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STATUS OF RESEARCH IN ACOUSTIC IMAGING AND HOLOGRAPHY

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Abstract

This paper reviews the results of research in imaging reported in the last two years approximately. The emphasis is placed on the high frequency applications of this subject and very little reference is made to sonar and none to geological applications. The subject is discussed under three main divisions, direct (pulse echo) imaging, holography and finally particular devices. Emphasis has been placed on the physical principles used. It is assumed the reader is conversant with the outlines of earlier work in the field.

Introduction

In reviewing the situation in ultrasonic imaging and holography one is faced with the task of choosing material for omission because the work which has been done is so remarkably extensive (even though it is mainly the achievement of the last ten years or so).

The methods of ultrasonic holography and imaging are a generalization of the processes which are used in conventional optics and high frequency electromagnetism. This state of affairs arises because of the special properties of sound waves. First, sound has several modes of transmission, both longitudinal and transverse waves exist. Second, the velocity of propagation is low and, usually, the frequencies used are low enough that detail processing of signals presents no problems, which is not the case with light for example. Consequently, methods which can only be imagined in other fields can be practised in acoustics. Finally, the absence of any acoustical receiving system which has such special virtues that it can be regarded as unique has presented experimenters with a challenge. Now an almost bewildering array of alternatives present themselves, each with its own special advantages. It is difficult to say at this time how much acoustical research has contributed to the general field of "imaging" and how far it has taken its ideas from its close physical relatives. I think that future assessments will show that acousticians have made a fairly substantial contribution to recent advances in the general area; a point that might be demonstrated in part in this review.

The subject will be discussed here first by reference to general principles and secondly by reference to particular applications. Of necessity, low frequency imaging related to geological surveying and sonar scanning is not generally discussed.

Receivers

Table 1[1] summarizes the many methods of detecting the ultrasound from which the image is to be formed. This table probably requires two additions, (i) the AOCC converter of Greguss[2] which uses nematic liquid crystals, and (ii) use of the pyroelectric effect in a Sokolov tube (Jacobs[3]).

The methods which have proved more popular are based on the piezo-electric effect, liquid and solid surface deformation and the optical detection of density variations. It is, of course, very possible that another method might become active again. The history of the topic almost suggests this will happen as is instanced by the considerable improvement in the Pohlman Cell[4] which arose from the work of Campolattoro *et al*.[5].

Non-holographic Imaging

Direct pulse echo visualization systems are widely used, particularly in medicine. Many different modifications of the simple single transmitting and receiving transducer system have been made. The most important developments in this field probably relate to the phasing of arrays. Some of the Australian work reported by Kossof[6] is perhaps of interest in this regard. He observed that there are three basic limitations to the techniques in use and lists them as:

i. lack of lateral resolution;
ii. the inability of mechanically moved (or hand operated) transducers to cope with mass screening of the population together with the inability of such systems to examine fast moving structures, such as the heart;
iii. "artifact echoes" related to multiple reflections which obscure the genuine echoes from the smaller internal organs.

He discussed methods of overcoming two of the difficulties starting from the use of a concentric annular phase array, see Figure 1. If the array is used for transmitting, then the relative phase between the elements will decide where the focal point of the energy will be. The quality of the focussing action is another and much more complex matter which will be discussed later. The reflected sound waves on their return

