ACOUSTICAL HOLOGRAPHY

Volume 4

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Proceedings of the Fourth International Symposium on Acoustical Holography, held in Santa Barbara, California, April 10-12, 1972

Edited by

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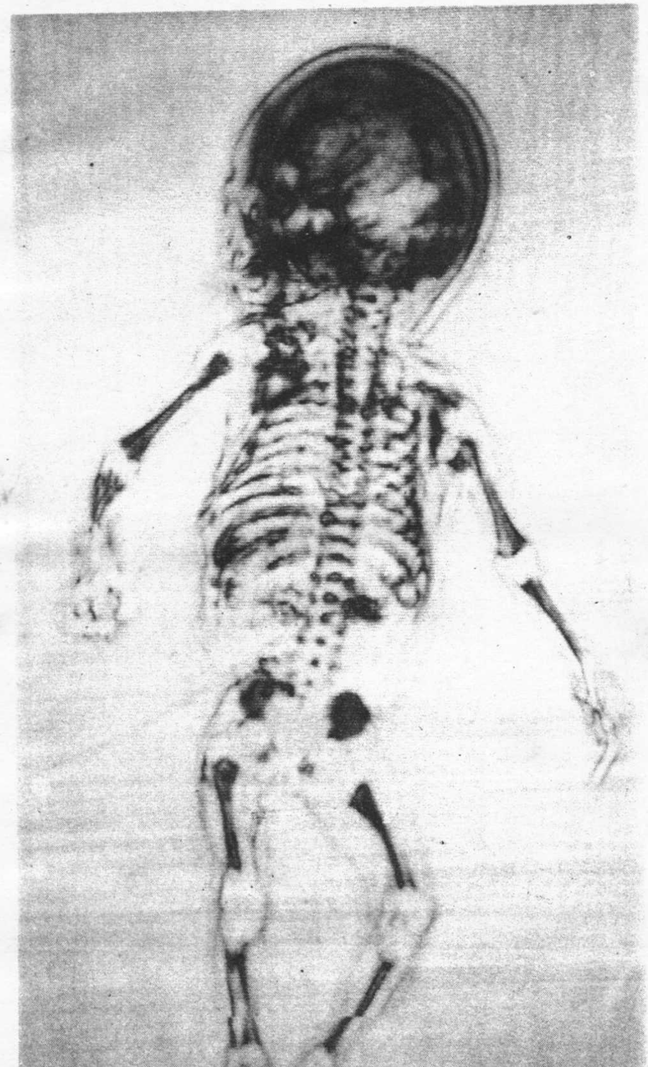

Transmission image of an aborted human fetus in approximately the 17th week. This non-holographic acoustic image was produced by mechanically scanning a 5-MHz ultrasonic transducer, focused in the fetal midplane.

PREFACE

The latest progress in acoustical holography and related research areas, generally involving imaging by means of acoustic waves, was discussed and treated in depth at the Fourth International Symposium on Acoustical Holography, held in Santa Barbara, California on April 10-12, 1972. This volume contains the proceedings of that symposium.

As the papers presented here indicate, a number of startling advances have been realized in the state-of-the-art since publication of Volume 3 of Acoustical Holography. Progress has been particularly impressive in the field of acoustical imaging. The Fourth International Symposium represents something of a landmark conference in this respect.

The scope of this volume is substantially broader than the term "acoustical holography' usually implies and encompasses the whole area of visualization, detection, and recording of sound fields whether with long wavelengths, microwaves, or with extrememly short sound wavelengths. The 37 symposium papers appear here each as a separate chapter. In general, the work reported deals mainly with experimental and theoretical developments in the above areas. This work has significant practical potential use in terms of seismic sensing, underwater imaging, non-destructive testing, real-time acoustic microscopy, and medical diagnosis.

The 37 chapters are grouped into the following 7 sections: I. Real-Time Imaging Systems, II. High-Resolution Imaging Systesm, III. Systems for Biomedical Applications, IV. Array-Imaging Techniques, V. Systems for Non-Destructive Testing, VI. Experimental Systems for Underwater and Seismic Exploration, and VII. Theory and Methods. It should be pointed out that the above sectional titles can serve only as a rough guide. Several of the chapters could logically have been placed into more than one of these sections. A reader interested in new methods of acoustical imaging, for example, will find that subject discussed in Section VII, but also in chapters from certain of the other sections as well.

