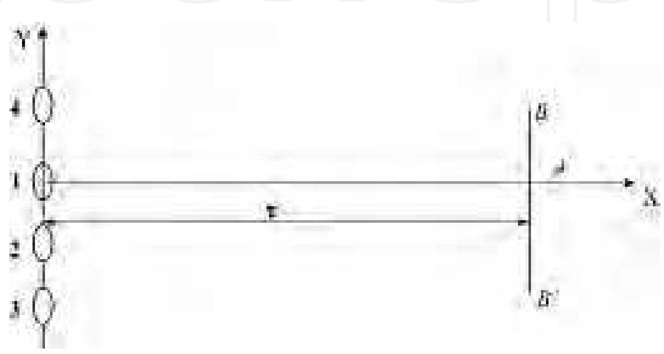

Fig. 1. Locations of radiation receivers for suppressing interference noise in a finite field of view.

Consequently, in a string of four receivers, two pairs of them are strictly in antiphase (at the centre and at the edge of the field of view). For n receivers, the number of such locations is n-1. We were looking so far at a one-dimensional case. To consider a two-dimensional case, the string of receivers has to be rotated K times around the X axis by an angle $\Delta\varphi$, so that $(K\Delta\varphi)=\pi$. The required number of receivers can be found as

$$N = \Omega/\Delta\Omega = \{2\pi(1 - \cos\theta/2)\}/\{(\pi/4)(D/4)^2\}.$$

Let us find the optimum location of two receivers for an arbitrary location of the object in the field of view. Let the object lie on the axis of the first receiver. The signals of the two receivers will be at opposite phases if

$$\frac{d(r_0+d)}{\sqrt{(r_0+d)^2+a^2}} - \frac{d(r_0+d)}{\sqrt{(r_0+d)^2+(a+y_0)^2}} = \frac{\lambda}{2}.$$

We conclude that for optimum suppression of interference noise the distance between the receivers must equal

$$y_0 = \left[\frac{r^2 d^2}{\left(\frac{rd}{\sqrt{r^2+a^2}} - \frac{\lambda}{2}\right)} - r^2\right]^{0.5} - a, r = r_0 + d.$$

Therefore, this method of forming radio images on the basis of an "isotropic" receiver (source) essentially consists in implementing the principle of spatial averaging. For instance, the object may be scanned by a focused beam of electromagnetic waves, the radiation scattered by the object being received by a systems of receivers located in space on the side of the irradiator, while the signals from them are added up non-coherently and are sent to the common system of reconstruction. The receivers are placed on the surface of a hemisphere whose centre lies on the object. As a result, it becomes possible to visualize objects using the difference between their reflection coefficient and the reflection coefficient for the background signal, that is, to visualize an image of a three-dimensional object. Non-coherent adding suppresses interference effects. When integrating narrow directed signals reflected from obstacles (the background signal), the received interference signal is proportional to the coefficient of reflection from the obstacle, and this is typically much lower than the coefficient of reflection from the object. On the whole, a system of N receivers proves to be more sensitive than a single receiver by a factor of $N^{1/2}$. Furthermore, averaging considerably reduces the dynamic range of signals recorded, which makes the requirements to systems reconstructing radio images less stringent.

Another important factor must be mentioned. In systems of direct vision, a receiving device is as a rule large and heavy which makes using this technique very difficult (for instance, the diameter of the objective is at least 200-300λ, so that even with a speed of 1 frame per second and the number of added layers $n \sim 30$, the objective that does mechanical scanning of the object over its depth must periodically move at a typical speed of about 350 m/s).

Attempts to use the conventional "optical" approach to constructing ultrasonic images of three-dimensional objects result in extremely unwieldy formulas. The resulting dimensions, weight and parameters of objective lenses fail to satisfy today's requirements.

Layer-by-layer construction of the image of a three-dimensional object without mechanical scanning over depth can be implemented by using the frequency characteristics of DOE in which the position of focusing area depends on the wavelength of the irradiating field. In this case the speed of the vision system improves considerably. It becomes possible to start with locating an object by scanning over the depth of the scene and then to carefully "scrutinize it" in detail.