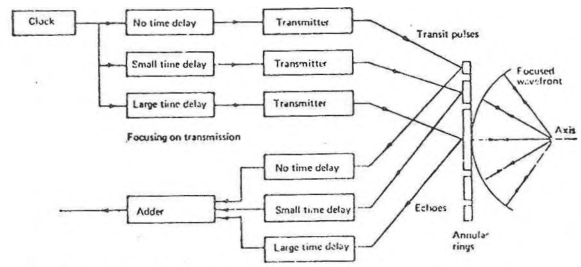


Fig. 1. Annular phased array

can be focussed on reception by introducing suitable time delays to the signals after their reception and prior to their summation; thus the phased array can be focussed on any point by introducing the correct delay in signal processing. The practical difficulties associated with this system led him to suggest linear phased arrays should be used. He concluded with the discussion of the crossed phased array transducer, see Figure 2. The ideas of using phased arrays are not new and have been the subject of interest in other fields for quite some long time. Halvice, Kino and Quate[7] described an elegant method for an electronically focussed two dimensional array, see Figure 3. From this they produced some very good images. This process is clearly capable of much extension and elaboration. Focussing can be achieved by any means of summing the elements of the wavefront which takes proper account of the phase relationships. Electronic, digital or refraction processes all allow this summation to be undertaken. It is not obvious which method has the greatest advantage because work on this topic is developing so rapidly. In more recent work, Macovski and Norton et al[8] considered segmented annular arrays, see Figure 4, and showed that very high resolution can be obtained from their use. This work is closely related to that of a Vilkomerson [9&10] who also demonstrated and discussed the properties of annular arrays of piezo-electric elements. Thurstone et al[11] discussed the use of sampled apertures and the summation of received signals to produce images of brain tissue using programmable delay lines, see Figure 5. The object was to correct for the phase abberations introduced by the skull. We can neglect the causes of the variations and treat the phase compensation as a general problem. If we do so, then

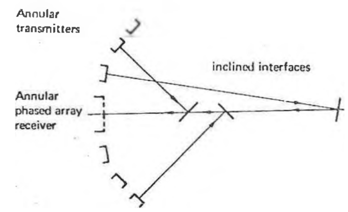
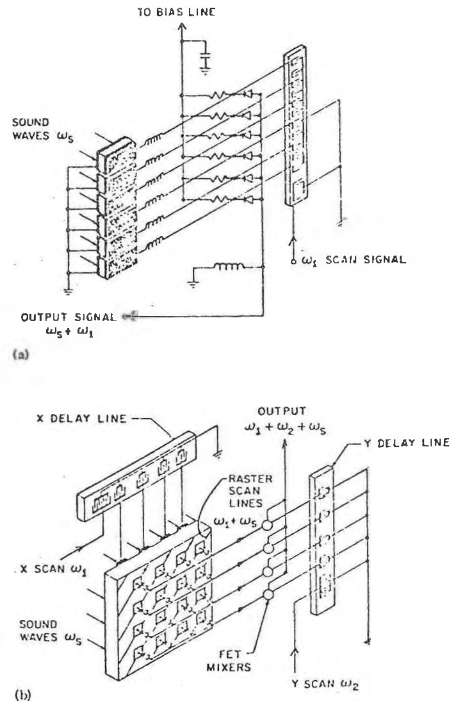


Fig. 2. Wide aperture array



←Fig. 3. Electronically focussed imaging device

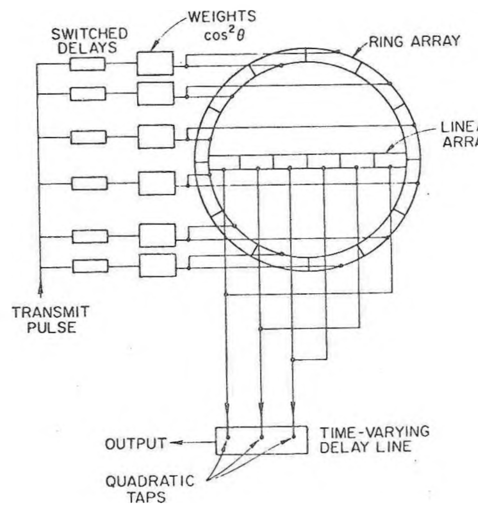


Fig. 4. → Sector scan system using a weighted ring transmitter and dynamically focussed line array receiver

we find that this leads us back to classical optics and to the work of Wild[12], Toraldo di Francia[13] and Luneburg[14]. The latter two authors demonstrated that any aperture can achieve any chosen resolution limit provided we satisfy two theoretical considerations and solve two practical problems. Theory demands that we must be able to modify the phase and amplitude of an incoming wavefront (shading) in any way which we choose after it has passed through a receiving aperture. If we can do this, then provided we can solve a massive set of simultaneous equations, we can decide on the shading characteristics. In practice we may find, unfortunately, that we are left with an image which is of nearly zero intensity. Remarkably, we can show that for any given aperture there is no unique solution for the shading. Luneburg demonstrates this very elegantly by providing three alternative solutions for a given aperture problem. The point can be explained by reference to the Fresnel-Kirchoff diffraction integral[43]

$$U(P) = -\frac{Ai}{2\lambda}\iint_A T\frac{e^{ik(r+s)}}{rs}\left[\cos(n_1 r) - \cos(n_1 s)\right]dS \qquad (1)$$