The program committee for the symposium deserves much credit for the quality of the work selected for presentation at the symposium and, therefore, for inclusion in this volume. The committee members spent many hours in soliciting outstanding contributions and in making assessments concerning all of the papers which were eventually contributed. The Editor wishes to thank the following persons who served as members of the program committee: E.E. Aldridge, A.E.R.E. Harwell, England; B.A. Auld, Stanford University; H.M.A. El-Sum, El-Sum Consultants; P.S. Green, Stanford Research Institute; A. Korpel, Zenith Radio Corporation; J.L. Kreuzer, Perkin-Elmer Corporation; A. Metherell, McDonnell Douglas Corporation/Actron Industries, Inc.; R.K. Mueller, Bendix Research Laboratory; and F.L. Thurstone, Duke University. The Editor would also like to express profound gratitude to Mrs. Oneita Wilde for her substantial and effective effort in compiling this volume.

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REAL TIME ACOUSTICAL IMAGING BY MEANS OF LIQUID SURFACE HOLOGRAPHY

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INTRODUCTION

The techniques of liquid surface acoustical holography have proven to be very effective and useful in applications to industrial testing and biomedical imaging. The most useful images have been produced by focused image techniques, that is, by using acoustic lenses to focus the image into the hologram. Because liquid surface holography has usually been illustrated by use of images focused into the hologram, there has been an erroneous but growing belief that liquid surfaces are not effective in forming true holograms capable of imaging outside the hologram plane. Although published papers (1,2,3) provide evidence that this belief is incorrect, further evidence at this time may be useful and will be presented in this paper.

Focused image techniques still provide the best images. Examples of recent biomedical images obtained by focused image holography are included to illustrate the most recent results.

LENSLESS HOLOGRAPHY

Figure 1 is the schematic diagram of the liquid surface holography system as normally used with an acoustic lens to image the object into the hologram plane. When the acoustical