Listed below are the main specifics of designing the ultrasonic vision system.

1. Row-by-row scanning for building the image of an object in real time is carried out by electronic scanning of the string of receivers.
2. Frame-by-frame scanning (column-by-column scanning) is implemented by mechanically moving the object controlled.
3. Mirror flashes in the image are removed and the images of the object in different orientations are obtained using quasi-isotropic illumination by a system of irradiators distributed in space.
4. Scanning of the controlled space is done by the electronically shifting the plane of focusing of the vision device (its focal length) by varying the irradiators' wavelength and using diffractive optics. The use of elements of diffractive optics on a non-flat surface makes it possible to extend the field of view of the vision device and improve the signal-to-noise ratio in the ultrasonic image.
5. Access to the object scanned is provided on one side only.

The vision set supports scrutinizing an object with a single frequency (scanning of a plane) or with a number of frequencies (scanning over the depth of the scene) in single-pass or continuous modes of recording the frames of image with an external coupling (to the motion sensor) or internal coupling to the motion of the object, and can also operate in adjustment mode to fine-tune individual components of the vision set.

The main component of any vision system of quasioptical type is an objective that must satisfy a number of requirements (Minin I. V., Minin O. V.,1986. Edward O.Belcher et al., 1999. Yuji Sato at al., 2009):

- to be multicomponent (to satisfy the requirements to field of view ($2\beta \sim 60^0$) and the number of resolved pixels on it ($N^2 \sim 100\times100$));
- to possess frequency characteristics adequate for inspecting three-dimensional scenes in real time;
- to have aperture ratio of at least 0.5 and lens aperture (D/λ) of at least 200 to provide high spatial resolution constrained by the diffraction limit over the entire field of view;
- to be fabricated of a material possessing low absorption of ultrasonic power, and be of minimal thickness.

In the active vision mode, when monochromatic radiation is used to illuminate the target object, it is possible to reshape the focusing surface by controlling the frequency of the illuminating radiation and scan the space over the depth of the scene by this surface (Minin I. V., Minin O. V., *et al.*1985). Therefore, frequency characteristics of diffractive objectives make it possible to remove limitations stemming from the small depth of definition of classical lenses. Such systems of image generation are capable of scanning space over depths exceeding the depth of definition by a factor of 10 to 20 without mechanical scanners (Minin I. V., Minin O. V. 1986. Baibulatov F. H., Minin I. V., Minin O. V. 1985.). Small thickness of diffractive objectives (on the order of radiation wavelength) allows designers to achieve high efficiency of using ultrasonic power.