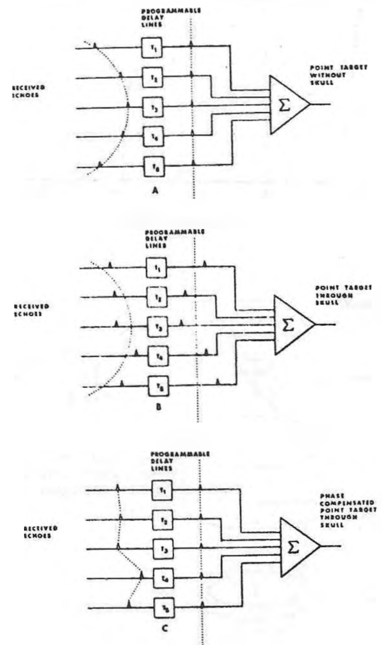
(See Figure 6) where U is the amplitude of the diffracted wave. If we choose to introduce a factor

$$T(x,y) = T'(x,y) + i\,T''(x,y) \qquad (2)$$

then it becomes

$$U(P) = -\frac{Ai}{2\lambda}\iint_A T\frac{e^{ik(r+s)}}{rs}\left[\cos(n_1 r) - \cos(n_1 s)\right]dS \qquad (3)$$

By a suitable choice of T we can produce any value we wish for U(P). Consequently we can, by "shading" the aperture in some arbitrary way, produce any diffraction patter we like at a given image plane. Toraldo di Francia described a method for choosing T' and T" for a circular aperture and provides examples of some of the difficulties which can arise.



←Fig. 5. Phase compensation technique in receiver mode

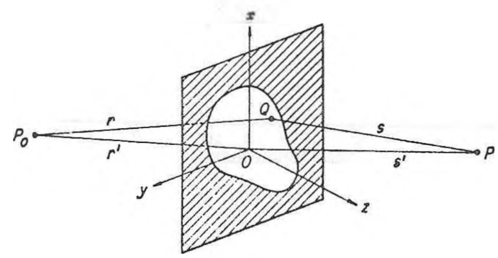


Fig. 6. → Diffraction at an aperture in a plane screen

If it is supposed that some ideal pressure diffraction pattern has been obtained and we have to use this information without degrading it, then the angular response of the receiver is important and this has been explored by Jones[15] and Ahmed[16]. Figures 7 and 8 show this response of PZT and quartz. The use of the Kirckoff integral as it is presented in Equation 3 implies that the receiver response is independent of the angle of incidence; if this is not the case then it has to be modified.

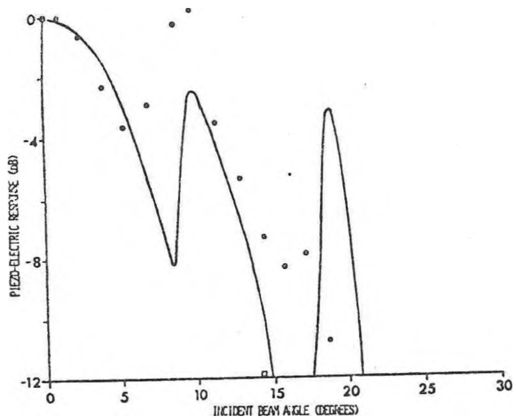
The effect of the aperture is clearly of considerable general concern and here it should be said that in principle there is no reason for an actual physical aperture to exist. Its existence can be inferred or synthesized by the use of suitable receiving and transmitting arrays. Much work has been done in this area, the purpose of which has been to produce the best resolution with the minimum number of piezo-electric elements. Examples of such work, apart from that already mentioned are given in reference 17, 18, 19.

At this point it is probably appropriate to digress sufficiently to mention a related point concerning scanning. Wade and Wang[20,21] discussed this question from the point of view of sensitivity and contrast and introduced the terms Positively Scanning Transmitter (PST), Positively Scanning Receiver (PSR), Negatively Scanning Receiver (NSR) and Negatively Scanning Transmitter (NST). They investigated the relative advantages of each system. These systems can perhaps be briefly explained by reference to the PST and NST systems. In the PST system the transmitter provides a beam which is focussed at and scans the object plane. A transducer (or array) at the receiver records the signal and the temporal output signal corresponds to the spatial structure of the object. In the NST system the only part which is not illuminated is that part of the object for which information is required, i.e., it is the negative version of the PST (and is only of theoretical interest). The authors show that the PST system allows the average intensity of the ultrasound used to be less than that required in other systems. They also discussed the use of an opto-acoustic transducer as the ultrasound source. This transducer switches on in the regions which are illuminated by a light beam. Several rather ingenious methods of scanning were introduced which depend on the use of holographic illumination patterns on the transducer to produce focussed scanning beams, see Figure 9.

Returning to Kossof's list of limitations, it can be noted that mass screening apparatus still appears to be a distant hope in spite of the ingenuity which has been applied to detail designs of direct imaging system.