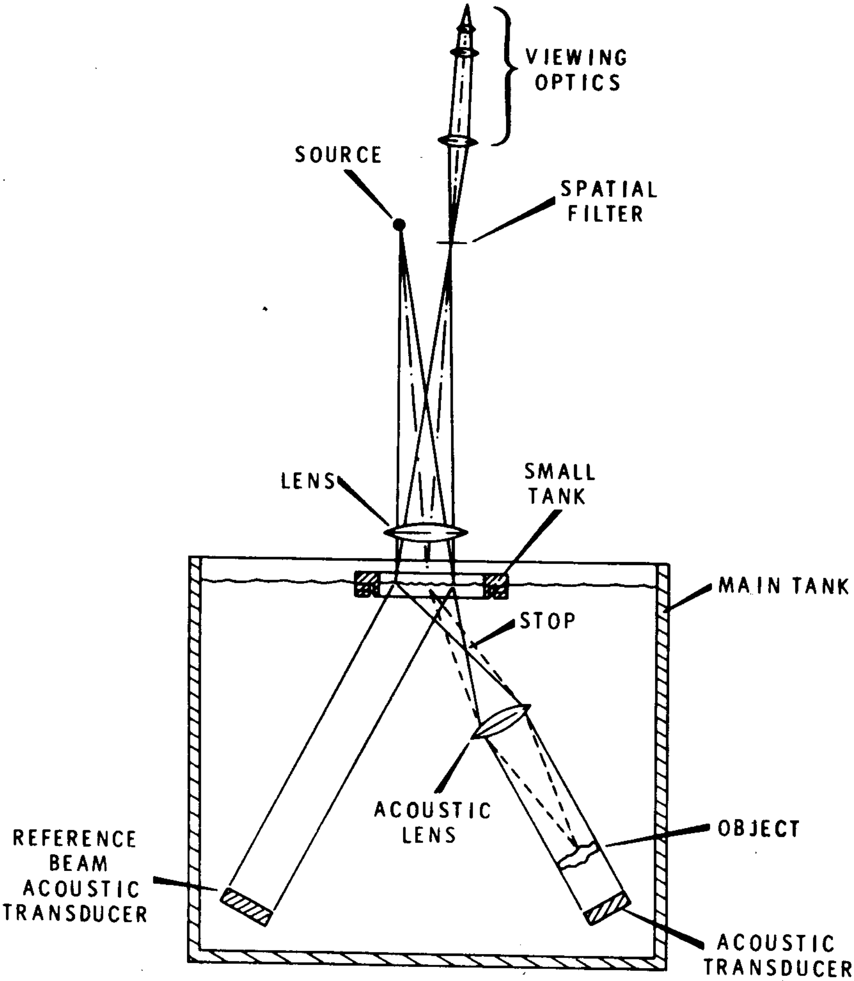

FIGURE 1: Schematic of Liquid Surface Imaging System

image exists in the hologram plane, the optical reconstruction of it also exists there. However, when the acoustic lens is removed, the optical image formed by reflecting coherent light off the liquid surface is located a great distance from the hologram. If r_1 represents the distance from the object to the liquid surface, r_2 the distance from the reference source to the liquid surface, and r_a the distance from the light source to the liquid surface, then the image will be located at a distance r_b from the surface such that (4,5):

$$\frac{1}{r_b} = \frac{1}{r_a} \pm \frac{\lambda}{\Lambda}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \tag{1}$$

where λ is the wavelength of the light and Λ the wavelength of the sound.

If the reference beam transducer generates a plane wave $r_2 = \infty$ and if the light source is in the focal plane of the optical lens $r_a = \infty$, so

$$r_b = \pm\frac{\Lambda}{\lambda} r_1 \ . \tag{2}$$

Two images are formed, one virtual, indicated by the negative sign, and one real, indicated by the positive sign. The virtual image is the true image and the real image is the conjugate image. An optical lens of focal length f will focus the undiffracted light to a point in its focal plane and will form the true and conjugate images at distances u, given by:

$$\frac{1}{u} = \frac{1}{f} - \frac{1}{r_b} \ . \tag{3}$$

Since r_b is usually very much greater than f because the ratio $\Lambda/\lambda \approx 1000$, the true and conjugate images are located near the focal plane of the lens with the true image being somewhat further from the lens and the conjugate image somewhat nearer.

Figure 2 shows a test object and the resulting true and conjugate images both recorded in the plane of sharpest focus for the true image. The zero order, undiffracted light normally appearing between the two first order diffracted light

Test Object
Wire Diameter 0.050"
Wire Spacing 0.125"

Focused True Image

Out-of Focus Conjugate Image

FIGURE 2

beam has been blocked out. No acoustic lens was used in forming these images at 10 MHz acoustic frequency with the object to hologram distance about 13 cm.

DISCUSSION OF LIQUID SURFACE RESPONSE TIMES

Analyses (3,4,5) of liquid surface response to continuous insonification by two plane waves incident at opposite but equal angles to the liquid surface shows that the liquid surface distortion buldge exceeds the amplitude of the hologram pattern by a factor of about 100. Such distortion would indeed destroy much of the effective image forming capability of a liquid surface hologram. Such distortion is never experienced, however, because in actual practice, using acoustical wave trains of 100 μs duration or less, the distortion buldge actually has a smaller amplitude than the hologram pattern (5). This favorable result occurs because the duration of the acoustical wave train is adjusted to a quarter period of the free oscillation of the hologram pattern. The natural period of the buldge oscillation is much longer and consequently the liquid surface displacement for such short excitation pulses is very small. Analysis indicates that the ratio of effective buldge amplitude, B_e, to hologram pattern amplitude A can be given by:

$$\frac{B_e}{2A} \simeq 0.48 \; . \qquad (4)$$

When the liquid surface is properly excited, the hologram pattern amplitude will be less than a quarter wavelength of light so that the phase distortions introduced by the distortion buldge B_e are not severe.

BIOMEDICAL IMAGING

For practical reasons, it is still desirable to operate in the focused image mode. Without acoustic lenses, it is difficult to place the object in a position which maintains a favorable numerical aperture. Furthermore, focused image holography permits the use of higher power levels and almost totally removes concern for maintaining a favorable $B_e/2A$ ratio. Focused image techniques are used in the examples that follow.

The real-time imaging capabilities of liquid surface systems are best illustrated by use of motion pictures, video tape or by direct viewing of the image. Swint, Yee and Godbold (6) and Clements (7) have presented examples of the application of these systems to industrial testing. Although many other examples of images related to industrial testing could be provided, I shall limit illustrations in this paper to biomedical imaging.