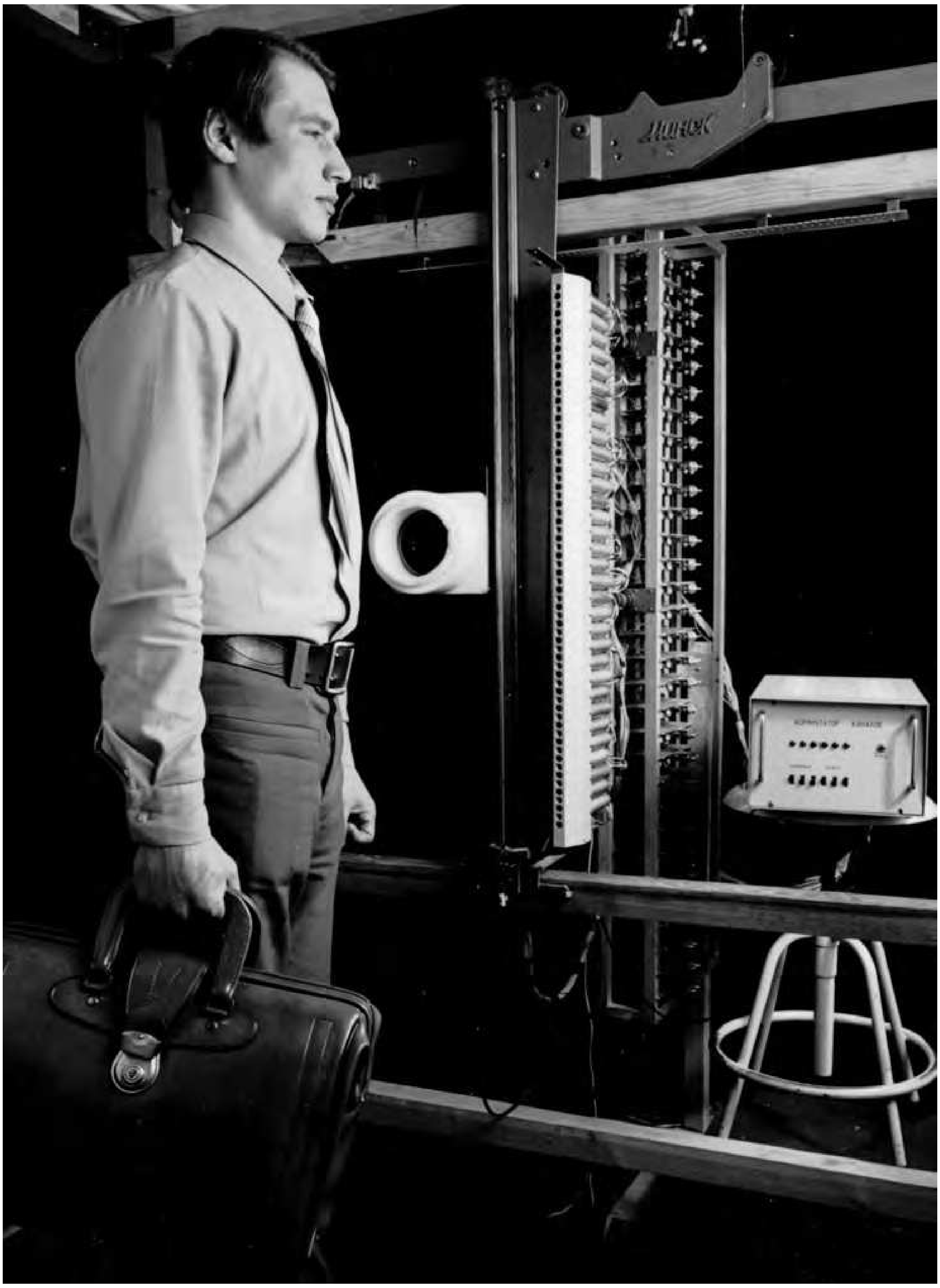

Fig. 2. The pilot version (1988) of 40 KHz real-time ultrasonic imaging system for concealed weapon detection, based on points 1,2,5 and developed under the scientific leadership of Professor V. F. Minin (Minin I.V., Minin O.V., 2003).

2. Fresnel lenses design by acoustic network

Fresnel zone plate (amplitude binary type) was designed by Shu Zhang (Shu Zhang., 2010) to pass only the odd (even) zones and obstructs the even (odd) zones. Fig.3 (left) shows the configuration of planar 1D Fresnel lens we designed. The lens is composed of an array of Helmholtz resonators. The resonators which resonate at 50 KHz in pass even zone are filled with water. The cells in odd zone are filled with air to induce large impedance mismatch, resulting large reflection to obstruct vibration.

Finite-element method was employed to study the focusing of the designed Fresnel plate lens. A collimated acoustic wave is incident on the plate, which is put inside water medium. More than 50dB pressure level difference is found between pass and obstruct zones in Fresnel zone plate based on acoustic network at 50 KHz. Compared with conventional Fresnel lens with the same thickness, the focus effect is more efficient through those based on acoustic network design .The focal length of the lens can be tuned at different frequency as well.