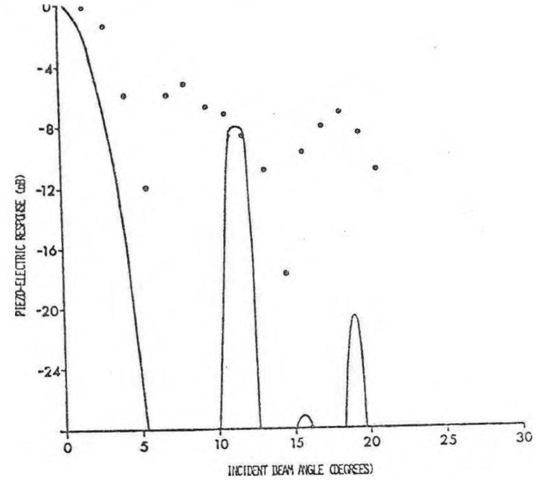
The question of artifact echoes has been addressed by several workers; that of Thurstone et al[11] has been mentioned. Korpel et al[22] have explored the effects of frequency modulation and concluded that for an experimental situation a "10% frequency sweep is, however, sufficient to eliminate these spurious images." There can be little doubt that this is a promising approach to the problem but it poses problems if phase correction and receiver response is a critical factor in an imaging system.

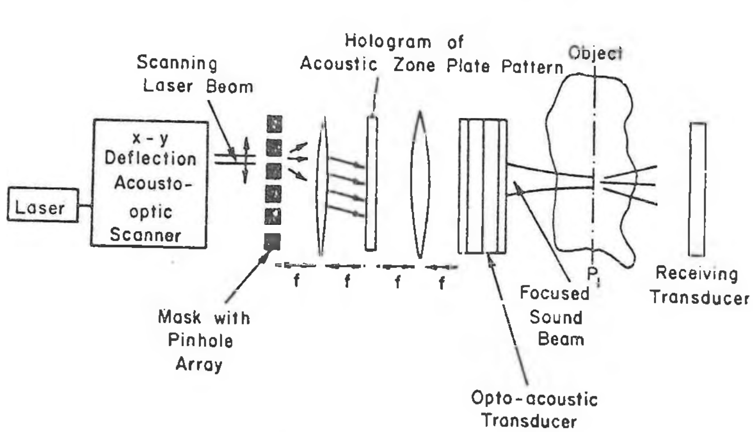
Perhaps before leaving the topic of direct "amplitude only" imaging a recent example of a system nonmedical application ought to be presented and that by C. H. Jones[23] is shown in Figure 10.



←Fig. 7
Angular response
of a quartz receiver

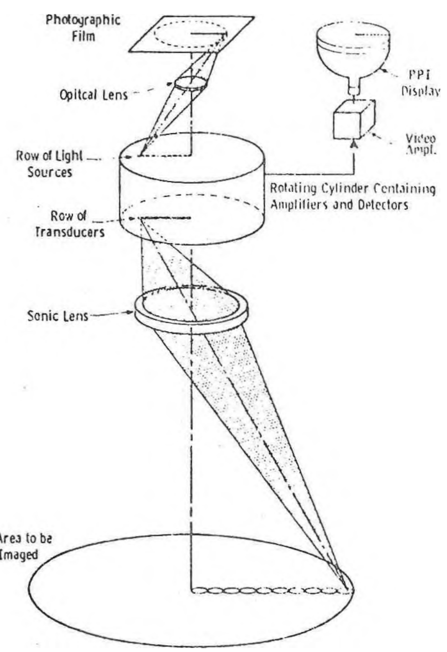
Fig. 8→
Angular response
of a PZT receiver





↑Fig. 9. Schematic of Zone Plate approach to generate a scanning focussed beam

Fig. 10. Schematic of circular scan camera→



Acoustical Holography

Essentially holography concerns itself with reconstructing wavefronts which carry the information about the objects; this requires that knowledge of both the phase and amplitude variation of the wavefront should be available. It may be of assistance to mention the differences between optical and acoustical holography. Because acoustic imaging generally concerns itself with frequencies which can be relatively easily processed by electronic systems it is possible to identify and record the amplitude and the phase of a received signal. Further, it is also possible to arrange, very readily, either linear or square law detection when this is required.

