Copyright Warning & Restrictions

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a, user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use" that user may be liable for copyright infringement,

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Please Note: The author retains the copyright while the New Jersey Institute of Technology reserves the right to distribute this thesis or dissertation

Printing note: If you do not wish to print this page, then select "Pages from: first page # to: last page #" on the print dialog screen



The Van Houten library has removed some of the personal information and all signatures from the approval page and biographical sketches of theses and dissertations in order to protect the identity of NJIT graduates and faculty.

INFORMATION TO USERS

This material was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

- The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.
- 2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.
- 3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again beginning below the first row and continuing on until complete.
- 4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.
- 5. PLEASE NOTE: Some pages may have indistinct print. Filmed as received.

University Microfilms International 300 North Zeeb Road Ann Arbor, Michigan 48106 USA St. John's Road, Tyler's Green High Wycombe, Bucks, England HP10 8HR

77-22,450

HANAFY, Amin Mohamed, 1942-ACOUSTICAL HOLOGRAPHY BY HOLOGRAPHIC INTERFEROMETRY.

| |

> New Jersey Institute of Technology, D.Eng.Sc., 1977 Engineering, Electronics and electrical

Xerox University Microfilms , Ann Arbor, Michigan 48106

ACOUSTICAL HOLOGRAPHY BY

HOLOGRAPHIC INTERFEROMETRY

BY

AMIN MOHAMED HANAFY

A DISSERTATION

PRESENTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE

 \mathbf{OF}

DOCTOR OF ENGINEERING SCIENCE

AT

NEW JERSEY INSTITUTE OF TECHNOLOGY

This dissertation is to be used only with due regard to the rights of the author. Bibliographical references may be noted, but passages must not be copied without permission of the College and without credit being given in subsequent written or published work.

> Newark, New Jersey 1977

ABSTRACT

The ability to "see" with sound has long been an intriguing concept. It is apparent that ultrasonic energy can give an image of an object not obtainable with light or even with x-rays.

In this dissertation, a novel "three-step acoustical holographic imaging system" is described and several means for its implementation are analyzed. A novel holographic acoustic image converter, which constitutes a fundamental link in the three step imaging method was also developed. The use of optical holographic techniques to convert an arbitrary acoustic image to a visible image is conducted and resulted in the introduction of the new technique of "Step-biased holographic interferometry", which is shown to permit increasing the sensitivity of conventional holographic interferometry methods by one order of magnitude.

A theoretical and experimental study of some possible "couplers", for augmenting and amplifying the displacement amplitude of an acoustical diffraction pattern as it is transferred from a surface bounded by water to a surface bounded by air, is conducted. A particularly detailed study is conducted on the two-quarter-wave acoustic impedance transformer, and on a mosaic of step horn velocity amplifiers. The theoretical relations describing the behavior of both the acoustic impedance transformer and the velocity amplifiers are developed and experimentally verified. As a result of using beryllium to construct the first quarter-wave matching plate in the acoustic impedance transformer and the addition of the microhorn structure in the output stage of the image coupler, interelement crosscoupling has been brought down to a minimum value of -25 db, and the coupler sensitivity has been improved. A mechanical advantage (gain) of 40 at 410 KHz across the water air interface with beryllium-epoxy structure has been achieved.

As a result of the increased sensitivity of both, the optical system by using the step-biased holographic interferometry, and of the image coupler by using the microhorn velocity amplifiers as well as the partial impedance matching of water to air, a "holographic

ii

sound image converter" having a threshold intensity of 1 mW/cm^2 at 410 KHz appears feasible. During the course of this experimentation, useful acoustical and optical methods for tuning and testing the image coupler materials is devised.

Finally, the ability of the system to cast real time shadowgrams of the insonified object appears useful for many practical applications requiring real time operation, and by utilizing computer processing, quasi-real time operation can be achieved for the three-dimensional acoustic imaging. APPROVAL OF DISSERTATION

ACOUSTICAL HOLOGRAPHY BY

HOLOGRAPHIC INTERFEROMETRY

AMIN MOHAMED HANAFY

FOR

DEPARTMENT OF ELECTRICAL ENGINEERING

NEW JERSEY INSTITUTE OF TECHNOLOGY

BY

FACULTY COMMITTEE

- -

APPROVED _____ Chairman

_____

NEWARK, NEW JERSEY

 $\boldsymbol{1977}$

PREFACE

This dissertation is concerned with techniques for the analysis, design and fabrication of an acoustic image detector for acoustical holography. Particular attention is given to the problem of improving the sensitivity of the optical and acoustical systems.

The problem of improving the system sensitivity is approached in the following manner. First, for the optical system a study on the use of optical holographic interferometry techniques to achieve a more satisfactory acousto-optical image conversion is performed. As a result the method of real time, step-biased holographic interferometry is introduced and analyzed. The application of the new method appears particularly desirable since, among other advantages, it inherently obviates the need for scanning the receiver aperture, beside allowing real time operation to be performed.

With respect to the acoustic system, the theory of acoustic impedance transformers and the velocity amplifiers is developed. A novel microhorn structure is consequently utilized in the output stage of the acoustic image coupler. The resulting acoustic image converter appears to combine the desirable characteristics of both scanned and non-scanned image detectors, such as higher sensitivity, minimum interelement cross coupling, better resolution and higher information handling rate.

The first chapter briefly discusses the various problems and limitations that presently confront the acoustical holographic imaging process. The need for a suitable image detector with such desirable characteristic is also discussed.

Chapter II provides a historical review of acoustical holography detectors and their performance, also **a** comparison between these detectors is offered.

Chapter III discusses in detail the most commonly used methods of optical holographic interferometry and their use for the detection and measurement of small vibration amplitudes. Further the original method of step-biased holographic interferometry is developed and introduced, both in theory and experimental verification.

v

Chapter IV proposes a novel, three-step acoustical holographic imaging system of which the holographic image converter constitutes a fundamental link. This converter is composed of the "step-biased holographic interferometer", and the full-wave acoustic image coupler incorporating several novel features, among which is a mosaic of step horn velocity amplifiers.

In Chapter V, the use of the acoustic impedance transformer, and the velocity amplifier in constructing the acoustic image coupler is investigated. In particular, the design, construction and tuning of such devices is discussed in detail.

Chapter VI offers the experimental results of the performance of the tuned acoustic image coupler, in particular its angle sensitivity, interelement cross coupling and the frequency dependance of the displacement amplitude transmission coefficient.

Chapter VII discusses the implementation of real time step-biased holographic interferometry in the imaging system, and offers the final imaging results obtained with the present system, proving the feasibility of two-dimensional real time acoustic imaging and of quasi-real time three dimensional holographic imaging.

Conclusions and further recommendations are discussed in Chapter VIII.

ACKNOWLEDGEMENT

If the full list of people and their contribution to the success of this project were presented, it would fill a chapter alone. One can only thank all the many people, staff, and faculty, as a group for their help, suggestions, and constructive criticism over the years.

In particular, Dr. M.H. Zambuto is thanked for his guidance, valuable suggestions and encouragement throughout this study. His advice and assistance have contributed a great deal to this dissertation. Special thanks is also extended to Dr. R. Misra, Dr. W. Ball and Dr. R. McMillan for thier assistance in the solution of many problems encountered throughout this study. Special gratitude must go to New Jersey Institute of Technology for the facilities provided by the electrical engineering department. Finally, my wife Sohier must come in for a great deal of appreciation because of her help, support, and perserverance throughout the course of this investigation.

TABLE OF CONTENTS

		PAGE
ABSTRA	СТ	. ü
PREFACE	Ε	. v
LIST OF 1	FIGURES	• x
LIST OF 7	TABLES . <th>· ivx</th>	· ivx
CHAPTER	R	
I	INTRODUCTION TO ACOUSTICAL HOLOGRAPHY	. 1
	Technological Problem	
	Desirable Characteristics	
	Acoustic Holography Steps	
II	HISTORICAL REVIEW OF ACOUSTICAL HOLOGRAPHY DETECTORS	. 4
	Scanned Detectors	
	Non-Scanned Detectors	
III	HOLOGRAPHIC INTERFEROMETRY AND SENSITIVITY IMPROVEMENT	. 35
	Double Exposure Method	
	Double Pulsed Method	
	Time Average Method	
	Real Time Method	
	Stroboscopic Method	
	Step-Bias Method	
IV	FOUR-STEP ACOUSTICAL HOLOGRAPHY AND ITS REDUCTION TO THREE-STEP ACOUSTICAL HOLOGRAPHY BY USING THE STEP-BIASED REAL TIME HOLOGRAPHIC INTERFEROMETER	. 65
	Four-Step Method	
	Three-Step Method	
	Acoustic Velocity Transformer	
	Acoustic Velocity Amplifier	

CHAPTER		PAGE
v	THE ACOUSTIC IMAGE COUPLER	7 9
	The Two-Quarter-Wave Velocity Transformer	
	The Two-Quarter-Wave Velcotiy Amplifier	
	Construction and Experimental Results	
VI	PERFORMANCE OF THE TUNED ACOUSTIC IMAGE COUPLE AND THE ILLUMINATING TRANSDUCER	R 123
	Frequency Response	
	Transducer Radiation Field	
	Experimental Results	
VII	IMPLEMENTATION OF THE STEP-BIASED HOLOGRAPHIC INTERFEROMETRY FOR ACOUSTICAL HOLOGRAPHY	142
	Experimental Acoustic Imaging Results	
VIII	CONCLUSIONS AND RECOMMENDATIONS	160
APPENDIX		
Ι	ACOUSTIC IMPEDANCE MATCHING BETWEEN TWO MEDIA	168
II	DETERMINATION OF THE AMPLITUDE TRANSMISSION COEFFICIENT "td" FOR MULTILAYER FILMS	171
III	LIQUID IMMERSION, PULSED SOUND TECHNIQUE FOR MATERIAL TESTING	178
IV	DESIGN OF A TRANSDUCER WITH UNIFORM AXIAL AND LATERAL INTENSITY DISTRIBUTION AND WITH FOCUSING CAPABILITY	181
	REFERENCES	190

LIST OF FIGURES

FIGURE		PAGE
2-1	Basic Scanned Detector	5
2-2	A mechanically scanned Image Converter	7
2-3	A mechanically scanned Image Converter	8
2-4	An ultrasonic Image Converter which scans the voltage on the face of a mosaic of crystals	10
2-5	The Basic Ultrasonic Camera	11
2-6	Acoustical Holography via the ultrasonic camera	13
2-7	Use of an Image Orthicon for ultrasonic image visualization	14
2-8	System for optically scanning a matrix of photodiodes to achieve image conversion	15
2-9	An optically scanned image converter which responds to the voltage of plane P_2	17
2-10	A converter responding to the slope of the surface displacement	18
2-11	The Pohlman Cell	22
2-12	Acoustical holography system utilizing Pohlman cell	24
2-13	Method after Sokolov, for imaging the analog relief pattern	25
2-14	Topler "dark-field" method for imaging the analog relief pattern	26
2-15	Method for minimizing unwanted disturbances of the surface deformation	28
2-16	Liquid Surface Holography	29
2-17	Arrangement for an ultrasonic grating in the liquid surface relief conversion system	30
2-18	Acoustic holography using liquid to air face plate	31
3-1	Geometry for calculating the phase difference δ (x)	38
3-2	Harmonic oscillation of object points	40
3-3	The shifted reference brightness distribution	47

FIG	URE
-----	-----

3-4	Shifted reference geometry	48
3-5	Low of motion for step-bias method	50
3-6	Modified degree of coherence in phasor form	52
3-7	Conventional brightness distribution	53
3-8	Step-bias brightness distribution	54
3-9	Real-time hologram of object with no excitation	56
3-10	Object with step-bias, no vibration	57
3-11	Object with small amplitude of vibration	58
3-12	Object with vibration and step-bias	59
3-13	Object with step-bias and large amplitude vibration	60
3-14	Object with no step-bias and large amplitude vibration	61
3-15	Biasing arrangement	63
3-16	Step-bias geometry and arrangement	64
4-1	Four-step method	66
4-2	Three-step method	68
4-3	Performance of thin membrane	71
4-4	Velocity transformer profiles	75
4-5	Electro-A coustic transducer	77
		••
5-1	Resonant impedance matching transformer	81
5-2	Frequency response of longitudinal velocity	85
5-3	Frequency response of displacement amplitude transmission coefficient	91
5-4	Arrangement for velocity and attenuation testing of materials	94

-

FIGURE		PAGE
5-5	Echo display for attenuation and velocity measurement	97
5-6	Construction of acoustic image coupler	102
5-7	Echo display of untuned plate	109
5-8	Echo display of tuned plate	109
5-9	Pulsed immersion ultrasound method	111
5-10	Acoustic image coupler with biasing arrangement	113
5-11	Arrangement used for testing and tuning image coupler	115
5-12	Illustrated testing arrangement	116
5-13	Detected signal for untuned image coupler	1 1 8
5-14	Detected signal for tuned image coupler	118
5-15	Image coupler with the biasing crystals arrangement	121
6-1	Angle sensitivity of image coupler	125
6-2	Interelement coupling level	127
6-3	Axial intensity distribution for disc transducer	129
6-4	Lateral intensity distribution for disc transducer	130
6-5	Multiple source wave front	132
6-6	Beam divergence due to crystal diameter	133
6-7	Near and far field distribution of disc transducer	136
6-8	Reflection losses at interfaces	137
6-9	Real-time hologram of image coupler at excitation level of 520 mw/cm 2	141
7-1	Step-rotation brightness distribution	144
7-2	Insonifying transducer	146
7-3	Insonified object	146