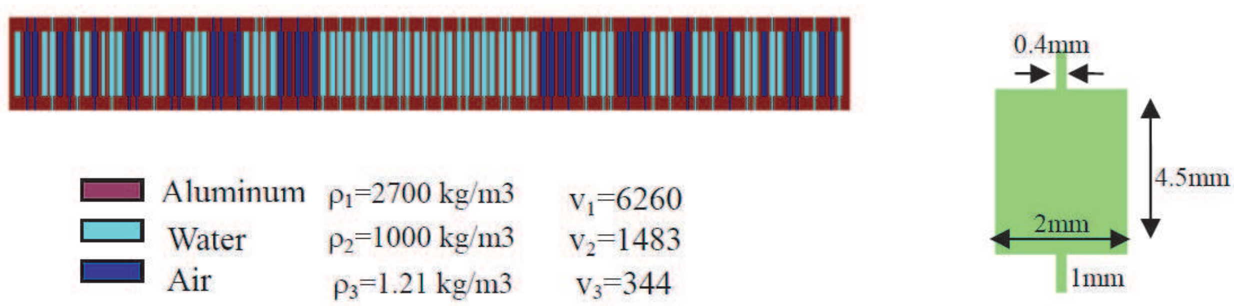

Fig. 3. Configuration of acoustic Fresnel lens (left) and the unit of Helmholtz resonator (right) (Shu Zhang., 2010)

3. Elementary principles of diffractive optics design in acoustics

Acoustic zone plates are used to demonstrate various physical processes (Kirilov V. A., Tverdohlebov V. I., Homenko V. I., 1964). Considerable difficulties are encountered, however, in creating acoustic zone plates that invert the phase of oscillations of one half of the zones. The reason is that the acoustic resistance ρu of any material is so high compared to the resistance of air that acoustic waves are nearly completely reflected. A phase zone plate can be produced using the method suggested by Kock (Kock W. 1965) for fabrication of microwave lenses. The method consists in forcing waves to move between tilted plates; the path length then increases by a factor of 1/cosQ which corresponds to the effective index of reflection n = 1/cosQ for the propagation of waves in free space.

The strip width l is found from the conventional relation $d(n - 1) = \lambda/2$ or $d(n - 1) = \lambda$, which in this particular case of n = 1/cosQ and strip width $l = d/\cos Q$ takes the simplest and physically transparent form:

$$l - d = \lambda/2 .$$

Also the circular Fresnel zone transducers may be made, for example, of sandwiched structure with *C*-axis oriented ZnO piezoelectric film between two Au electrodes (QIAO DongHai, LI ShunZhou, WANG ChengHao. 2007).

3. Ultrasonic piezoelectric transducer based on diffractive optics

For active focusing systems the surface of a rigid plate makes bending oscillations, and allocation of their amplitudes of particle displacements along radius of a plate looks like standing waves. Each point oscillations surfaces radiate an ultrasonic wave in an air medium. As is well know, in condition of central exciting of thin flat disk, which radius is multiple to half of flexural waves (in disk material), distribution of oscillating displacement on the disk surface will look like stationary waves. The radial boundaries on the plate from centre of a plate calculating according to the formula from microwaves (Minin O.V., Minin I.V. 2003). In this case the waves radiated of each exact plate will come to a focal point in one phase. The Noise level in a focal point in that case reaches values 200-220 decibel and above, and around of focal point surfaces of equal phases where the noise level reaches values 140-170 decibel is formed. The vibration amplitude of a radiating surface is about 200 micron.