A linear electro-acoustic receiver allows the use of an electronic process to synthesize the reference beam.[44] It is possible to simulate any required reference, off axis or point source for example, simply by varying the phase (and if necessary, the amplitude) of the electronic reference in a suitable way during the scanning process. The two methods of using the reference are available as the following shows:

It can be written for the received signal[24]

$$s(\nu t,y) = a_1(\nu t,y) \cos (\omega_1 t + \phi_1(\nu t,y)) \tag{4}$$

(Refer to Figure 11 for the definition of the terms.)

Using the circuit shown in Figure 11a, the received signal is multiplied by a reference at the same frequency (i.e., that driving the transmitter) and the resulting signal is:

$$y(t) = a_0 a_1(\nu t,y)\cos(\omega_1 t + \phi_1(\nu t,y))\cos\omega_1 t \qquad (5)$$

which after passing through a low pass filter gives:

$$z(t) = \frac{a_0 a_1(\nu t,y)}{2}\cos\phi_1(\nu t,y) \qquad (6)$$

which provides the information required for a reconstruction. Using the alternative system, Figure 11b, it follows that output will be given by:

$$z(t) = \tfrac{1}{2}(a_0^2 + a_1^2(\nu t,y)$$
$$+ 2a_0 a_1(\nu t,y)\cos(\phi_1(\nu t,y)) \qquad (7)$$

which contains the information (c.f. Equation 6) for reconstruction together with two unwanted terms.

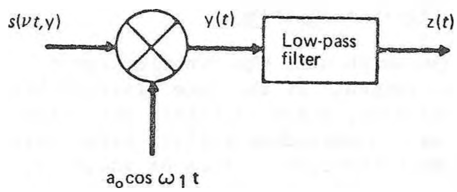
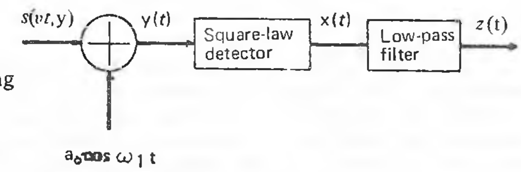


Fig. 11a & 11b.
Detection methods for producing a hologram using a linear receiver and an electronic reference



New developments have taken place in several areas; i) some development of scanning methods, ii) improvements in signal processing, iii) detailed studies on particular aspects of existing apparatus, and iv) work on holographic interferometry.

Concerning items (i) and (ii), Keating[25] discussed the relationship between phased array and holographic receivers and showed that the only difference between them lay in the order in which the temporal and spatial processing operations were carried out. He was able to show that compared with multibeam sonar the holographic approach had a decided signal to noise ratio advantage. It would be interesting to see how far his ideas applied to some of the existing medical ultrasonic apparatus.

Mueller et al[26] described a holographic "weak signal enhancement technique" (WSET) which was applied by M. J-M Clément[27,28] to a translated circular scanned system. The following is Clément's description of (WSET):

"(1) linear detection of the object field (e.g. by scanning) leading to an electronic signal:

$$s(x,y,t) = S(x,y)[\cos\omega_s t + \phi(x,y)] = \mathrm{Real}\{\underline{S}(x,y)e^{i\omega_s t}\}$$

where S is its amplitude, ϕ its phase, $\underline{S}$ its corresponding complex amplitude and $\omega_s/2\pi$ the ultrasound frequency.

(2) point by point formation of the intensity $|\underline{S}(x,y)|^2 = |\underline{S}_1 + S_2|^2$

(3) temporal high pass filterings of $|\underline{S}|^2$ (denoted $|\tilde{S}|^2$).

(4) multiplication of s by $|\underline{\tilde{S}}|^2$.

(5) record of $s.|\underline{\tilde{S}}|^2$, as in conventional holography, multiplied by a reference signal R.

(6) reconstruction (e.g. optically) of the "weak-signal" hologram obtained in step (5).

The multiplication in step (4) being performed onto electronic signals, it effectively represents electronic holographic reconstruction, where the reconstructed field of representation $|\underline{\tilde{S}}(x,y)|^2.s(s,y,t)$ is obtained point by point as a time varying electronic signal.