FIGURE

PAGE

7-4	Time average hologram of static image coupler (no excitation)	147
7-5	Image coupler with free step rotation (real time hologram)	148
7-6	Real time hologram of coupler with acoustic insonification and no bias	149
7-7	Real time hologram of object at power level of 370 mw/cm 2 , no step bias	150
7-8	Real time hologram of object with step bias at $47~{ m mw/cm}^2$	152
7-9	Geometry for holographic recording and reconstruction	154
I-1	Sound transmission between three media	169
II-1	Sound transmission from water to air through intervening layer	172
III-1	Pulsed-sound immersion technique	179
IV-1	Axial and lateral intensity distribution for disc transducer	182
IV-2	Driving cricuit for uniform intensity transducer	184
IV-3	Intensity distribution of new design	186
IV-4	a) Transducer configuration	
	b) Lateral intensity versus voltage drive ratio	187
IV-5	Transducer assembly	189

LIST OF TABLES

TABLE

PAGE

2-1	Various Ultrasound Detectors	33
5-1	Acoustic Properties of Various Materials	87
5-2	Acoustic Properties of Some Materials For Plate 2	96
5-3	Response of Beryllium Epoxy System	98
5-4	Response of Steel Epoxy System	99
5-5	Tuning Data For Beryllium Epoxy System	122
6-1	Angle Sensitivity	124
8-1	Acoustic Characteristic of \mathtt{PVF}_2	166

CHAPTER I

INTRODUCTION TO ACOUSTICAL HOLOGRAPHY

Visual data acquisition, which is so important in our life is possible because a light wave, after being diffracted by an object acquires characteristic that contain all the information required to obtain an optical image of the object. In the final analysis this is due to the wave nature of light.

A sound wave, being also characterized by the wave equation, carries, after diffraction, similar information about the diffracting object. Retrieval of this information, i.e., acoustic imaging, is more than an intriguing and alluring possibility.

Seeing with sound rather than with light can open new avenues of data acquisition and develop numerous potential applications in several fields, including medical research diagnostics, surgical techniques, underwater data acquisition by target classification and echo synthesis and non destructive testing.

Acoustic imaging can further open perspectives that are not available with conventional optical viewing, even when extended by utilizing x-rays. At the same time; if properly processed, the information carried by the acoustic wave could be presented in the familiar visual way. Permitting the observer to utilize directly his experience in interpreting optical images. The realization of the full advantages of the acoustic imaging process is impeded, however by several limitations.

Technologically the implementation of acoustic equivalents to optical hardware; such as high resolution lenses; is a major problem. Holography eliminating the need for much of this hardware, appears a promising approach. Still the conversion of an acoustical hologram to an optical image presents many difficulties which must be overcome. Theoretical and technological difficulties arise in view of the necessity to use visible radiation to reconstruct an acoustic hologram in a form suitable for vision. The very large discrepancy in wavelength between acoustical and optical radiation, three to four orders of magnitude for supersonic radiation in liquids, poses large problems in scaling. The necessity to convert an acoustical hologram, which is essentially a pattern of mechanical vibrations on a solid or liquid surface to a visible pattern requires the development of a suitable detector device of acceptable characteristics.

Much work has been performed in an effort to solve this problem and many devices have been proposed. A brief summary of the state of the art is genuine to this work and is offered in chapter II.

Essentially the devices proposed are classified in two categories: scanning and non-scanning devices. The most important characteristics of these devices, from the point of view of practical application are:

- a) Sensitivity: acoustic to optical conversion must be efficiently achieved for a limited acoustic power density distribution on the acoustic hologram plane, under penalty of having to use impractically large, even destructive or harmful acoustic powers to obtain data acquisition.
- b) Resolution in the reconstructed image.
- c) Time delay between acoustic hologram formation and acquisition of the optically converted hologram. For applications requiring real time or quasi real time operation most of the scanning detectors are impractical even when real time operation is not vital. If the object to be visualized is in motion, most scanning devices appear impractical, unless a means to "store" the acoustic hologram over the scanning interval is devised.

It should be noted that the complete acoustical holographic process requires:

2

- a) The production of an acoustical interference pattern in the form of a pattern of mechanical vibration at acoustic frequencies on a surface (acoustical hologram).
- b) The recording of this acoustical interference pattern in terms of an analogous distribution of optical density to obtain the converted acoustical hologram.
- c) The reconstruction of the converted acoustical hologram with optical radiation.

In spite of the existence of a great variety of ultrasonic detectors, none of these at present fulfill their function in such an admirable manner as does their counterpart, the photographic emulsion, in optical holography.

The research described in this dissertation is concerned with the problem of recording optically the acoustical diffraction pattern. In particular the concept of using the interferometric properties of optical holographic techniques to record the acoustical diffraction pattern is explored. The work includes a detailed study of using acoustical resonant "matching" plates to augment the vibration amplitude of points within the acoustical interference pattern. A microhorn structure is added in the output stage of the acoustic transformer to increase the amplification.

CHAPTER II

HISTORICAL REVIEW OF ACOUSTICAL HOLOGRAPHY DETECTORS

Acoustical holography is quite similar to optical holography except that acoustical energy replaces light.

The basic steps of acoustical holography have been indicated in Chapter I. Step 2, obtaining the converted acoustical hologram, implies the use of some detection system to achieve the optical recording of a distribution of acoustic energy. At the present state of the art, the most important problem to be solved is the lack of such a suitable detection system.

Although there exist a great variety of ultrasonic detectors, which we will discuss in the following pages, none of these detectors serve as effectively as does the photographic emulsion in optical holography. These detectors have been classically subdivided into two broad categories, namely scanned and non-scanned detectors. Scanned detectors are further classified on the basis of the type of scanning used, while non-scanned detectors are classified in accordance with the dominant mechanism responsible for detection.

A comparison of scanned and non-scanned detectors with respect to desirable characteristics is given after the review. Further surveys and listings of acoustic image detectors can be found in references (1, 2, 3, 4).

Scanned Detectors.

These are linear detectors which sense both phase and amplitude of the acoustic pressure. The basic scanned detecting system usually consist of the following (see Figure 2-1):

- 1) A small sensor S which is scanned across the acoustic hologram plane H.
- 2) An electro-acoustical transducer which converts some characteristic of the acoustic energy to an electrical signal.
- 3) An amplifier A to amplify the electrical signal.



Figure 2-1 Basic Scanned Detector System

.

- 4) An electro-optical transducer which converts the electrical signal to an optical signal.
- 5) A drive system, to drive the ensuing light over the converted hologram plane H¹ in synchronism with the sensor motion, so that a one to one correspondence exists between a point P on the acoustic hologram plane and a point P¹ on the plane of the converted acoustical hologram.
- 6) An optical recording system.

Somewhere, generally either at the electro-optical or at the electro-acoustical transducer, some nonlinearity must be introduced.

Mechanical Scanning.

A simple, scanned image converter^(5,6) is illustrated in Figure (2-2). A microphone S mechanically scans the aperture plane by means of the X, Y driving signal. The amplified and rectified signal then intensity modulates (z-modulates) a CRT whose electron beam is deflected by the same X, Y drive, so that the radiance of a point on the CRT is proportional to the acoustic intensity of the corresponding point in the aperture plane. The resulting radiance distirbution may be photographed to obtain a permanent record of the diffraction pattern of the object.

Since the microphone is a linear device, it is possible to simulate electronically an acoustical reference wave. This was demonstrated by $Massey^{(7)}$ and $Metherell^{(8)}$ as shown in Figure (2-3). In this arrangement the phase of the electrical "reference" signal is independent of the instantaneous sensor position; hence, a plane wave, normally incident to the hologram plane is simulated.

Similar arrangements, using a piezoelestric crystal as the "point" transducer, have also been used in mechanically scanned detection system^(9,10,11). The piezoelectric crystal is chosen to resonate in its fundamental thickness mode, i.e., thickness = $\lambda/2$.



Figure 2-2 A mechanically scanned image converter using a microphone as a point detector and a cathode ray tube for visual display.



Figure 2-3 A mechanically scanned image converter using a plane wave, electronically simulated reference wave.

The image converter described thus far have used a point transducer to scan the aperture plane.

Sokolov⁽¹²⁾ discovered that a large piezoelectric crystal essentially behaves as a mosaic of many "point" crystals in that the voltage induced across the crystal at a certain point is directly proportional to the instantaneous pressure at that point. Although there is not an exact one to one correspondence between voltage and pressure at each point due to transverse mode coupling, the lateral spread can be minimized by resonating the crystal in its fundamental thickness mode. Sokolov proposed an electronically scanned system to record the charge distribution across the face of the piezoelectric crystal as described in the next section.

Based on Sokolov discovery, $Suckling^{(13)}$ devised an image visualization system in which a capacity probe mechanically scans the surface of a mosaic of nine, one square inch, x-cut piezoelectric quartz crystal [see Figure (2-4)].

Electronic Scanning.

As was mentioned before, the voltage or charge distribution across a piezoelectric crystal due to a corresponding pressure distribution can be evaluated at each point by electronic means -- usually a scanning electron beam, as proposed by $Sokolov^{(12)}$ in his ultrasonic camera.

The Sokolov tube resembles the cathod ray tube, (see Figure 2-5) in that both contain an electron gun in vacuum. The faceplate of the Sokolov tube is a piezoelectric crystal which is chosen to resonate in its fundamental thickness mode. Incident ultrasound creates resonant vibrations of this crystal and leads to the formation of charges of alternate sign on the inside surface of this crystal. As the high energy electron beam strikes a point on this surface, the crystal charge at that point influences secondary emission. Hence the secondary emission current amplitude modulates the anode current as the beam scans the crystal surface.



Plastic plate (3" x 3" x 3/16")

Figure 2-4 An ultrasonic image converter which scans the voltage distribution on the face of a mosaic of piezoelectric crystals.



The performance of the ultrasonic camera has been investigated by several authors $^{(14, 15, 16)}$, and an excellent description of the history and the present state of the art of the ultrasonic camera is given by Smyth $^{(17)}$. These investigations indicate that, due to mode coupling, the resolution capability at the face plate is of the order of the crystal thickness. The crystal thickness cannot be made arbitrarily small, however, since the faceplate must support a vacuum. For the same reason, the size of the aperture cannot be made arbitrarily large. Practical sensitivities of 10^{-7} to 10^{-9} Watt/cm² have been reported. The usefulness of the ultrasonic camera in the area of non-destructive testing has been well established.

Fritzler and Mueller⁽¹⁸⁾ demonstrated its use in an acoustic holography system (Figure 2-6). In the system shown, the angular separation between the object and reference waves was maintained at 10° in order to minimize mode coupling. Davidson & Hull ⁽¹⁹⁾ devised a different electron beam scanned detector, in this system the acoustic image is focused on a matrix of individual piezoelectric crystal, each of which is connected to an individual integrating network, rectifier, and amplifier (see Figure 2-7). An image orthicon scans, by means of an electron beam the voltage distribution on the faceplate; thereby generating a TV signal which is monitored on a TV screen, a threshold sensitivity of 10^{-11} Watt/cm² has been reported.

Optical Scanning. Instead of scanning the piezoelectric surface with an electron beam Green⁽²⁰⁾ proposed scanning it with a revolving pencil of light. In this system the piezoelectric crystal is segmented and each segment is connected to a photodiode which is illuminated by a revolving pencil of light. As each photodiode turns "on" its non linear characteristics generate sum and difference frequency signals in that diode. Upon proper filtering, amplification, and rectification, the image of the ultrasound can be displayed on a cathode ray tube. Electronic simulation of an acoustical reference wave can also be included (see Figure 2-8). A threshold sensitivity of 5×10^{-12} Watt/cm² has been quoted.



Figure 2-6 Arrangement for performing acoustical holography via the ultrasonic camera.

.



Figure 2-7 Use of an image orthicon for ultrasonic image visualization.



Figure 2-8 System for optically scanning a matrix of photodiodes to obtain an image of the ultrasound at the piezoelectric faceplate.

Massey⁽²¹⁾ demonstrated an optical heterodyne converter which responds to other characteristics of the acoustic diffraction pattern, namely the velocity of the acoustic wave. Referring to Figure (2-9) a monochromatic beam of light of frequency W_1 is split into two parts by a beam splitter (1). One beam is incident on plane P_2 at the point m which is vibrating at the acoustic frequency Ω . The other beam is slightly shifted in frequency from W_1 to $W_1^{\mathbb{N}}$ by means of frequency translator Δ . Due to the vibratory motion of point m, the instantaneous frequency $W_1^{\mathbb{N}}$ of the reflected light varies sinusoidally in time about the optical carrier frequency $W_1^{\mathbb{N}}$. By means of the beam splitter (2), this light is mixed with the light emerging from the frequency translator. The emerging light impinges on a photocell PC, where sum and difference frequency components are generated by the nonlinearity of the photocell. Finally, by proper filtering and FM demodulation yields a signal of frequency Ω whose instantaneous value is directly proportional to the speed of the vibrating point m. As the incident light scans the plane P_2 in synchronism with a display network, an image of the velocity distribution of the vibrating plane can be obtained. Massey reported a threshold intensity of 1.46 x 10^{-8} Watt/cm².