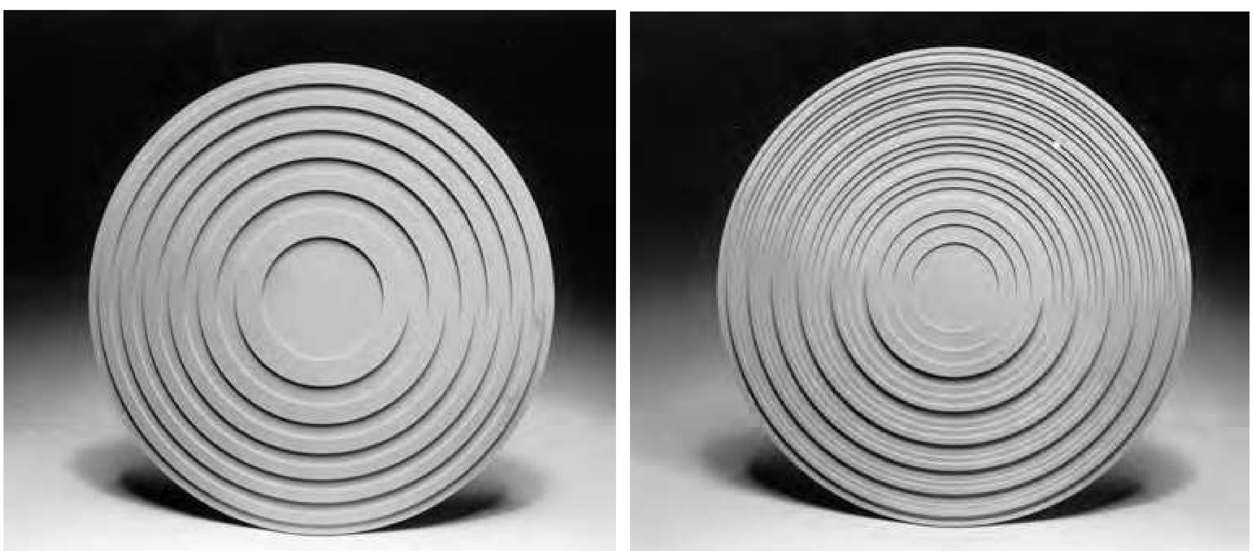

Fig. 4. The active ultrasonic diffractive transducers of half-wave (left) and four-level (right) types.

It could be noted that the advantages of diffractive plate-type emitters are: the possibility of forming ultrasonic vibrations of high power and provide frequency tuning of the radiation due to transition from one harmonic to another. The same diffractive plate-type emitter can create vibrations of different frequencies, operating at different harmonics.
For example, for the circular membrane in an common case we can use polar co-ordinates (r,θ). The spatial part of the wave function will be of the form R(r)Θ(θ). The boundary conditions will act specifically on R(r) which will be a Bessel function $J_m(kr)$ with zeros at well known (tabulated) values x_{mn} (m for the function and n for the n^{th} zero). This leads to the relation $k_{mn}a=x_{mn}$ to force a zero at r=a, the radius of the membrane. These results in the following relation for computing the angular frequency associated with the different modes:

$$\omega_{mn} = \frac{x_{mn} v}{a},$$

where v is the velocity of the wave in the membrane. The solution of our problem for the mode (m,n) is, basically, of the form:

$$S(r,\theta,t) = J_m(k_{mn}r)\cos(m\theta)\cos(\omega_{mn}t) .$$

A dependence with sin(mθ) is also possible, giving rise to the existence of 2 degenerate modes for each m (except for m=0). In general, a linear combination of both modes will be excited.
For the case of a transducer we need only the modes with m=0. The distribution of oscillations amplitude on the first three oscillation modes of disk radiator is shown in Fig 5.

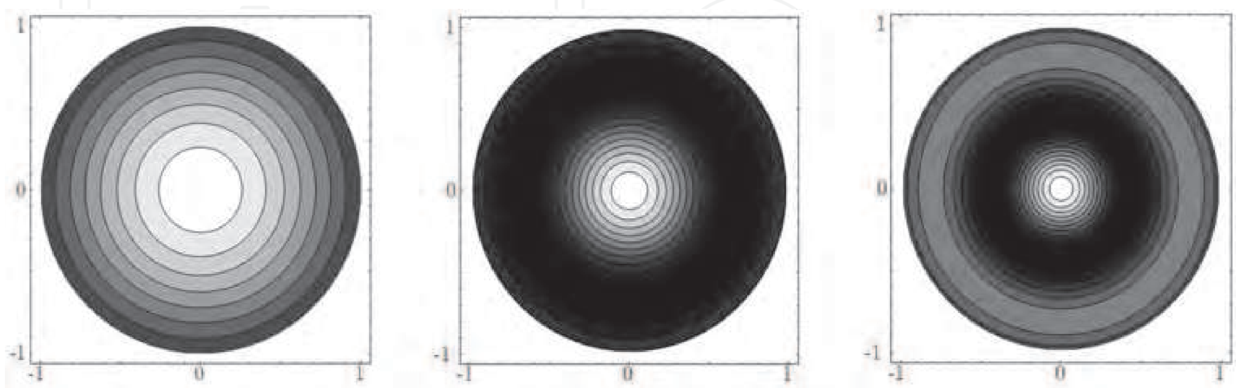

Fig. 5. The distribution of oscillation amplitude of diffractive radiator on the different oscillation modes: n=1, 2, 3.