The analysis remains similar, although the space dependent complex amplitudes (1) - (4) become implicitly dependent on the scanning time τ. For simplicity, the calculations are done with complex amplitudes (i.e. exponential form) rather than with the electronic signal representation (i.e. cosine form). This gives a reconstructed complex amplitude (eq.(4)) (step 5):

$$\underline{S}_p(\tau) = S_p(\tau)e^{i\phi_p(\tau)} = (|\underline{S}_1|^2 + |\underline{S}_2|^2)S_2 + 2|\underline{S}_2|^2 S_1 + S_1{}^* S_2{}^2 + S_1{}^2 S_2{}^* \qquad (5)$$

As the steps 1 to 4 are performed electronically, the wanted reconstructed wave of complex amplitude $\underline{S}_p$ (eq.5)) is not available physically. Instead, a signal $s_p(t)$ analog to it is obtained, whose amplitude and phase correspond to that of the complex amplitude (5), i,e,:

$$s_p(t) = |\tilde{\underline{S}}(\tau)|^2 . s(t,\tau) = S_p(\tau)\cos[\omega_s t + \phi_p(\tau)] \qquad (6)$$

This signal is then mixed (e.g. multiplied) with a reference signal R as in conventional ultrasonic holography, yielding the weak-signal enhanced (W.S.E.) hologram:

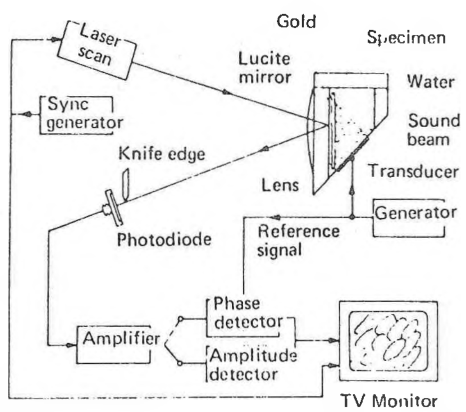
$$H_{wse}(x,y) = C + (\underline{S}_p \underline{R}^* + \underline{S}_p{}^* \underline{R}) \qquad (7)$$

where C is a constant and the implicit time dependent complex amplitude $\underline{S}_p(\tau)$ has been converted into a space varying one by a suitable hologram recorder. When illuminating the W.S.E. hologram (7) with a reconstructing wave $\underline{U}\, e^{i\omega t}$, and for simplicity assuming that the hologram has not been demagnified, the complex amplitude of the reconstructed wave of interest would be:

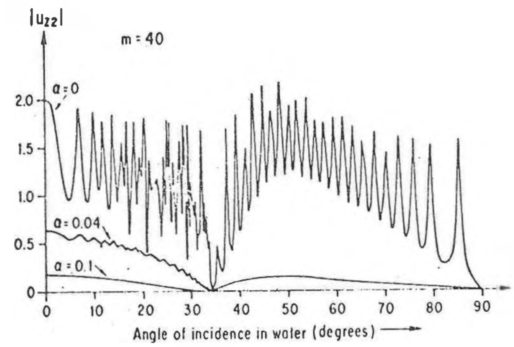
$$C\underline{U}^{i\omega t} + \underline{S}_p(\underline{R}^*\underline{U})^{i\omega t} + \underline{S}_p^*(\underline{R}\ \underline{U})e^{i\omega t} \qquad (8)$$

Assuming $\underline{R}^*\underline{U}$ to be real (e.g. by taking the reference and reconstructing waves as identical plane waves), then it can be seen that the second term of the complex amplitude (8) is identical to that of (5) and (4), in which we find the enhanced image $(|\underline{S}_1|^2 + |\underline{S}_2|^2)\underline{S}_2$."

Korpel et al[29] have done much detailed work on their acoustic microscope which uses the dynamic ripple technique, see Figure 12. Ahmed et al[30] published a detailed study of the response of the face plate of this system, see Figure 13, showing the complex response which occurs. This analysis, which is fairly extensive and has its origins in the work of Brekhovskikh[31], treats the face plate as a homogeneous solid. Later this work was extended to non-homogeneous solids[32] and has, consequently, become a formidable piece of analysis; unfortunately the details of this have not yet been published.

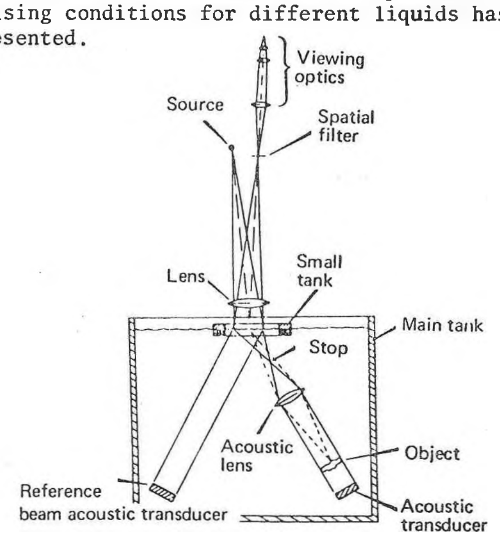


←Fig. 12. Dynamic Ripple Imaging System



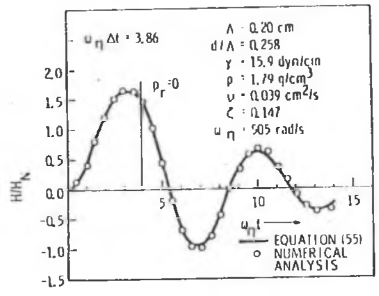
↑Fig. 13. Amplitude response of solid-air interface of 20A thick plate.