Korpel⁽²²⁾ devised a simpler image converter, (see Figure 2-10). In this system a laser beam is focused to a diffraction limited spot at a point m on the vibrating surface P_2 . The reflected light which is periodically deflected due to the motion of point m, is partially intercepted by a knife edge K. This action converts the periodic deflection into a variation of irradiance at the photocell PEC whose output maybe mixed with a "reference" signal. After filtering, amplification and rectification at E, the signal z modulates a CRT so that, by proper scanning, an image of the vibration distribution on plane P_2 can be obtained. Korpel reported a threshold intensity of 10^{-7} Watt/cm² at 1 MHz.

Non-Scanned Detectors

These are generally, roughly square law detectors, which measure the time average acoustic intensity at the recording plane. These detectors are also classified in

16



Figure 2-9 An optically scanned ultrasonic image converter which responds to the velocity of the vibrating plane P_2 .




accordance with the dominant mechanism responsible for detection. Most of these devices have the advantage of directly providing an optical transparency corresponding to the acoustic intensity at the recording surface. However, for practical operation, they require relatively large acoustic intensities ranging from 1 W/cm^2 for the photographic film to $10^{-5} \text{ Watt/cm}^2$ for the water-air interface method.

Thermal. Any material which is irradiated with sound waves will absorb a certain amount of energy and will convert most of this into heat. This heating effect can be utilized either directly or indirectly for detection. Ernst (23) made use of this effect by irradiating thermochromatic materials (the color of these materials depends on their temperature) and recording their change in color in areas of high acoustic intensity. This method was further advanced by woodmansee (24) who suggested the use of liquid crystals. Woodmansee noted that certain mixtures of cholesteric liquid crystals change their color from red to blue within one second for a temperature change of 1° C. Holograms using a liquid crystal display have been reported by Augustine (25).

Using the heating effect to affect the luminescence of thermo-sensitive phosphors which is previously saturated, Petermann ⁽²⁶⁾ saturated a phosphor with ultraviolet radiation, and then removed the ultraviolet source and ultrasonically exposed the phosphor from 25 to 60 seconds. He reported a threshold intensity of 5×10^{-2} Watt/cm² with a resolution of 0.2 mm at 3 MHz and with a one minute exposure time.

Photographic and Chemical. The fact that ultrasonic radiation influences photographic emulsion was reported by several workers (27, 28). Marinesco (29) utilized the fluorescence which is associated with cavitation of the medium to cause a latent image.

Bennet (30) demonstrated that luminescence is not a necessary feature to produce an image, i.e., a direct action of the acoustic radiation on the emulsion exists. He used both water and a developer solution as the transmitting medium, and reported that the degree of softening of the emulsion affected the speed of the image formation. This effect was confirmed by Berger (31), noting that by pre-soaking the emulsion for 3 or 4 hours, the ultrasonic exposure time can be reduced from 4 hours to one hour. He also reported exposures without darkroom techniques. With an iodine-water solution as the transmitting medium, a light exposed photographic emulsion yellowed in irradiated areas, furthermore, these areas became more resistant to fixing. Thus, upon fixing, the film is clear in unirradiated regions and yellow in irradiated areas. Arkhangel'skii (32) exposed ultrasonically an ordinarly light-exposed photographic paper suspended in a developer solution. It was reported that the ultrasonic field is able to accelerate processes which are associated with the diffusion of the developer into the gelatin layer of the photographic paper. Arkhangel'skii also determined the relative blackening of the paper as a function of the ultrasonic exposure time and the acoustic intensity. A threshold intensity of 5 x 10^{-2} Watt/cm² for a 40 seconds exposure time was reported. He further noted that the resolution of the detector could be equal to the thickness of the photolayer (0.01 mm) if streaming effects are eliminated.

When water, containing air bubbles, is subjected to ultrasound if intensity greater than 0.4 Watt/cm², cavitation of the water medium results. This process releases oxygen which in turn produces hydrogen perioxide ($H_2 O_2$). This can be used to oxidize organic compounds. Bennet ⁽³⁹⁾ utilized this criterion. He constructed a starch plate and placed it in water to which a diluted solution of iodine has been added. In the areas irradiated by ultrasound, the starch plate is tinted blue, and the resulting picture is semi-permanent. A sensitivity of 1 Watt/cm² for one minute exposure time was reported.

Mechanical and Optical. Avery simple and quite sensitive mechanical detector is the Pohlman Cell, which makes use of the tensorial characteristic of the radiation pressure of acoustic waves in the following manner. Referring to Figure (2-11), the aluminum disks of radius R in the cell without the presence of ultrasound are randomly oriented due to normal thermal motion, and light reflected from these disks uniformaly illuminates the screen. However, under the action of ultrasound the radiation pressure exerts shearing forces on the disks and aligns them normally to the ultrasonic beam. The resultant light distribution on the screen will then consist of bright areas due to light reflected from aligned disks, superimposed on a grey background due to light reflected from randomly oriented disks. A threshold intensity of 3×10^{-7} Watt/cm² with reaction time of several minutes was reported.



Figure 2-11 The Pohlman Cell

Brenden and Hildebrand ⁽³⁴⁾ utilized the pohlman cell, and constructed an acoustic imaging system, referring to Figure (2-12), the pohlman cell PC is placed at the hologram plane H. A light source S illuminates the particle cell through the optical window W_1 . As described before the transmitted light through the particle cell, carries information about the acoustic image, which can be received on a screen after passing through the optical window W_2 . This system has the drawback that the light must propagate through the water which must be clear, also the sound wave has to impinge almost perpendicularly on the membrane in order to orient a large number of aluminum disks. Therefore the angle between the object and reference sound beams must be small. A threshold intensity of 10^{-4} Watt/cm² with a reaction time of a few minutes was reported.

The radiation pressure may also be used to deform a surface. If the surface is a liquid-air interface, it has been shown (35) that the surface deformation due to two interfering acoustic waves consists of the superposition of the following three components:

- 1) A large, static and spatially uniform displacement.
- 2) A spatially varying deformation independent of time.
- 3) A small space and time varying deformation.

The time independent, spatially varying deformation is the dominant informationcarrying process and it is a function of the resultant acoustic intensity distribution at the interface.

Sokolov ⁽³⁶⁾ suggested a method whereby the deformed liquid surface (analog relief pattern) can be observed by reflecting light from the surface, (see Figure 2-13). The curvature of the surface elements is used to focus the light in proportion to their redii. Consequently, in the image, insonified regions of the surface appear darker, while those regions which are not insonified appear lighter.

Sette (37) utilized the Topler "dark field" method in visualizing the surface deformation (see Figure 2-14). In this system the lens L is positioned so that it images



Figure 2-12 Acoustical Holography System Utilizing Pohlman Cell



Figure 2-13 Method after Sokolov for imaging the analog relief pattern.



Figure 2-14 Topler "dark-field" method for imaging the analog relief pattern.

the water surface onto screen S, and the spatial filter F (which is situated in the focal plane of the lens) is adjusted, in the absence of ultrasound at the interface, so that none of the light is allowed to pass. When the surface is deformed by a sound wave, some of the light is deflected past the "stop" and illuminates the screen. Hence, regions of the surface which are insonified are bright on a dark background.

Although the analog relief pattern method is a simple conversion method, analysis show (38) that the surface deformation is not directly proportional to the acoustic intensity at the interface; but rather, the conversion process suppresses high spatial frequencies.

The high frequency loss increases with the surface tension of the liquid, this decreases resolution and introduces image distortion, also the streaming and oscillatory disturbances of the water surface decrease the quality of the image obtained. Gericke and Grubinskas $^{(39)}$ minimized the surface disturbances by using a separate container for the deforming liquid. This also permits the use of a liquid having a low surface tension to increase the spatial frequency response of the surface (see Figure 2-15). Brenden $^{(40)}$ utilized the same principle and used an acoustic lens to focus the image into the hologram plane, thus minimizing the image distortion and improving the resolution. He reported a sensitivity of 10^{-3} Watt/cm² at 1 MHz (see Figure 2-16). Green $^{(41)}$ eliminated the acoustic reference wave and used instead an ultrasonic diffraction grating to modulate the acoustic image onto a high frequency spatial carrier (see Figure 2-17). Using this approach the technique appears limited, however, to "focused image holograms".

Fischer (42) used an acoustic transformer to transfer the acoustical interference patterns from surface bounded by water to surface bounded by air, (see Figure 2-18) and then utilized the interferometric characteristic of optical holography to record the output vibration pattern. A threshold intensity of 2.9×10^{-3} Watt/cm² has been reported.



_____ THIN MEMBRANE

Figure 2-15 Method for minimizing unwanted disturbances of the surface deformation.



Figure 2-16 Liquid Surface Holography.

COLLIMATED, COHERENT LIGHT







Figure 2-18 Acoustic holography system utilizing impedance matching transformer.

Conclusion

From the previous survey, it is possible to list some basic characteristics of each of the ultrasonic image converters as follow:

- a) Scanned Detectors.
 - 1) High sensitivity due to the utilization of electronic amplification.
 - Good resolution capability with some limitation in case of resonant detectors due to mode coupling.
 - 3) Large processing time to obtain the final image, which limits the real time imaging applications.
 - 4) Systems are usually mechanically complex and, as a result, their cost is high.
 - 5) Good frequency selectivity (i.e., signal to noise ratio is large) due to the utilization of the mechanical resonance of the detector.
- b) Non-Scanned Detectors.
 - 1) Low sensitivity, except for the Pohlman Cell, the sensitivity of these devices is several orders of magnitude lower than that of the scanned detectors, this is largely due to the fact that electronic amplification is impractical.
 - 2) Good resolution, the resolution of the final image often approaches the theoretical limit.
 - Simultaneous recording of all points in the acoustical hologram plane. Reconstruction time can vary from seconds to minutes, some time instantaneous as in liquid surface levitation method.
 - 4) Extreme simplicity and economy.
 - Poor frequency selectivity since they do not take advantage of mechanical resonance.

LIST OF VARIOUS ULTRASOUND DETECTOR

Detector	Sensitivity W/cm ²	Resolution Millimeter	Image Formation Time Seconds	Reference
Mechanical Scanning with a microphone	1 x 10 ⁻²	2 x 10 ⁻³	>10	Metherell 5, 6
Mechanical Scanning with a point piezoelectric crystal	1 x 10 ⁻⁵ c	0.5	>10	Preston 9, 10, 11
Mechanical Scanning of piezoelectric cry stal with a capacity prob.	5 x 10 ⁻¹²	approximately twice crystal thickness	>10	Suckling 13
Ultrasonic Camera	1 x 10 ⁻¹¹ 1 x 10 ⁻⁹	twice crystal thickness	10 cycles of ultrasonic field	Sokolov ¹² Smyth ¹⁷
Electronic Scanning of a piezoelectric crystal and an image orthicon	1 x 10 ⁻¹¹	same as crystal thickness	Image dis- played at the fram rate of system used	Davidson 19
Optical Scanning of photo diodes	5 x 10 ⁻¹²		>10	Green 20
Optical Scanning of a vibrating surface with optical hetrodyne	1.46 x 10 ⁻⁸		>10	Massey 21
Optical Scanning of vibrating surface with a Schlieren arrangement	1 x 10 ⁻⁷			Korpel 22
Phosphor persistence changes	5 x 10 ⁻²	0.2	60	Petermann 26

Detector	Sensitivity W/cm ²	Resolution Millimeter	Image Formation Time Seconds	Reference
Starch Plate in an iodine solution	1	Limited to several mm by streaming	60-600	Bennet 33
Light exposed photographic film	1	Limited to several mm by streaming	40-100	Berger 31
Light exposed photographic paper	5 x 10 ⁻²	0.01 at 2MHz	100-200	Arkhangel'skii 32
Pohlmann Cell	3 x 10 ⁻⁷	few mm	Less than one but more time for higher sensitivity	Pohlman 35
Liquid surface levitation method	3 x 10 ⁻³ 1 x 10 ⁻²	few mm	Less than 1.0	Sette ³⁷ Smith
Impedance matching transformer	2. 9 x 10 ⁻³	few mm	Less than 1	Fischer 42

CHAPTER III

HOLOGRAPHIC INTERFEROMETRY AND SENSITIVITY IMPROVEMENT

Holography permits different and unique types of interferometry, all based on the fact that the images formed are produced by coherent light with well defined amplitude and phase distributions. Any use of holography to achieve the superposition of two coherent images will result in a potential method of interferometry.

Holographic interferometry is concerned with the formation and interpretation of the fringe patterns which appear when a previously generated wave, stored in a hologram, is later reconstructed and caused to interfere with a comparison wave. The storage or time delay aspect gives the holographic method a first unique advantage over conventional optical interferometry. A second important advantage occurs because diffusely reflecting or scattering surfaces which are subjected to motion can be interferometrically compared with their normal state, thereby permitting interferometric measurements of the displacement of each and all points of an object simultaneously. There are various holographic interferometric techniques which are commonly practiced for the detection and measurement of small (fraction of a wavelength) sinusoidal vibration amplitudes.