4. Some other diffractive optical elements applications in acoustics

Fresnel zone plates can be used in audiovision (Greguss P. 1980) and nondestructive ultrasound testing (Stamnes J. J., Cravelsxter J., Bentsen O., 1982. Ermolaev I. N., Kanevskii I. N., Kofolev V. D. *et al.* 1980. Chernoverskii M. P. 1988), both in reception and emission modes. In reception mode, the zone plate consists of a sequence of alternating transparent and opaque zones. This zone plate behaves as a conventional acoustic lens.
If used as focusing emitter, the acoustic converter is fabricated as a zone plate. For instance, a binary zone plate with 10 zones made as a sequence of gold electrodes on the surface of a ceramic converter was described in (Stamnes J. J., Cravelsxter J., 1982). The other side of the converter has a common metal coating. When used to transform electric fields, only transparent zones emit. This means that the same zone plate can be used to generate both an "audio" picture and an image of an object.
Acoustically emitted diffractive focusing elements possess another very interesting and very promising property (Kock W., 1965. Greguss P., 1980). If zones made of gold electrodes are replaced with photoconducting layers and placed between a converter and an optically transparent electrode, this device can be controlled by light. If an optical image of a diffractive element is projected onto such a converter and is moved transversally, the point of acoustical focus will also move. Therefore, two-dimensional scanning can be realized.
The design and development of a low cost, electro-mechanical ultrasonic scanner for obtaining high resolution C-scan images of the friction skin ridge structure found on the digits of the hands or feet in order to create imagery of sufficient quality for use in automated personal identification systems were discussed in (J.K. Schneider, S.M. Gojevic. 2001). It has been shown the optical scanner is unable to image through the contamination, while the ultrasonic scanner is unaffected.
A breadboard ultrasound sensor has been developed for remotely detecting and imaging concealed weapons (Applied Technologies - Jaycor http://www.jaycor.com/eme_sens_

ultra.htm). The breadboard sensor can detect metallic and non-metallic weapons concealed on a human body under heavy clothing at ranges up to 8 m and can image concealed weapons at ranges up to 5 m.
This breadboard sensor has produced the only remote ultrasound images of concealed weapons, including lexan (plastic) knives and a handgun concealed under a heavy sweatshirt at 15 feet. The sensor includes a highly efficient source of high-power, tunable ultrasound radiation suitable for remote imaging in air. Together with millimeter-sized, highly sensitive ultrasound detectors and high-gain transceivers, these advances make possible the centimeter-resolution imaging of concealed weapons at ranges between 1 m and 5 m.
Ultrasound is also a "technology that uses high-pitched sound waves to create images of hidden internal anatomy" to detect a land-mine (C. P. Gooneratne, S. C. Mukhopahyay, G. Sen Gupta. 2004). Conventional ultrasound detection involves the emission of a sound wave with a frequency higher than 20 kHz into a medium. This sound wave reflects on boundaries between materials with different acoustical properties. A strong enough ultrasound signal could penetrate the ground and detect otherwise unobtainable signatures of buried mines. It is also capable of operating in wet ground. Ultrasound systems encounter problems at the interface of air and ground.
One of the classical applications of the ultrasonic imaging system is a nondestructive method of inspection. For example (SERDP PP-1134, Final Report, November 2001), the inspection of very thin metallic sheets (0.06 inches up to 0.125 inches thick) was shown to be difficult for the reflection method of ultrasound imaging to undertake; this was due to the extremely short time delay between the front and back surfaces of the thin sheets. By injecting the sound beam into the metallic sheet at an appreciable angle it was found to cause multiple reflections progressing along the sheet with the end result of illuminating a large region of the sample with sound energy. A prototype angle beam ultrasound camera was fabricated at the Becker Labs of the Naval Air Warfare Center Aircraft Division (Figure 6) and has proven that rapid ultrasound imaging of thin sheet is practicable and is unaffected by painted coatings.