Liquid surface holography[33], Figure 14, has, to quote one of its originators, "matured". Pille and Hildebrand[34] have published a rigorous analysis of the liquid surface behaviour including the effects of the presence of the "mini-tank." The previous analyses were confirmed and somewhat better information on optimum pulsing conditions for different liquids has been obtained; Figure 15 shows an example of the information presented.



←Fig. 14. Liquid surface imaging system.

Fig. 15→
The response of liquid surface to pulse of radiation pressure.



Interest in interferomic holography has quickened somewhat as is instanced by references 35 & 36. Metherell[35] extended his earlier work to investigate a number of methods of using interferomic techniques. He derived conditions for "linearized subfringe holographic interferometry" which required suitable phased modulation of the optical illuminating beam; Figure 16 shows the image intensity which is produced as a function of the liquid surface displacement. Metherell develops the argument to show how vibrational phase and amplitude information can be recorded. He estimates that using an argon laser at 5145Å holograms can be recorded at 1 MHz with a (surface) acoustic intensity of 0.00165 w/cm^2. He shows a reconstructed hologram of a forearm which was recorded by this process. The application of this work to stroboscopic holography is discussed.

Fox et al[36] discusses the principles of acoustic holographic interferometry and performed some pilot experiments in air at frequencies in the 15 - 20 KHz region.

Other Topics

Three other topics require mention in even the tersest of reviews; GHz microscopy, Bragg imaging and image contrast.

The high frequency ultrasonic microscopy work of Quate and Lemons[37], see Figure 17, is based on a scanning method in which the object is moved to produce the image. The rigid requirements of the lens system led to this choice of geometry. Resolution is sufficient for the shape of individual red blood corpuscles to be clearly identified. A major part of their future programme of work is identifying the special advantages of acoustic micrographs in relation to their optical equivalent. It is pointed out that contrast arises in the acoustic images from the usual ρ c differences and also, at these frequencies, from the viscous differences in the specimen.

Bragg imaging is too large a subject to be covered adequately in a paragraph, consequently only one or two topics are mentioned. Wade's[38] activity in this field continues with the recent publication of work on acoustic lenses and low velocity fluids for improving images[38]. A distinction between Raman Nath and Bragg imaging was made by R.A. Smith[39] in which he shows that low frequency imaging is of the former type if the light interaction length is greater than about 35 cm. Tobochnik et al[40] evaluated Bragg imaging in the 1 - 5 MHz region for medical purposes by comparing it with radiography. They concluded among other points that "a simple imaging model indicated that one must balance resolution and depth of field considerations in the design of an ultrasonic system."

In presenting visual information, contrast in the image is a factor of vital importance. Much imaging has suffered from a lack of contrast which has been associated with limitations of the dynamic range of the overall system (often the oscilloscope). Mention of this point was made at the beginning of this paper. Sutton et al[41] reported work on various methods of electronic processing of signals from an array and demonstrated the usefulness of active integrator circuits in this regard. Further work in this general area on standard phantom objects was reported by Nigam[42] in which he discussed the performance of three such objects in relation to high resolution pulse echo imaging.

Conclusion

It is hardly possible to summarize the foregoing. If a general comment is appropriate, then it appears that the nature of the scientific endeavour is changing from an emphasis on general principles to the development and exploration of particular areas in greater depth. Finally, I emphasize that the reader must be cognizant of the omissions required to meet the limitations of the publishing requirements.