In this chapter, a theoretical discussion of the conventional holographic interferometry techniques is presented. The step-biased holographic interferometry technique is also described. This technique yields one order of magnitude increase in sensitivity over previous techniques is introduced.

Double Exposure Holographic Interferometry

In this method, two exposures of the hologram are made at different instants during the motion of the object, and therefore the respective images are stored as superimposed prior to processing. Each exposure is made with the identical reference wave. After the exposure of the hologram is completed the exact positioning, during recording of the object and of the other optical components used are no longer of concern. This method was introduced by Gabor et al (43). By means of multiple exposures of holograms, coherent additions of complex wave fronts can be achieved. This property is generally proved as follows. Let a photographic emulsion be exposed sequentially by N different intensity distributions I_1, I_2, \ldots I_N . The total exposure to which the emulsion is subjected may be written as:

$$E = \sum_{k=1}^{N} T_k I_k$$
(3-1)

Where $T_1, T_2, \ldots T_N$ are the N individual exposure times. Now suppose that during each interval T_k , the incident radiation is the sum of a fixed reference wave R (x, y) and an object wave $a_k(x, y)$, which changes from one exposure interval to another.

The total expsoure becomes:

$$E = \sum_{K=1}^{N} T_{k} |R|^{2} + \sum_{K=1}^{N} T_{k} |a_{k}|^{2} + \sum_{K=1}^{N} T_{k} |a_{k}|^{2} + \sum_{K=1}^{N} T_{k} |R|^{2} a_{k}$$

$$+ \sum_{K=1}^{N} T_{k} |R| a_{k}^{*}$$
(3-2)

Assuming operation in a linear region of the t-E curve of the emulsion, we find a component of amplitude transmittance.

$$t_{\alpha} = B \sum_{K=1}^{N} T_{K} R^{*} a_{k}$$
(3-3)

and

$$t_{\beta} = B \sum_{K=1}^{N} T_{k} R a_{k}^{*}$$
(3-4)

From equation (3-3) it is clear that illumination of the transparency by a wavefront R will generate a transmitted field of amplitude proportional to the weighted sum of the complex wavefronts $a_1, a_2, \ldots a_N$. As a consequence, N coherent virtual images of the original object producing the *a*'s will be linearly super-imposed in space and will, of course, mutually interfere.

In similar fashion illumination of the transparency by a wavefront \mathbb{R}^* will from equation (3-4) generate N coherent real images which will likewise interfere. From another point of view, it has been shown ⁽⁴⁴⁾ that double (or multiple) exposure holography can be considered as a special case of time average holography.

Double Pulsed Holographic Interferometry

In this technique powerful pulses of light (1-10 m Jouls) of short pulse duration (10 - 30 nano seconds) and with controlled interpulse separation is used to generate super-imposed holograms on the same photographic plate, just as in the double exposure method. A Q switched Ruby Laser with large coherence length is suitable for this method. Double pulsed interferometry permits the measurement of vibrational amplitudes of any waveform distribution over large areas, beside the ability to detect transient stresses and displacements.

Considering a sinusoidally vibrating object, and from the geometry of Figure (3-1), the phase variation generated in the rays scattered to the observer or the hologram plane by the displacement of an object point from position A to position A^{1} is given by:

$$\delta(\mathbf{x}) = -\frac{2\pi}{\lambda} [\overline{\mathbf{F}}\overline{\mathbf{A}} + \overline{\mathbf{A}}\overline{\mathbf{G}}] = -\frac{2\pi}{\lambda} (\overline{\mathbf{A}}\overline{\mathbf{A}}^{1}) [\cos\phi_{1} + \cos\phi_{3}] \qquad (3-5)$$



Figure 3-1 Geometry for calculating the Phase Difference $\delta(x)$.

Assuming a simple harmonic motion of the object point A:

$$\overline{AA^{1}} = D(x, t) = D(x) \cos \omega t$$
(3-6)

Substituting from equation (3-6) into equation (3-5) gives:

$$\delta(\mathbf{x}, \mathbf{t}) = -\frac{2\pi}{\lambda} D(\mathbf{x}) \cos \omega \mathbf{t} (\cos \phi_i + \cos \phi_s)$$
(3-7)

where

•

 λ = wave length of illumination

D(x) = amplitude of vibration

- ω = frequency of vibration
- ϕ_i = incident angle
- ϕ_{s} = scattering angle

Let a(x) be the complex amplitude of the light from A arriving at point P, and $a(x) \exp [i \delta (x,t)]$, the complex amplitude of the light arriving at P from A¹.

The resulting interference pattern has an intensity distribution which is given by:

$$I(x,t) = \{a(x) + a(x) \exp [i\delta (x,t)]\} \{a(x)^* + a(x)^* \exp [-i\delta (x,t)]\}$$

$$= 2 |a(x)|^{2} [1 + \cos \delta(x,t)]$$
(3-8)

In this technique the exposure times of the holograms are the same as the light pulse width, which are very short relative to the vibration period of the object as shown in Figure (3-2).



.

Figure 3-2 Harmonic oscillation of object points.

From equation (3-8) a minimum intensity is obtained if the following condition is satisfied.

$$\delta(\mathbf{x},t) = \cos^{-1}(-1) = (2n-1)\pi$$
(3-9)

Using equations (3-5), (3-6), (3-7), (3-9) and letting the first light pulse occur at time t_1 , and the second pulse at time t_2 , then the object displacement between the two pulses for sinusoidel vibration of amplitude D, is :

$$D(t_2) - D(t_1) = D(\cos \omega t_2 - \cos \omega t_1) = \overline{AA^1}$$
(3-10)

and by substitution from equations (3-9) and (3-5):

$$(2n-1)\pi = \delta(\mathbf{x},t) = -\frac{2\pi}{\lambda} D(\cos \omega t_2 - \cos \omega t_1) (\cos \phi_1 + \cos \phi_s)$$
(3-11)

Since points of equal displacement are connected by interference fringes, the relative motion between two object points can be determined by counting the number of interference fringes n between these two points.

From equation (3-11) the relative object displacement is given by:

$$\overline{AA^{1}} = \Delta d = \frac{n\lambda}{\cos\phi_{s} + \cos\phi_{i}}$$
(3-12)

Where n is the number of complete interference fringes between the two relative points.

The propagation velocity can be obtained from equation (3-12) by dividing the relative displacement Δd by the interpulse separation.

Time Average Holographic Interferometry

In time average holographic interferometry a single long exposure hologram is made while the object is in motion. For vibrational motion the method was proposed and demonstrated by Powell and Stetson (45, 46, 47). This technique may be regarded as ageneralization of the multiple exposure interferometry method to the case of continuous time exposure of vibrating object.

To form a hologram of a vibrating object, a photo sensitive medium is exposed to a reference wave whose complex amplitude at the hologram plane is R, and to object waves diffused from the vibrating object to the hologram plane each of which produces a complex amplitude a(x,t) at point P on the hologram.

At any time t the intensity at P on the hologram due to illumination from point A^1 on the object plus the reference wave is:

$$I(x,t) = [R + a(x,t)] [R^* + a^*(x,t)]$$
(3-13)

The exposure of the hologram is proportional to the time average of I(x,t) over the exposure time T.

$$I = \frac{1}{T} \int_{0}^{T} I(x,t) dt$$

$$= \frac{1}{T} \int_{0}^{T} [a(x,t) a^{*}(x,t) + R^{2} + R a^{*}(x,t)] dt$$

$$+ \frac{R^{*}}{T} \int_{0}^{T} a(x,t) dt$$
(3-14)

The last term in equation (3-14) is the term of interest. After exposure and proper processing, illumination of the hologram obtained by the original reference wave reconstructs the time averaged original subject wave given by the product.

Wa R
$$\frac{R^*}{T}$$
 $\circ \int^T a(\mathbf{x},t) dt$ (3-15)

$$W \alpha \frac{1}{T} \int_{\alpha}^{T} a(x,t) dt = \frac{1}{2\pi} \int_{\alpha}^{2\pi} a(x,t) d\omega t \qquad (3-16)$$

Using the geometry of Figure (3-1), and equation (3-5) for the phase difference therefore,

$$a(\mathbf{x},t) = a(\mathbf{x}) \exp \left[i \delta(\mathbf{x},t) \right]$$

= $a(\mathbf{x}) \exp \left\{ -i \frac{2\pi}{\lambda} \quad D(\mathbf{x}) \cos \omega t \left[\cos \phi_i + \cos \phi_s \right] \right\}$ (3-17)

Substituting from equation (3-17) into equation (3-16)

$$W = \frac{a(x)}{2\pi} \int_{0}^{2\pi} \exp\left\{-i\frac{2\pi}{\lambda} D(x) \cos\omega t \left[\cos\phi_{i} + \cos\phi_{s}\right]\right\} d\omega t$$
$$= a(x) J_{0}\left\{\frac{2\pi}{\lambda} D(x) \left[\cos\phi_{i} + \cos\phi_{s}\right]\right\}$$
(3-18)

Where J_0 is the Bessel function of zero order and of argument $\frac{2\pi}{\lambda}$ D(x) (Cos ϕ_i + Cos ϕ_s), therefore the intensity at the observation point P is:

$$W \cdot W^* \alpha a(\mathbf{x}) \cdot a^*(\mathbf{x}) \quad J_0 \left\{ \frac{2\pi}{\lambda} D(\mathbf{x}) \left(\cos \phi_i + \cos \phi_s \right) \right\}^2$$
(3-19)

Equation (3-19) shows that the dark fringes in the observed interference pattern of a sinusoidally vibrating object correspond to the zeros of the J_0^2 function, and the bright fringes correspond to the maxima of the function.

Real Time Holographic Interferometry

Real time holographic interferometry can be achieved as follows:

- 1. Forming a hologram of the stationary object.
- 2. Replacing the processed hologram in its original position with respect to the reference source and the object.
- 3. Setting the object into motion.
- 4. Observing the object through the hologram illuminated by the reference source, due to superposition of images in space the observer's eye performs a time average of the intensities of a sequence of interference patterns formed between light appearing to scatter **from** the static image and that scattered by the moving object.

From the geometry of Figure (3-1), let us consider an object point A on the virtual image of the stationary object generated when the hologram is illuminated by the original reference wave. Let a(x) be the complex amplitude of the light from A arriving at an observation point P. At any instant the observer at P detects the intensity of the interference of light from the virtual image point A with that from the corresponding point A¹ on the actual moving surface. Let $a(x) \exp [i \delta(x,t)]$ be the complex amplitude of the light arriving at P from A¹, where $\delta(x,t)$ is the phase difference and is given by equation (3-5), therefore the intensity at time t is:

$$I(x,t) = \{a(x) + a(x) \exp [i \delta(x,t)]\} \{a^{*}(x) + a^{*}(x) \exp [-i \delta(x,t)]\}$$
$$= 2 |a(x)|^{2} [1 + \cos \delta(x,t)]$$
(3-8)

An average taken over one period of vibration yields (48)

$$\langle I \rangle = 2 |a(x)|^{2} \frac{1}{T} \int_{0}^{T} [1 + \cos \delta(x,t)] dt$$
 (3-20)

Substituting from equation (3-5) into equation (3-20) and performing the integration yields (48)

$$\langle \mathbf{I} \rangle = 2 \left| a(\mathbf{x}) \right|^{2} \left\{ 1 + J_{0} \left[\frac{2\pi}{\lambda} D(\mathbf{x}) \left(\cos \phi_{s} + \cos \phi_{i} \right) \right] \right\}$$
(3-21)

From equation (3-21), it is clear that the fringe intensity goes to minimum when the amplitude of vibration D(x) corresponds to the zero's of the Bessel function $(J_0(z) = 0)$.

Real Time Stroboscopic Holographic Interferometry

This technique (49) is similar to real time holographic interferometry except that illumination now consists of short pulses of coherent light, synchronized to the vibrational motion of the object. In this method the real time fringes are observed by:

- 1. Forming a hologram of the stationary object.
- 2. Replacing the processed hologram in its original forming position.
- 3. Setting the object into vibration.
- 4. Illuminating the object once each vibration period with a short pulse of light, then by altering the phase at which the light flash appears, the vibrating object may be compared with the static image at any phase in its vibration cycle. One can vary the vibration frequency still keeping the light pulse and object vibration in synchronism, and so examine the full range of frequency response of the vibrating object, including narrow band resonances.

In this case the brightness of a vibrating point in the reconstruction is given by:

I
$$\alpha \operatorname{Cos}\left(\frac{4\pi A}{\lambda}\right)$$
 (3-22)

Where λ is the wave length of the light used, and A is the instantaneous displacement at the instant of the strobe flash.

In practice the sensitivity of the previous holographic interferometry method is less than that of the optical interferometers, but other advantages make holographic interferometry practical for many applications. According to Rayleigh Criterion a 10% variation in the radiance represents the limit of detectability. With the geometries most often employed by researchers, and by using H_e - N_e lasers, the minimum detectable amplitude of vibration that can be achieved by the previous techniques is of the order of 250 Å. Although the sensitivity attained is sufficient for many applications, it is desirable to increase such sensitivity, possibly by one order of magnitude, which can make the holographic interferometer the most accurate and practical instrument for interferometry applications.