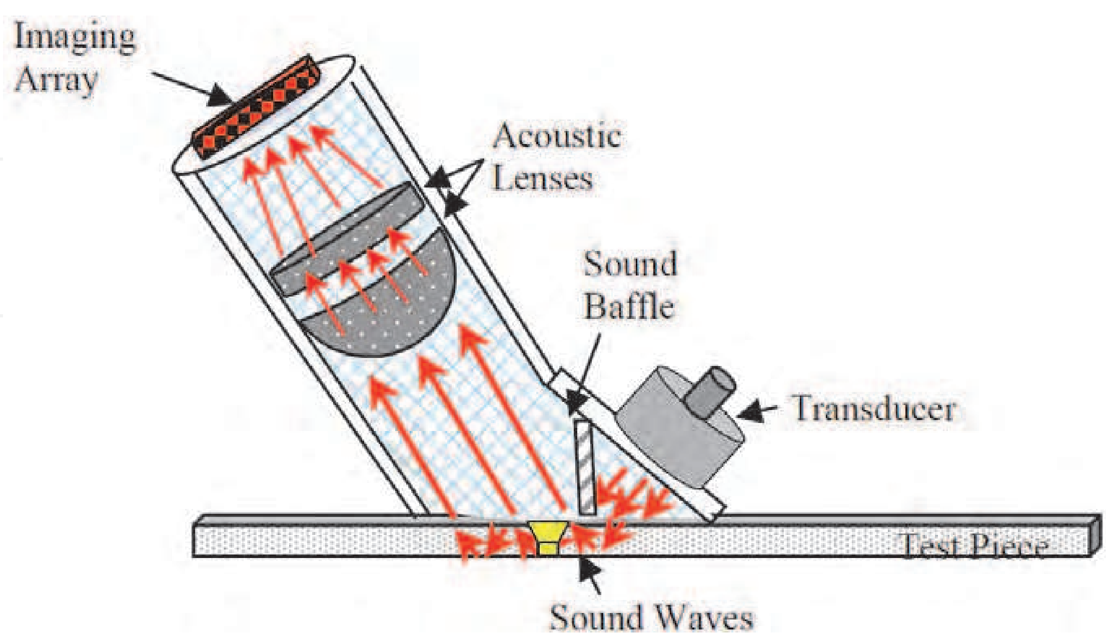

Fig. 6. Schematic of oblique angle reflection camera for real-time ultrasound imaging (SERDP PP-1134, Final Report, November 2001).

The Acoustocam system (Development of Innovative Nondestructive Evaluation Technologies for the Inspection of Cracking & Corrosion Under Coatings SERDP PP-1134, Final Report, November 2001) was shown to be able to respond to the dynamic range of the multiple bounces with an image very similar to that of a through transmission image with the exception that recurring images of a defect are observed in the oblique angle reflection mode owing to the fact that the sound beam continues to reflect (See Figure 7). The concept, however, has proven to be viable for the inspection of corrosion under painted coatings at high speed and with high sensitivity. Application has been made for the issuance of a patent based on the oblique angle beam system.