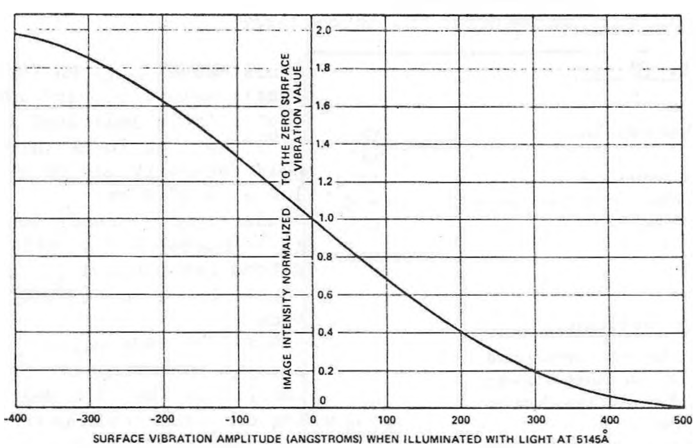


Fig. 16. Linearized subfringe holographic interferometry (modified Powell-Stetson)

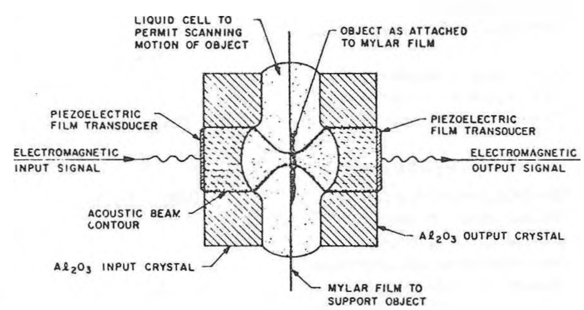


Fig. 17. Schematic diagram of acoustic system (acoustic microscope) showing the lens configuration

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TABLE I showing approximate threshold sensitivity (W/cm^2)

PHOTOGRAPHIC AND CHEMICAL METHODS			
Direction action on film	1 – 5	Liquid surface deformation	10^{-3}
Photographic paper in developer	1.0		10^{-5}
	0.1*	Solid surface deformation	10^{-6} ‡
Starch plate in iodine solution	1	Mechanical alignment of flakes in liquid	2.8×10^{-7}
Film in iodine solution	1	Acoustic birefringence	10^{-1}
Colour change effects	0.5 – 1†		
THERMAL TECHNIQUES			
Phosphor persistence changes	0.05 – 0.1		
Extinction of luminescence	1	ELECTRONIC METHODS	
Stimulation of luminescence	–	Piezoelectric detector — mechanical	
Thermosensitive colour changes	1	movement of transducer or object,	
Change in photoemission	0.1	or use of an array of transducer to	10^{-11} **
Change in electrical conductivity	0.1	form an image	5×10^{-12}
Thermocouple and thermistor detectors	0.1	Probe detection of potential on back	
		of piezoelectric receiver	(*)
OPTICAL AND MECHANICAL METHODS		Electron scan of piezoelectric receiver	2×10^{-11}
		Electron scan of piezoresistive receiver	10^{-7} ††
Optical detection of density variations	10^{-3}	Piezoelectric — electroluminescent	
	3×10^{-4}	phosphor detector	10^{-6}

*This value is given for a 'satisfactory picture quality'. It is indicated in ([12]) that the lower threshold intensity can be as low as 0.05 W/cm^2.

†Under special conditions ([15]) indicates that this method can respond to intensities as low as 0.07 W/cm^2.

‡This technique was brought up during the discussion at the 74th Meeting of Acoustical Society of America, Miami Beach, Fla., Nov.13-17, 1967, by A. Korpel, Zenith Radio Corp., Chicago, Ill.

(After Berger)

Question submitted by A. A. Read, Iowa State University:

Would you comment on the use of shock waves from explosive charges for the generation of holograms?

Answer: This has been the subject of a study by G. L. Fitzpatrick (Denver Mining Research Center, U.S. Bureau of Mines, Denver, Colorado) who concerned himself with geological applications of the subject. I have an informal communication on the topic and I would suggest that he be approached by the questioner. The information I have indicates that a complete and cohesive study of this subject has been made by him. Related relevant work could be that of J. F. Farr, Chapter 16 "Acoustical Holography", Vol. 2, Plenum; A. Fontanel and G. Grau, 39th Annual International Meeting of the Society of Exploration Geophysicists, Institute Francais du Petrol, reprint ref. 17.353, Sept., 1969; J. B. Farr, "Acoustical Holography", Vol.6, 435 etseq. Plenum.

Question submitted by Glen Wade, University of California:

Would you comment on the differences in the character of the focusing available from phased arrays if continuous waves are used as opposed to pulses?

Answer: The primary difference appears to arise from the frequency spectrum differences. The use of phased arrays implies the choice of delay times which relate to a particular frequency. If a pulse train is used, the Fourier components could well be at frequencies which did not relate to the original intent with consequences for shape of a transmitted beam pattern and probably a defocussing effect for the received signal. It would be interesting to see a general theoretical treatment of this problem.