The method of shifted reference holography, (50) affords, among many other advantages, just such an improvement in sensitivity, for proper choice of the reference beam frequency. This is obtained by making the radiance of a vibrating point proportional to $J_1^2(4\pi A/\lambda)$, rather than to $J_0^2(4\pi A/\lambda)$ as in the conventional method. Figure (3-3) shows the radiance of a sinusoidel vibrating point using the shifted reference method.

The increment in sensitivity is due not so much to the greater magnitude of the slope of the first order Bessel function in this region, but mostly to the fact that, under these conditions, nodal points appear dark, vibrating points light in the reconstruction. Consequently for the same difference in absolute radiance, the resulting brightness ratio, and so the visibility, is greatly increased. A ten-fold increment in sensitivity can be achieved easily in practice.

Unfortunately, the method requiring optical frequency hetrodyning with its accompanied losses, presents some difficulty in implementation and lends itself rather poorly to real time interferometry. Figure (3-4) shows the geometry of the shifted reference holographic interferometer.

46



Figure 3-3 Brightness distribution in the reconstruction of sinusoidal vibrating points using the shifted reference method.



Figure 3-4 Shifted-Reference Holographic Interferometry.

A sufficient enhancement in the sensitivity of real time holographic interferometry has been obtained by comparativly simple means through the introduction of the step-biased method of holographic Interferometry (51, 52, 53) as follows.

Step-Biased Interferometry

The new method is based on the superposition of a calibrated quarter wavestep motion on the motion to be detected. The sensitivity improvements are due to a reversal of the brightness distribution, so that vibrating points appear lighter, nodal points darker.

In this technique a hologram is formed first while the object is completely stationary, and then processed in its exact position using the real time plate holder.

Reconstructing this hologram by the same source used as reference during hologram recording, while at the same time observing the object now in vibration simultaneously subjected to a uniform step displacement (the bias), the reconstructed static virtual image is superimposed in space on the real vibrating object. The interference between these two optical patterns generates the real time interference hologram. Figure (3-5) represents the law of motion of a vibrating point during observation. In this figure, x(t) is the law of motion, A the amplitude of the vibration to be detected, D the amplitude of the biasing step and T the duration of observation.

As is well known (54, 55, 56) the radiance of the reconstructed point is proportional to the square of the magnitude of the modified degree of coherence.

$$g_{\rm mR}^{\rm (o)} = \frac{1}{T} \int_{-\infty}^{-\infty} \int_{-\infty}^{-\infty} \exp\left[J\frac{4\pi}{\lambda} x(t)\right] dt$$
 (3-23)

In our case due to the superposition of two images in space, therefore,



 $x(t) = D + A \operatorname{Sin} \Omega t \quad \circ < t < T$



$$g_{mR}^{(0)} = \frac{1}{T} \left\{ \int_{0}^{T} \exp \left[J \frac{4\pi}{\lambda} 0 \right] dt + \int_{0}^{T} \exp \left[J \frac{4\pi}{\lambda} (D + A \sin \Omega t) \right] dt \right\}$$
$$= \left[g_{mR}^{(0)} \right]_{virtual image} + \left[g_{mR}^{(0)} \right]_{real image}$$
(3-24)

Where λ is the wavelength of the laser light used, and $\Omega = \frac{2\pi}{\tau}$ the angular frequency of the mechanical vibration.

Assuming the observation time T to be much larger than the period of the mechanical vibration τ , and by obvious mathematics, it follows that

$$g_{\mathrm{mR}}^{(0)} = \left\{ 1 + \left[\exp\left(J \frac{4\pi D}{\lambda} \right) \right] \left[J_{\mathrm{o}} \left(4\pi \frac{A}{\lambda} \right) \right] \right\}$$
(3-25)

As represented in phasor form in figure (3-6), and

$$\left|g_{\mathrm{mR}}^{(0)}\right|^{2} = \left\{1 + 2J_{\mathrm{o}}\left(4\pi \frac{\mathrm{A}}{\lambda}\right) \operatorname{Cos}\left(4\pi \frac{\mathrm{D}}{\lambda}\right) + J_{\mathrm{o}}^{2} \left(4\pi \frac{\mathrm{A}}{\lambda}\right)\right\}$$
(3-26)

If the biasing is such that $D = \lambda/4$

$$\left| g_{\mathrm{mR}}^{(0)} \right|^{2} = \left\{ 1 - J_{\mathrm{o}} \left(\frac{4\pi}{\lambda} \mathrm{A} \right) \right\}^{2}$$

$$(3-27)$$

So that in the reconstruction the vibrating points will appear bright on a dark background of non-vibrating point. Consequently, for the same difference in absolute radiance the brightness ratio, and so the visibility is greatly increased, a one order of magnitude increase in sensitivity is easily achieved.

Figures (3-7) and (3-8) show the radiance distribution in the reconstruction of a sinusoidal vibrating point in the conventional method and the step bias method.



Figure 3-6 Modified degree of coherence in phasor form.



Figure 3-7 Brightness distribution in the reconstruction of sinusoidal vibrating points using conventional holographic interferometry methods.



Figure 3-8 Brightness distribution in the reconstruction of sinusoidal vibrating points using the step-biased holographic interferometry method.
The following experimental results were obtained to verify this new technique of holographic interferometry. The object chosen was the face of a barium titante piezoelectric crystal 5 cm in diameter. Both the vibratory and biasing step motions were induced by electrical excitation.

In the experiments depicted in Figures (3-9) to (3-13) and with the symbolism already introduced A = 30Å, $\Omega = 2\pi \times 10^6$ rad/sec., $\lambda = 6328$ Å.

Figure (3-9) is the reconstruction of a hologram of the object in the absence of electrical stimulation superimposed on the real image of the stationary object. (A = D = 0).

In Figure (3-10) a D.C. electrical stimulation was applied to induce a calibrated quarter wave step displacement, the crystal face was completely dark in accordance with equation (3-26) for A = 0, $D = \lambda/4$.

In Figure (3-11) the vibration excitation alone was applied as in conventional unbiased real time holographic interferometry. Due to the small amplitude of vibration induced almost no interference pattern is noticed and the vibration is virtually undetected.

In Figure (3-12), the step biased real time holographic interferometry was fully implemented, as described, so that the low of motion was as shown in Figure (3-5), i.e., the A.C. & D.C. stimulation was applied plus the superposition in space of the two images. Notice a clearly visible lighter portions in the center and at the edge of the crystal indicating that the vibratory motion in these regions has been detected.

Figures (3-13), (3-14) in which the vibratory motion has greater amplitude $(A = 800\text{\AA})$ permit detection in both techniques, by showing more evidently the circular symmetry of the distribution of the vibration amplitude on the crystal face.



Figure (3-9) Real time holographic interference image of object. No motion.



Figure (3-10) Real time holographic interference image of object with calibrated quarter-wave step motion only.



Figure (3-11) Real time holographic interference image of vibrating object. Vibration amplitude ~ 30 Å.



Figure (3-12) Real time holographic interference image of object with 30Å vibration superimposed on calibrated quarter-wave step motion.



Figure (3-13) Real time holographic interference image of object with 800Å vibration superimposed on calibrated quarter-wave step motion.



Figure (3-14) Real time holographic interference image of vibrating object. Vibration amplitude 800Å. No step bias applied.

In order to obtain exact quarter-wave step motion of the object, the piezoelectric disc under study, was pin mounted from the back electrod as shown in Figure (3-15), and the mounting plate rested on three piezoelectric crystal that are bonded to a back plate which is fixed to the optical bench, at the same time a layer of RTV used to seal the two plates together, therefore, by applying D.C. voltages on the PZT crystals the object with the front mounting plate was free to move as a piston according to the D.C. voltage applied. Figure (3-16) shows the arrangement used to verify the new technique experimentally.

5

In conclusion, step-biasing permits an improvement of about one order of magnitude in the sensitivity of holographic interferometry, and is easily applicable in practice to all the above mentioned methods of holographic interferometry, particularly to real time interferometry. The relative ease of achieving the sensitivity improvement in the step bias technique as well as its ability to detect the displacement amplitude of every point of a vibrating, diffusely reflecting object make this technique suitable for detecting motion induced by acoustic waves. Such an ultrasonic detector and its use in acoustic imaging system is described in the next chapter.



Figure (3-15) Arrangement used to obtain calibrated step motion.



Figure (3-16) Arrangement used to verify the new step biased Holographic Interferometry technique.

CHAPTER IV

FOUR-STEP ACOUSTICAL HOLOGRAPHY AND ITS REDUCTION TO THREE-STEP ACOUSTICAL HOLOGRAPHY BY USING THE STEP BIAS HOLOGRAPHIC INTERFEROMETER

In previous work (57, 58), the use of optical holographic interferometry for the conversion of an acoustic hologram to visible form (converted acoustic hologram) has been proposed. In its original form the technique is a four-step acoustical imaging system, illustrated in Figure (4-1).

FOUR STEP ACOUSTICAL HOLOGRAPHY

Step 1: Acoustic Hologram Formation and Transfer

Insonification of object o by supersonic source S_0 generates an acoustic object beam B_0 . Supersonic source S_R generates an acoustic reference beam B_R which interferes with B_0 at the first surface of acoustic transducer T, forming there an interference pattern of acoustic vibration that constitutes the acoustic hologram H_1 . This pattern of vibration propagates through transducer T and generates a second acoustic hologram H_2 on the second surface of T.

 H_2 is a faithful reproduction of H_1 , but the amplitude of the vibration pattern is greatly amplified, because of the transfer characteristics of T (several ways of obtaining this result are discussed in Chapter V). Step one then produces H_2 , the amplified acoustic hologram.

Step 2: Interferometric Hologram Formation

By conventional optical holographic techniques an optical hologram H_3 of the vibrating surface H_2 is recorded. Because, during recording, various regions of H_2 were in motion, H_3 is then interferometric hologram of the acoustic hologram.













Figure (4-1) Four step acoustic imaging system.

Step 3: Converted Acoustical Hologram Recording

An optical image of H_2 is obtained from H_3 by conventional reconstruction and photography techniques. In accordance with the principles of holographic interferometry^(59, 60) this picture H_4 is an optical reproduction of H_2 in which vibrating points (peaks of the interference pattern) appear dark, while stationary points (nodes of the interference pattern) appear light. H_4 therefore is an optical representation of the pattern of mechanical vibration that constitutes the acoustic hologram. This constitutes the converted acoustic hologram.

During the recording of H_4^4 a scale change is produced by the camera to compensate partially for the discrepancy between the two wave-length of the acoustical and optical radiations.

Step 4: Image Reconstruction

Converted acoustic hologram H_4 is reconstructed by conventional optical holographic techniques. The result is a three dimensional image O^1 of the originally insonified object O. Scaling constants will depend on the characteristics of the processing.

Although the system is non-scanning, operation does not take place, in real time, a delay being produced by the recording and processing of holograms H_3 and H_4 . This time delay between acoustic hologram formation and acquisition of the optically converted hologram limits the system's usefulness in applications requiring real time or quasi real time operation as in several medical applications. This time delay drawback is drastically reduced in the three step acoustical holography technique.

THREE STEP ACOUSTICAL HOLOGRAPHY

Step 1: Generation and Transference of Acoustical Hologram

From Figure (4-2), insonification of object O by supersonic source ${\rm S}_{\rm O}$ generates an





Figure (4-2) Three step acoustic imaging system.

acoustic object beam B_0 . Supersonic source S_R generates an acoustic reference beam B_R which interferes with B_0 , at the first surface of image converter T, forming there an interference pattern of acoustic vibration that constitutes the acoustic hologram H_1 . This pattern of vibration propagates through the converter T and generates a second, amplified, acoustic hologram H_2 on the second surface of T. Step one therefore, generates the amplified acoustic hologram, H_2 .

Step 2: Converted Acoustic Hologram Formation and Recording

Hologram H_3 is a hologram of the output surface of the converter T, recorded once and for all before the acoustic hologram formation and while the surface was therefore completely stationary. By reconstructing this hologram by means of mirror M, while at the same time observing T, now in vibration, the reconstructed static virtual image appears superimposed in space on the real surface of T. The interference between these two optical patterns generates in the camera the converted acoustic hologram H_4 in a single step. Step biasing is introduced at this stage to increase sensitivity, consequently^(61,62), H_4 is an optical reproduction of H_2 in which vibrating points (peaks of interference pattern) appear bright on a **dark** background of non-vibrating points (nodes of the interference pattern). H_4 therefore, is an optical representation of the pattern of mechanical vibration that constitutes the acoustic hologram.

Step 3: Image Reconstruction

Converted acoustic hologram H_4 is reconstructed by conventional optical holographic techniques. The result is a three dimensional image of the originally insonified object O. Scaling is added here to compensate for the wavelength discrepancy between the acoustical and optical radiations.