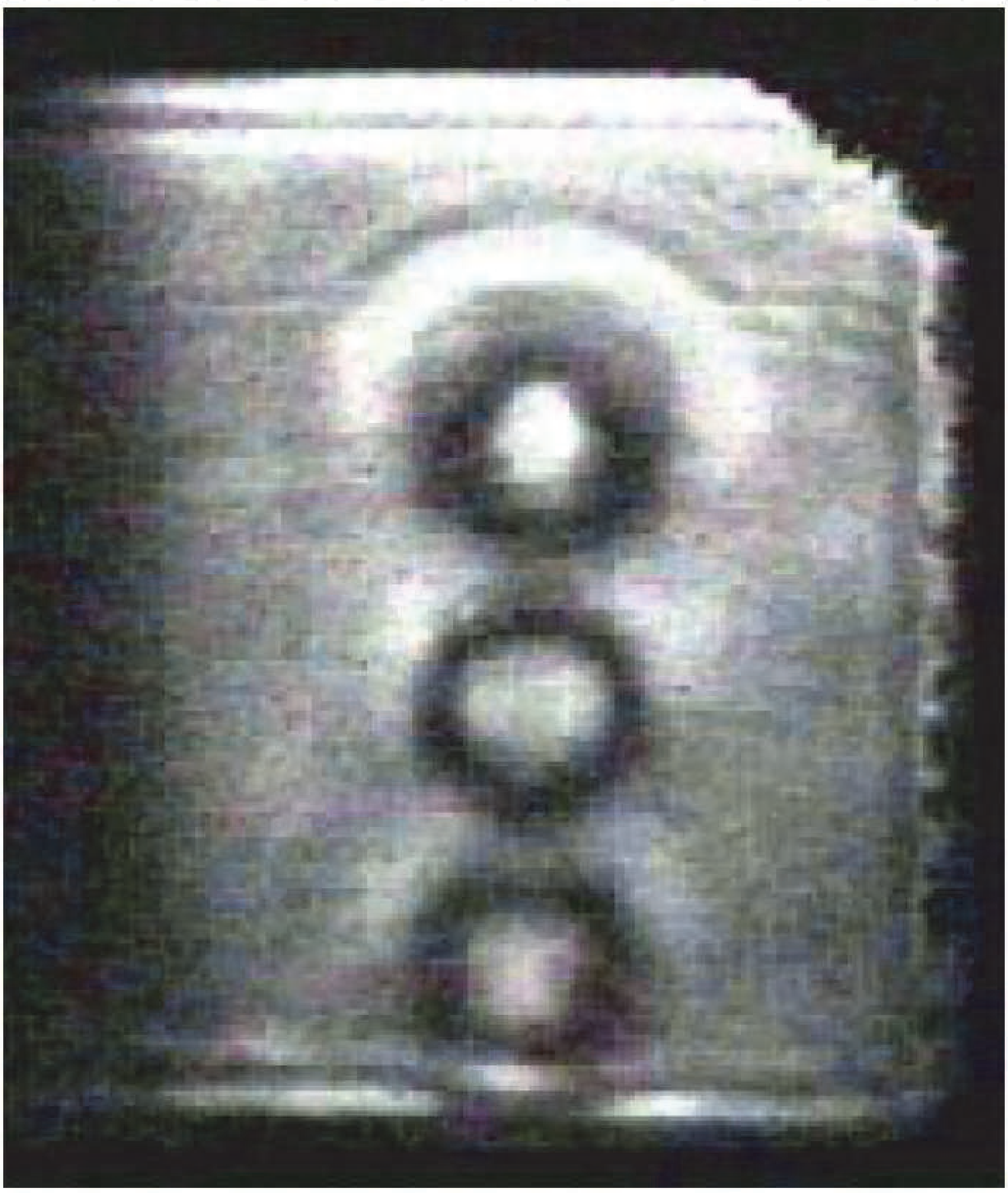

Fig. 7. Angle beam image of a flat bottom hole showing the multiple images that occur (C. P. Gooneratne, S. C. Mukhopahyay, G. Sen Gupta. 2004).

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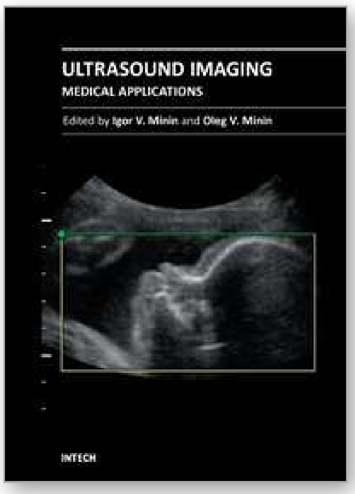

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This book provides an overview of ultrafast ultrasound imaging, 3D high-quality ultrasonic imaging, correction of phase aberrations in medical ultrasound images, etc. Several interesting medical and clinical applications areas are also discussed in the book, like the use of three dimensional ultrasound imaging in evaluation of Ashermanâ€™s syndrome, the role of 3D ultrasound in assessment of endometrial receptivity and follicular vascularity to predict the quality oocyte, ultrasound imaging in vascular diseases and the fetal palate, clinical application of ultrasound molecular imaging, Doppler abdominal ultrasound in small animals and so on.