One of the most striking examples of the capability of liquid surface holography to delineate soft tissue structure is given in Figure 3. Figure 3 is the acoustical image of the upper arm just above the elbow. The edge contours of the humerus appear much more irregular than anticipated on the basis of x-ray images. The primary reason for the irregular contour is that ultrasound interacts with soft tissue to a much greater extent than do x-rays. Thus, rather than seeing true bone edge contours, we actually see soft tissue attachments. The major soft tissue attachments to the humerus shown in Figure 3 are those of the tendons of the muscles of the forearm, namely, the brachioradialis and the extensor carpi.

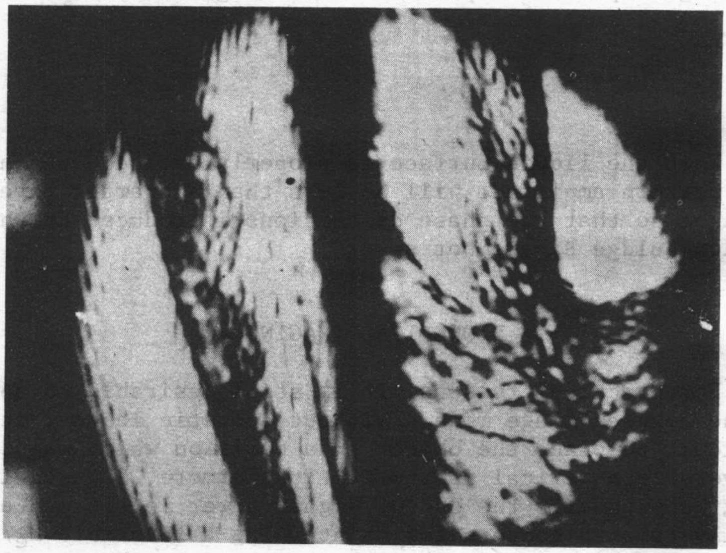

FIGURE 3: Acoustical Images of the Mucles and Muscle Attachments of the Upper Arm. Picture Courtesy of Holosonics, Inc.

In the particular view presented in Figure 3, the attachment pads are glowing with ultrasound. These large glowing areas completely obscure the edge contour of the humerus. The tendon of the biceps running perpendicular to the tendons of the brachioradialis is also quite evident.

Liquid surface holography shows considerable promise for early diagnosis of cancer of the breast. Figure 4 shows the configuration used to bring the breast into the field of view. One of the first acoustical images of a malignant tumor produced by liquid surface holography techniques is shown in Figure 5. As anticipated from earlier studies with rats (8,9), tumors absorb more ultrasound than normal tissue. Furthermore, hard tumors can readily be distinguished from cysts which transmit more energy than the surrounding tissue and therefore appear as bright areas as compared to the surrounding tissue whether that surrounding tissue be normal or diseased.

In Figure 5, the main large tumor is labeled 1 and two smaller tumors are labeled 2 and 3. Three cysts occurred in the locations 4, 5 and 7. The contour of the breast is identified by a Figure 6. The field of view was approximately 13 cm in diameter. This picture, one of the first of tumors in the breast, is due to Dr. J. Hevezi of M. D. Anderson Hospital and Tumor Institute, Houston, Texas and G. N. Langlois of Holosonics, Inc.

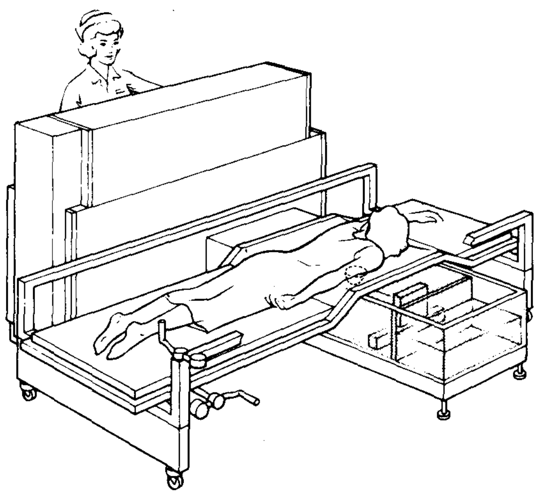

Figure 4: Machine Configuration for Mammography