By these means the time delay between acoustic hologram formation and final image reconstruction can be brought down to a matter of less than a second, by Kalmar-type photoresist techniques or by computer processing. This latter would have the advantage of automatically taking care of all scaling problems, but would loose some of the real 3 dimensionality of the image, unless special provisions are taken. The converted acoustic hologram H_4 , obtained in step 2 of the three step imaging system is actually a real time shadow cast of the object placed close to the image coupler and therefore represent a two step, two dimension real time imaging method which is discussed in detail in Chapter VII.

The three step acoustical holographic imaging system just described is made possible by the use of the step-bias real time optical holographic interferometer discussed in Chapter III, together with an appropriate transducer, which is discussed in greater detail in Chapter VI. These two devices form a subsystem of the overall imaging process and will be referred to as the "holographic acoustic image converter". This nomenclature is appropriate since the coupler transfers the acoustical diffraction pattern from water medium to a surface bounded by air and the real time interferometer converts this acoustical image to an optical image. The sensitivity of the step-biased holographic interferometer is of the order of, 30Å, which has been already analyzed and verified experimentally in Chapter III.

In order to evaluate the acoustic power required to obtain a vibration amplitude of 30Å, let us consider the ideal case shown in Figure (4-3). A plane sound wave propagating in water medium is normally incident on an infinitely thin and supple membrane which couples the water medium to air. Due to nearly 100% reflection at the interface, the peak-to-peak vibration amplitude A_m of a point on the membrane is twice the incident amplitude of vibration. Therefore the minimum sound intensity that can be detected by the step bias interferometer is ⁽⁶³⁾.

$$I_{\min} = \frac{Z_{\omega}}{2} (\pi f A_{\circ})^2$$
(4-1)



COUPLER (INFINITELY THIN MEMBRANE)

- $A_i = peak$ vibration amplitude of the incident sound wave
- $I_i = sound intensity of the incident wave$
- A_r = peak vibration amplitude of the reflected sound wave
- I_r = sound intensity of the reflected wave
- $A_0 = peak$ vibration amplitude of the transmitted wave
- I_0 = sound intensity of the transmitted wave
- Z_{ω} = characteristic acoustic impedance of the water medium, 1.5 x 10⁶ kgm/m²sec
- Z_a = characteristic acoustic impedance of air, 420 kgm/m²sec
- Figure (4-3) Performance of an infinitely thin membrane used as a coupler.

 Z_{ω} = characteristic acoustic impedance of water

 $\mathbf{f}' = \mathbf{operating frequency}$

 $A_0 = A_m$ = Peaks vibration amplitude

Substituting into equation (4-1) to determine the threshold intensity in water that can be detected yields

$$I_{min} = \begin{cases} 1.13 \text{ mw/cm}^2 \text{ at } f = 0.410 \text{ MHz} \\ 6.7 \text{ mw/cm}^2 \text{ at } f = 1 \text{ MHz} \\ 670 \text{ mw/cm}^2 \text{ at } f = 10 \text{ MHz} \end{cases}$$
(4-2)

Which indicates that for those frequencies (0.1 - 10M) commonly used for acoustic imaging, at the high frequency end, some means should be provided for increasing the vibration amplitude. This vibration amplification must be performed by the coupler, which should therefore couple the vibration distribution from the water to the air interface and augment it at the same time.

The suitable coupler should also satisfy the following two additional requirements:

- 1. It should resolve all of the interference fringes of the acoustic image.
- 2. It should be insensitive to the angle of incidence of the sound waves.

Before discussing the different types of coupler that can be used, a "figure of merit" is applicable to any coupler will be defined. Referring to Figure (4-3), consider the thin membrane to be any coupler whose surfaces S_1 and S_2 are bound by water and air, respectively. Under the condition of normal sound incidence, let

$$t_{d} = A_{o}/A_{i} \tag{4-3}$$

= displacement amplitude transmission coefficient, or the gain of the coupler.

The discussion at this time is concerned primarily with devices that can couple and augment the vibration amplitude distribution, these devices can be classified as follow:

a) Velocity transformers:

These devices transform specific acoustic impedances for the purpose of matching two different media acoustically. They consist of a sandwich of extended, resonant matching plates, such as the two quarter-wave matching system, which is discussed in detail in Chapter V.

The maximum gain of the velocity transformer is achieved when the impedance of air is matched to that of water, that is

$$|t_{d}|_{max} = (Z_{\omega}/Z_{a})^{\frac{1}{2}} = 60$$
 (4-4)
when $(\frac{Z_{1}}{Z_{2}})^{2} = \frac{Z_{\omega}}{Z_{a}}$

Where Z_1 and Z_2 are the characteristic acoustic impedances of the quarter wave plates 1, and 2 respectively.

b) Velocity Amplifiers:

These are mechanical impedance transformers (mechanical impedance = area x specific acoustic impedance), and they couple a differential area of the total surface S_1 bounded by water to a corresponding differential area of surface S_2 bounded by air. Therefore in order to provide a spatial sampling of the vibration amplitude distribution in the imaging plane, an adequate number of samples must be taken. Hence the complete coupler must consist of a mosaic of such transformer with maximum elements spacing of peak to null width of the acoustic diffraction pattern.

An example of the velocity amplifiens are the ultrasonic horns, which are diagramatically shown in Figure (4-4). These velocity transformers vibrate as half-wave resonance at the operating frequency, and because of the unequal areas of the input and output cross sections, velocity amplification is possible by virtue of the law of conservation of momentum. The horn equation is given by (64):

$$\frac{1}{C^2} \frac{\partial^2 A}{\partial t^2} - \frac{1}{S} \frac{\partial S}{\partial x} \frac{\partial A}{\partial x} - \frac{\partial^2 A}{\partial x^2} = 0 \qquad (4-5)$$

or

$$\frac{\partial^2 V}{\partial x^2} + \frac{1}{S} \frac{\partial S}{\partial x} \frac{\partial V}{\partial x} + \frac{\omega^2}{C^2} V = 0$$
(4-6)

equations (4-5), (4-6) are a special form of the wave equation where

- V = Velocity potential in the materialC = Speed of sound in the materialA = Displacement amplitude
- S = Cross section area
- ω = Radian frequency

$$\frac{\partial s}{\partial x}$$
 = Cross section taper

now substituting into equations (4-5), (4-6) for different types of horns one can obtain [refer to Figure (4-4)].

a) Stepped Horn

$$\frac{V_1}{V_2} = \frac{A_1}{A_2} = \frac{S_2}{S_1}$$
(4-7)



b) Exponential Horn

a)

Stepped Horn



Figure (4-4) Velocity amplifier profiles.

V,	=	Velocity potential in section one
S ₁	=	Cross section area in section one
A ₁	=	Displacement amplitude at input section
V 2	=	Velocity potential at section two
S_{2}	=	Cross section area at section two
A_2	-	Displacement amplitude at output section

b) Exponentially Tapered Horn

If the cross section is given by

$$S = S_{i} e^{-\delta X}$$
(4-8)

where $\delta = \text{taper factor}$

$$\frac{V_{1}}{V_{2}} = \frac{A_{1}}{A_{2}} = \frac{D_{2}}{D_{1}}$$
(4-9)

where D_1 , D_2 are the diameters of the input, output cross section respectivly.

Other amplifier profiles can be used such as, wedge shaped horn, conical horn, catenoidal horn or fourier horn, the construction and fabrication of such small complex devices to satisfy the spatial sampling requirement may be difficult or sometime impractical.

Another type of velocity amplifier is the electroacoustic transformer and amplifier device shown in Figure (4-5), which consists of a matrix of quartz crystals which vibrate at half-wave resonance in their fundamental thickness mode at the frequency of the incidence sound wave. The voltage generated piezoelectrically at the other face of





each crystal element is amplified electronically and then applied to the corresponding element in the output crystal matrix. As a result the incident amplitud vibration pattern is faithfully transferred to the output mosaic with great amplification. It is clear that in the middle stage of this electro acoustic transducer, a simulated electronic reference beam can easily be added. The sensitivity that can be achieved by these device is limited by the gain of the electronic amplification stage (v_1/v_2) and the signal to noise ratio.

$$\left| \text{td} \right|_{\max} = \left(\frac{Z\omega}{2Z_a} \right)^{\frac{1}{2}} \left(\frac{\nu}{2} / \frac{\nu}{1} \right)$$
(4-10)

In conclusion, the holographic acoustic image converter combines the advantages of both linear and non-linear ultrasonic detectors discussed in Chapter II.

Depending on the type of the coupler used, the threshold sensitivity that can be achieved in practice, may vary from 10^{-3} Watt/cm² to 10^{-11} Watt/cm² at a frequency of 400 Kc/sec. However, it must be remembered that these values are given for normal sound incidence. Angle sensitivity is discussed in Chapter VI

CHAPTER V

THE ACOUSTIC IMAGE COUPLER

In this chapter, the use of the mechanical velocity transformer, and the velocity amplifier in constructing the acoustic image coupler is investigated. In particular, the design, construction and performance of such transformers is discussed in detail.

One type of acoustic image coupler consists of two sections each of which is half wave resonant at the operating frequency. The main function of these two sections is to optimize the transfer of the acoustic diffraction patterns from the surface bounded by water to the surface bounded by air. By partially or completely matching the acoustic impedances of the two media the power transferred is maximized. The resulting amplification of the vibration amplitude is then further increased by additional velocity amplification.

In the image coupler herein proposed the first half-wave section constitutes the mechanical velocity transformer matching acoustic impedances, and it consists of two quarter-wave matching plates. The second half-wave section is a microhorn structure which performs as a high gain mechanical velocity amplifier.

The Two Quarter-Wave Velocity Transformer

It is well known that, for normally incident plane sound waves, a single loss-less quarter-wave plate can match any two media if its acoustic characteristic impedance equals the geometric mean of the acoustic characteristic impedances of the two media (see Appendix I), i.e.,

$$Z_{2} = (Z_{1} Z_{3})^{\frac{1}{2}}$$
 (5-1)

Z₂ = Acoustic characteristic impedance of matching plate
 Z₁ = Acoustic characteristic impedance of medium one
 Z₃ = Acoustic characteristic impedance of medium two

If these media are water and air at ambient pressure, the acoustic impedance of the quarter-wave matching layer must be 2.5×10^4 Kg/m² sec. Any material with such low acoustic characteristic impedance would exhibit very high losses. In practice these losses would prevent any effective velocity gain in the desired operating frequency band. In order to obtain velocity amplification at reasonably low losses a multiple quarter-wave construction can be used.

The two quarter-wave velocity transformer which is investigated in this chapter is shown in Figure (5-1). It is assumed that a plane sound wave propagating in water and having a maximum displacement amplitude A_i is normally incident on plate 1. Of this incident energy, a part is reflected back into the water and a part is transmitted to the air. It is further assumed that the air medium extends to infinity so that no reflected wave exists in the air. Under these conditions, the displacement amplitude transmission coefficient td (the gain) of the system is defined by equation (4-3) previously introduced.

From the theory of multilayer films (65) as applied to acoustic plates, each individual plate can be described by a unique transfer matrix, which is given by

÷

$$M_{i} = \begin{vmatrix} m_{1} & m_{2} \\ m_{3} & m_{4} \end{vmatrix} = \begin{vmatrix} \cos \gamma_{i} & JZ_{i} \sin \gamma_{i} \\ \frac{J}{Z_{i}} & \sin \gamma_{i} & \cos \gamma_{i} \end{vmatrix}$$
(5-2)



Figure 5-1 A resonant mechanical transformer used for velocity augmentation across the air/water interface.

 $m_1, m_2, m_3, m_4 = matrix element$

 Z_i = Acoustic characteristic impedance of the medium

 γ_i = Complex phase angle of the medium

$$= \frac{2\pi}{\lambda_i} \quad d_i - J \alpha_i d_i$$

and $d_i = medium$ thickness

 λ_i = wave length of sound wave in medium

$$\alpha_i$$
 = attenuation coefficient in medium

For multilayer system the overall equivalent transfer matrix Meq is the product of all the individual transfer matrices, i.e.

$$Meq = M_1 \qquad M_2 \qquad M_3 \qquad M_4$$
$$= \frac{i=n}{|i|} \qquad M_i = \qquad \begin{vmatrix} \mathbf{m} & \mathbf{m} \\ \mathbf{n} & \mathbf{m} \\ \mathbf{m} & \mathbf{m} \\ \mathbf$$

Once Meq has been determined for the multilayer system the amplitude transmission coefficient is given by (see Appendix II)

$$td = \frac{2Z\omega}{m_1 Z_A + m_2 + m_3 Z\omega Za + m_4 Z\omega}$$
(5-4)

Substituting into equation (5-4) for the case of two quarter wave velocity transformer one can obtain

$$td = 2 Z\omega / (A \cos \gamma_{1} \cos \gamma_{2} - \beta \sin \gamma_{1} \sin \gamma_{2})$$
$$+ i (C \cos \gamma_{1} \sin \gamma_{2} + D \sin \gamma_{1} \cos \gamma_{2})$$
(5-5)

 $Z\omega$ = acoustic characteristic impedance of water

Za = acoustic characteristic impedance of air

$$A = Za + Z\omega \qquad \beta = Z_1 Za/Z_2 + Z\omega Z_2/Z_1$$
$$C = Z_2 + Za Z\omega/Z_2 \qquad D = Z_1 + Za Z\omega/Z_1$$

 Z_1 , Z_2 = characteristic acoustic impedance of plate 1 and 2 respectively

and the remaining parameters are defined in equation (5-2).

The two quarter wave velocity transformer has been studied by several investigators (66, 67, 68), encouraging results have been obtained (42, 69) by using brass, stainless steel, Al and Mg for the first quarter-wave matching plate coupled to epoxy, wax and plexglass for the second quarter-wave matching plate.

Although, the gain td | achieved in some design was adequate, all of the previous coupler design suffered from severe angle sensitivity, which results from mode coupling within the plate material. This major drawback limits the system applications, since the system resolution is governed by the ability of the coupler to respond to a wide angular spectrum of incident acoustic plane waves.

For the above mentioned systems an off-set of approximately 5° from normal incidence was reported (42) to decrease the coupler gain by 50%. In order to avoid these severe limitations in the acceptable angle of incidence it is necessary to minimize mode coupling within the plates by properly selecting the material for the first quarter wave matching plate.

Beryllium was selected for the first layer in the coupler to receive the acoustic diffraction patterns from water, since it exhibits a unique combination of acoustic properties that make it potentially attractive for this coupling component. These properties are:

Sound Velocity (70)

The velocity of longitudinal sound waves in beryllium is about 13,000 meter/ second, which is almost twice that of other metals. This higher velocity means an increased wavelength for any sound wave in the structure, on the other hand resonance dimensions can be precisely controlled. Also due to the low poisson's ratio of beryllium (as described in the following section) the sound velocity in beryllium is less dependent on frequency than in most of the other materials as shown in Figure (5-2). Consequently in pulsed imaging systems the ultrasonic pulse shape remains undistorted.

Poisson's Ratio

Poisson's ratio is the ratio of the elastic change in area to the change in length under uniaxial loading. In beryllium it has the unusually low value of 0.02 as compared with 0.3 to 0.4 for other metals. In ultrasonic applications, a low Poisson's ratio means reduced coupling of sound waves from one mode of propagation to another. For example, a longitudinal wave will remain longitudinal without transferring any significant energy to the shear mode of wave propagation. This ability to keep the different modes of propagation separated can be of great importance in acoustic imaging, where the signal could be greatly degenerated, if it is transferred into several interacting propagation modes, each with its own velocity of propagation and with its own dispersion relationship. The dependence of sound wave velocity on poisson's ratio is shown in Figure (5-2) and is investigated in reference (67).

Debye Temperature

Sound waves attenuation adversely affects the sensitivity of ultrasonic devices used for low amplitude (low power) sensing and imaging. This attenuation, sometimes called amplitude damping, arises as a result of internal friction within the material. In solids there



Figure (5-2) Sound velocity of plane longitudinal waves for infinite plate.

are several mechanisms for this internal loss of acoustic energy. Some of these mechanisms involve thermal diffusion, dislocation motion, impurity concentration and grain size. In general the losses are dependent on frequency, temperature and stress amplitude. The thermal effects are particularly important at the higher ultrasonic frequencies and in metals, relate closely to the Debye temperature.

The Debye temperature is the maximum temperature at which the crystal lattice remains in order. It is a measure of the acoustic losses in the material at high frequency. The Debye temperature of beryllium is more than two times that of most other metals. This results in increased detection sensitivity and improved signal to noise ratio. Table (5-1) gives a comparison of the acoustic properties of beryllium versus several other materials. The pre-mentioned unique acoustic properties of beryllium afford great improvement in coupler performance as discussed in Chapter VI.

The ability to keep the different modes of propagation separated increases the coupler angle of acceptance and therefore the coupler resolution. This, property complemented by the addition of a velocity amplifying micro-horn structure, result in a reduction of the interelement coupling and therefore improves the contrast of the output image.

The second quarter-wave matching plate of the mechanical velocity transformer uses epoxy resin (System 88) manufactured by NL Industries. The selection of epoxy resin to form the second matching plate eliminates the technological need to bond another matching plate to the beryllium, beside offering an acoustic characteristic impedance $(Z_2 = 2.5 \times 10^6 \text{ Kg/m}^2 \text{ sec})$ which closely matches beryllium to air. Another important consideration in the choice of this compound is that it offers low acoustic losses relative to other compounds, as shown in Table (5-2). This of course, in turn enhances coupler sensitivity. **TABLE 5-1**

PHYSICAL CONSTANTS FOR MATERIALS USED IN IMAGING SYSTEM

	Density	Young's Modulus	Poisson's	Longita Velocity	udinal Wave Impedance	Debye Temp	Attenuation at 1 GHz
Material	(gm/cm ³)	$(N/m^2 \ge 10^{-10})$	Ratio ^(a)	(m/s x 10 ⁺³)	(kg/m ² s x 10 ⁻⁶)	°K)	(nepers/m x 10
Aluminum	2.70	7	0.36	6.4	17	398	2.1
A1 Alloy	2.79	7-11	0.34	6.3	17		~2.3
Beryllium	1.85	31	0.02	12.9	24	1000	0.02
Copper	8.9	12	0.37	5.0	45	315	4.4
Iron	7.8	21	0.29	6.0	46		
Lead	11.4	1.5	0.43	2.0	22	88	30
Magnesium	1.74	4.2	0.31	5.8	10	290	73
Nickel	8.9	21	0.34	6.0	53	370	0.4
Stainless Steel	1.91	20	0.30	5.8	46		
Titanium	4.50	10.5	0.34	5.9	27		
Ti Alloy	4.5	11.5		6.1	27		
Tungsten	19.2	36	0.35	5.4	103	310	0.5
Fused Quartz	2.5	7.3	0.17	6.0	13		(q)
Polyethylene	0.93	-		1.9	1.8		
Water	1.0			1.6	1.4		0.0062
Air 1	l.2 x 10 ⁻³			0.33	0.0004		
Barium Titanate	5.6	11.8		~ 5.5	24		
Quartz 0° X-Cut	2.65	8.0		9~	15		

It is shown on previous pages, that under the condition of normal incidence, the displacement amplitude transmission coefficient is given by equation (5-5)

td =
$$2Z\omega/(A \cos \gamma_1 \cos \gamma_2 - \beta \sin \gamma_1 \sin \gamma_2) + i (C \cos \gamma_1 \sin \gamma_2)$$

+
$$D \sin \gamma_1 \cos \gamma_2$$
) (5-5)

Referring to Figure (5-1) the following additional conditions must also be satisfied by the beryllium-epoxy design.

1) Both plates are nearly a quarter-wave thick so that

$$K_1 \ell_1 \simeq \pi/2$$
 and $K_2 \ell_2 \simeq \pi/2$

2) Plate 1 is a metal and plate 2 is a plastic-like material such that

$$Z_1 > Z_2$$
 or $Z\omega$ and Z_2 or $Z\omega > Za$
Therefore $A \approx Z\omega$, $C \approx Z_2$, $D \approx Z_1$

- 3) The losses in each plate are small so that $\alpha_i d_i$ is small (i.e., $\cosh \alpha d \approx 1$ Sinh $\alpha d = \alpha d$)
- 4) The plates are homogeneous and of uniform thickness.

Assuming our design meets the previous assumptions, it follows from equation (5-5)

$$td = 2 Z\omega / (A^* \cos \theta_1 \cos \theta_2 - B^* \sin \theta_1 \sin \theta_2)$$

+ i $(D^* \sin \theta_1 \cos \theta_2 + C^* \cos \theta_1 \sin \theta_2)$ (5-6)

•

$$\theta_{1} = K_{1}d_{1}$$

$$\theta_{2} = K_{2}d_{2}$$

$$A^{*} = A + DL_{1} + CL_{2} + BL_{1}L_{2}$$

$$B^{*} = B + CL_{1} + DL_{2} + AL_{1}L_{2}$$

$$C^{*} = C + BL_{1} + AL_{2} + DL_{1}L_{2}$$

$$D^{*} = AL_{1} + BL_{2} + D + CL_{1}L_{2}$$

$$L_{1} = \alpha_{1}d_{1}$$

$$L_{2} = \alpha_{2}d_{2}$$

By evident algebra and introducing into equation (5-6) the Taylor series expansion of Cos 2θ and Sin 2θ about $\pi/2$, we obtain:

$$\left| \text{td} \right|^{2} = 4Z_{\omega}^{2} / [B^{*2} + a(f/f_{1} - 1)^{2} + b(f/f_{2} - 1)^{2} + 2C(f/f_{1} - 1)(f/f_{2} - 1) - d(f/f_{1} - 1)^{2}(f/f_{2} - 1)^{2}]$$
(5-7)

where

a =
$$(\pi/2)^2 (C^{*2} - B^{*2})$$

b = $(\pi/2)^2 (D^{*2} - B^{*2})$
c = $(\pi/2)^2 (D^{*}C^{*} - A^{*}B^{*})$
d = $(\pi/2)^4 (C^{*2} + D^{*2} - A^{*2} - B^{*2})$
f = $C_1/4d_1$ = frequency at which plate 1 is a quarter wave thick
 $f_2 = C_2/4d_2$ = frequency at which plate 2 is a quarter-wave thick

f = frequency of the incident sound wave Formula (5-7) holds for:

$$Z_1 > Z_2$$
 or $Z\omega$, $Za < Z_2$ or $Z\omega$,
C < b or d and $a \ge B^{*2}$

The previous parameters $A^* B^*$, C^* and D^* and therefore a, b, c and d vary with frequency since the attenuetion coefficient and the speed of sound in the two plates are frequency dependent. However, for small variations (nearly quarter wave plates), one may consider these parameters to be constant. Also for the beryllium plate, these parameters are very nearly frequency independent as shown in Figure (5-2) and Table (5-1), which results in an improvement of the coupler frequency response.

The two quarter-wave velocity transformer can be accurately tuned by using the tuning techniques discussed in detail in this chapter. The assumption of perfect tuning of the system can then be justified in this case so that the two plates can be assumed to be quarter-wave at the same frequency, $f_1 = f_2 = f_0$. Under this condition, equation (5-7) reduces to

$$td = 2Z\omega / [B^{*^{2}} + (a + b + 2c)(f/_{f_{0}} - 1)^{2} - d(f/_{f_{0}} - 1)^{4}]^{\frac{1}{2}}$$
(5-8)

. .

which gives a peak in the response at $f = f_0$ as shown in Figure (5-3).

Refering to Figure (5-3), one may define the following parameters

 $|td| max = maximum gain at f = f_0$

- $\triangle f = Band width$ (half-power points)
- $\Delta f |td|_{max} = gain-bandwidth product$
- $Q = f_0 / \Delta f = mechanical Q of the system$


Figure (5-3) Typical frequency response of the displacement amplitude transmission coefficient.

These parameters can be determined from equation (5-8) as follows;

$$At f = f_0$$

$$|td|_{f=f_0} = |td|_{max} = \frac{2Z\omega}{B^*} = \frac{2Z\omega}{(B + CL_1 + DL_2 + AL_1L_2)}$$
(5-9)

using the small losses approximation equation (5-9) reduces to

$$|td|_{max} = 2Z\omega/(Z_1 Z_2 Z_2 + Z\omega Z_2 Z_1 + Z_2 L_1 + Z_1 L_2)$$
(5-10)

Since $Z_1 > Z_2$, it is clear that the term $Z_1 L_2$ in equation (5-10) is the governing (dominant) factor in controlling the maximum attainable gain for the coupler. In conclusion the resonant coupler gain is determined essentially by the losses of medium two ($\alpha_2 d_2$). By neglecting the fourth-order term in the denominator in equation (5-8), the bandwidth can be deduced approximately as

$$\Delta f \simeq \frac{4 f_0 B^*}{\pi \left[\left(C^* + D^* \right)^2 - 2 B^* (A^* + B^*) \right]} \frac{1}{2}$$
(5-11)

Using equations (5-11), (5-9) it follows that the gain bandwidth product $\Delta f |td|_{max}$ is

$$\Delta f \left| td \right|_{\max} = \frac{8f_0 Z\omega}{\pi \left[\left(C^* + D^* \right)^2 - 2B^* (A^* + B^*) \right]^{\frac{1}{2}}}$$
(5-12)

and that the mechanical is

$$Q \simeq \frac{\pi}{4B^*} [(C^* + D^*)^2 - 2B^*(A^* + B^*)]^{\frac{1}{2}}$$
 (5-13)

Considering the previous discussion, the fact that the losses of plate 2 essentially determine the performance of the tuned system as shown by equation (5-10), makes it vitally important to develop an accurate testing method to measure the attenuation coefficient of each material used to construct the coupler.

Figure (5-4) shows a block diagram of the test arrangement used to measure the attenuation coefficient. The sample under test is sandwiched between two transducers, a short pulse is applied to the transmitting transducer and at the same time starts a precision counter. The pulse received by the second transducer is used to trigger off the counter; therefore the propagation time t_i of the pulse through the sample is directly displayed on the counter. Knowing the sample thickness d_i and the propagation time t_i we deduce

$$C_i = (t_i/d_i)^{-1}$$
 (5-14)

By repeating the test without the sample i.e., with the transducers directly coupled to each other and using the series attenuators of the figure to make the received signal level the same in the two cases, the attenuation coefficient can be computed by

$$\alpha_{i} = \frac{\text{attenuators reading in dbs}}{d_{i} \text{ in Centimeter}} \qquad \text{db/cm} \qquad (5-15)$$

The above assumes 100% energy transfer in the case of the directly coupled transducers and zero reflections at all interfaces. In order to achieve more accuracy in the measurement, by eliminating the effect of the reflection factor between the transducers and the sample, a differential method was devised. In this case a thin and a thick sample of each material under test was made, and proceeding as previously it follows

$$C_{i} = \left(\frac{t_{2} - t_{1}}{d_{2} - d_{1}}\right)^{-1}$$
(5-16)



Figure (5-4) Arrangement used for testing attenuation and sound velocity in Materials.

where

 C_i = speed of sound in the material d_2, d_1 = thickness of thick and thin samples under test t_2, t_1 = propagation times in sample 2 and 1

and

$$\alpha_{i} = \frac{R_{2} - R_{1}}{d_{2} - d_{1}} \quad db/cm \quad (5-17)$$

where α_i = attenuation coefficient of the material under test

 R_2 , R_1 = attenuators measurements for sample 2 and 1 respectively

Table (5-2) displays the results obtained for different materials used for constructing various couplers.

Figure (5-5) shows the display obtained on the CRT for the transmitted and received pulse, also the propagation time through the sample.

Having developed the mathematical expressions for the parameters indicated in Figure (5-1), it will be useful to examine some numerical examples using potential materials for constructing the coupler. Table (5-3) lists the design parameters for the system shown in Figure (5-1) when media 1 and 2 are quarter-wave plates (at $f_0 = 410$ KHZ) of beryllium and epoxy, respectively and assuming different couples of values for the attenuation coefficients. It is noticed from Table (5-3), as the materials are made lossy, both the maximum transmission coefficient td max and the Q decrease such that the gain bandwidth product remains constant.

ACOUSTIC PROPERTIES OF SOME MATERIALS FOR PLATE 2

Material	Density Gm/Cm³	Velocity Cm/Sec x 10 ⁵	Impedance Acoustic Gm/Cm ² Sec x 10 ⁵	Attenuation db/Cm at 500 KHZ
StyCast 2651	1.5	2.89	4.5	0.79
NL System 88	1.09	2.29	2.5	0.68
Plex Glass	1.2	2.71	3.25	4.1
EpoTek 301	1.15	3.1	3.57	6.3
Dow Cor ning Sylgard 184	1.3	2.95	3.84	4.12
Polypropylene	1	2.06	2.06	2.109
Lexan	1.22	2.15	2.62	10.13
Lucite	1.33	2.68	3.56	4.72
Teflon	2.18	1.178	2.57	16.93
Rexolite	1.06	2.318	2.457	2.36
PVC	1.18	2.303	2.7175	6.24







.

TUNED RESONANT PLATES WATER-BERYLLIUM-EPOXY-AIR $f_0 = 410 \text{ KHZ}$

$\Delta f |td|_{max}$ td max $\Delta \mathbf{f}$ Q α, α₂ x 10³ KHz neper/m 0.00 0.00 19.47 60.16 132.6 3.09 0.01 15.76 3.8 59.9 107.9 1 0.01 9.25 6.39 60 64.2 5 0.01 6.09 9.85 60 41.6 10

$$Z_{1} = 24 \times 10^{6} \text{ Kgm/m}^{2} \text{ sec}$$

$$Z_{2} = 2.5 \times 10^{6} \text{ Kgm/m}^{2} \text{ sec}$$

$$C_{1} = 12.9 \times 10^{3} \text{ m/sec}$$

$$C_{2} = 2.29 \times 10^{3} \text{ m/sec}$$

$$d_{1} = 8 \times 10^{-3} \text{m}$$

$$d_{2} = 1.398 \times 10^{-3} \text{ m/sec}$$

TUNED RESONANT PLATES WATER - STEEL - EPOXY - AIR $f_0 = 410 \text{ KHz}$

α ₁ α ₂		td max	$ riangle \mathbf{f}$	≏f td max	Q
nepe	er/m				
0.00 0.00		30.63	1.17	35.83	350
0.03 1	1	11.31	3.167	35.8	129
0.03 5	1	3.21	11.152	35.8	36.8
0.03 10		1.69	21.18	35.8	19.4
Z ₁	$= 41.2 \times 10^{-10}$) ⁶ Kgm/m ² sec		$Z_{2} = 2.5 \times 10^{6} \text{ Kgm}$	n/m ² sec
C ₁	$= 5.29 \times 10^{-10}$) ³ m/sec		$C_2 = 2.29 \times 10^3 \text{ m/}$	sec
d ₁	$= 3.23 \times 10^{-10}$) ⁻³ m		$d_2 = 1.398 \times 10^{-3} m$	n

Table (5-4) lists the parameters of a tuned steel-epoxy resonant system assuming the same attenuation coefficients that were used in Table (5-3).

As predicted from the pervious discussion, it is apparent that the performance of the two quarter-wave plates shown in Figure (5-1) is essentially determined by plate 2 since the maximum gain of the overall system is limited mainly by the attenuation coefficient α_{a} of material 2.

The Velocity Amplifier (Microhorn Structure)

The velocity amplifier constitutes the second section of the acoustic image coupler, which transfers with amplification the acoustic diffraction patterns received from the velocity transformer to the output medium (air). The basic function of the microhorn structure is to couple a differential area of the total output surface S_1 of plate 2 of the first section of the image coupler to a corresponding differential area bounded by air, thereby providing a spatial sampling of the vibration amplitude distribution in the imaging plane. An adequate number of samples must be taken to perform this task, and the integrity of each sample must not be degraded by acoustic cross coupling between the coupler elements in the microhorn structure.

In order to resolve all the diffraction patterns the array elements should be sampled at least at each peak to null width of the diffraction pattern (Nyquist rate of the maximum spatial frequency of the diffraction pattern). This is discussed in greater detail later.

Additional care must be taken in fabricating the microhorn structure in order to minimize the acoustic coupling between adjacent elements, since a large signal on one element will tend to excite adjacent elements and will be observed on the display as a smeared area rather than a distinct point. In the present structure the array elements were fabricated in the form of stepped horns of the same type of epoxy (system 88) used in constructing plate 2 in the impedancematching velocity transformer, therefore reflection losses between the two sections of the coupler are eliminated. Solving the wave equation for the stepped horn equations (4-5), (4-6), the velocity amplification is given by equation (4-7).

$$\frac{V_{1}}{V_{2}} = \frac{A_{1}}{A_{2}} = \frac{S_{2}}{S_{1}}$$
(4-7)

where

V₁, V₂ = Velcoity potential in sections 1, 2 respectively
 A₁, A₂ = Displacement amplitudes at sections 1, 2 respectively
 S₁, S₂ = Cross section area of section 1, 2 respectively

It is clear from equation (4-7) that the velocity gain can be increased by increasing the areas ratio but, on the other hand, this ratio is limited by spatial sampling requirements. Figure (5-6) shows the complete construction of the image coupler.

In the holographic detection of an object by a planar array of microhorn elements, it is important that the array possess a field of view and resolution consistent with object size and detail and also be capable of recording acoustical data at some minimum permissible signal to noise ratio.

The microhorn structure samples the time average acoustic intensity distribution at a discrete number of points on the imaging plane. The two dimensional sampling theorem for band-limited functions essentially states that to preserve a frequency band limited.



Figure (5-6) Acoustical image coupler.

.

function, samples are required at spacing of half the smallest fringe spacing. If the array is desired to have an angular field of view 2θ , the smallest fringe spacing is produced by the two waves incident on the recording plane at $+\theta$ and $-\theta$.

Thus, if the wavelength of the acoustic radiation is λ , the smallest fringe spacing is $\lambda/\sin \theta$. Hence the maximum spacing δ of array elements should be

$$\delta \leq C/2f_0 \sin\theta \tag{5-18}$$

or, alternately, the angular field of view of a given array is

$$\sin \theta = \frac{C}{2\delta f_0}$$
(5-19)

Where C is the sound velocity and f_0 the acoustic frequency of the object beam. For a given array δ is fixed. Equation (5-19) therefore gives the angular field of view of the array as a function of frequency.

Based on this, the lower frequency limit f_1 of array operation can be considered as that for which $2\theta = 180^{\circ}$ in equation (5-19). Below this frequency f_1 the array oversamples the acoustic field leading to decreased effective aperture. Similarly the upper frequency limit f_2 of array operation can be considered as one for which the angular field of view becomes too small for practical holographic purposes. As a rough estimate f_2 may be taken to correspond to $2\theta = 10^{\circ}$. Thus $f_2 - f_1$ gives an estimate of the frequency range in which the microhorn structure can be efficiently utilized in a general holographic situation.¹

¹In the preceding discussion the angular limitations of the impedance-matching velocity transformer (first section of the coupler) was not taken into account, since the beryllium quarter-wave plate has no mode coupling and the only angular limitation was contributed by the epoxy quarter-wave plate.

Since the microhorn structure is a tuned system which operates as a half wave resonant at the operating frequency f_0 , we conclude that f_0 must satisfy the inequality $f_1 < f_0 < f_2$. The physical aperture A of the microhorn structure is determined by the total number of microhorn elements, (spaced δ apart), contained in the structure. The aperture is related to the depth of field D_r and the resolution desired in the reconstructed image.

The depth of field D_r provided by microhorn structure (i.e., the image coupler) is given by (71)

$$D_{r} = \frac{4r^{2}\lambda}{A} \qquad \text{for } r < \frac{A}{2\lambda} \qquad (5-20)$$

where

r = Distance between object and the image coupler

 λ = Wavelength of sound in water

$$A = NS_{2}$$

N = Number of microhorn elements

 $S_2 = Cross$ section area of microhorn tip.

For $r > A / 2\lambda$ all objects are "in focus" with respect to the image coupler considering its inherent resolution.

The angular resolution $\triangle \theta$ of the microhorn structure derived by analogy with a rectangular antenna is given by (72)

$$\Delta_{\theta} = \lambda / \cos \theta \sqrt{A}$$
 (5-21)

where θ is the selected angular location. Similarly the resolution in the depth coordinate is given by⁽⁷³⁾

$$\Delta_{\mathbf{r}} = \lambda \mathbf{r} / \cos \theta \sqrt{\mathbf{A}}$$
 (5-22)

As for cascaded amplifiers the gain of the overall image coupler is given by the product of the gain of the individual stages, therefore by using equations (4-7) and (5-4) the total coupler gain is given by

$$td_{t} = \frac{i = n}{i = 1} td_{i} = \frac{S_{1}}{S_{2}} \frac{2 Z\omega}{m_{1} Z_{A} + m_{2} + m_{3} Z\omega Za + m_{4} Z\omega}$$
(5-23)

Using the mathematical expressions given by equations (5-19), (5-20), (5-21), and (5-22) yielding the performance parameters of the acoustic image coupler, let us compute some numerical value, valid for the beryllium epoxy image coupler under design.

$$f_0 = 410 \text{ KHZ}$$
 $\delta = 0.125'' \text{ A} = 19.4 \text{ Cm}^2$
= 0.317 Cm

Angular Field of View = 2θ = 70° Minimum Operating Frequency = 236 KHz Maximum Operating Frequency = 2.71 MHz Operating Frequency Band = $f_{max} - f_{min}$. = 2.474 MHz

Depth of field in the near field region

$$D_{r} = 0.004r^{2}$$

where

r = Distance between object and detector

Angular Resolution $\triangle \theta$

$$\Delta \theta = 56 \ge 10^{-3} / \cos \theta$$

$$at \theta = 0^{\circ} \qquad \Delta \theta = 0.056^{\circ}$$

$$at \theta = 60^{\circ} \qquad \Delta \theta = 0.112^{\circ}$$

Range resolution at a range r cm and an angle θ is

$$\triangle_{\rm r} = \frac{\rm r \times 10^{-3}}{\rm Cos \,\theta}$$

The above numerical values give an idea of the performance to be expected from the beryllium-epoxy image coupler. In Chapter (VI) an experimental verification of the previous characteristics will be offered.

CONSTRUCTION OF THE IMAGE COUPLER AND TUNING PROCEDURE

Starting with the beryllium substrate the following procedure was followd to prepare the quarter-wave beryllium plate of the velocity transformer (first section of the coupler):

- 1. The beryllium plate was hand-ground to the calculated thickness ($\lambda/4$ at f_0). The plate's thickness should be maintained as uniform and its face should be as flat as experimental conditions permits. An optical flat was used to check flatness with final tolerance of ± 2 microns in this stage.
- 2. The surface facing the epoxy was polished. This is desirable since the thickness tolerance of the epoxy is expected to be more critical in tuning than that of the beryllium.

- 3. The plate was then immersed in water and by using the pulse-echo immersion method described in appendix (III) was tuned for a half wave resonance at twice the operating frequency $2f_0$.² This process was repeated and the plate was ground until maximum transmission was achieved by monitoring the echo display on a CRT. Figures (5-7), (5-8) show the echo display of an untuned and tuned plate.
- 4. The beryllium plate was then chemically cleaned and vapor degreased using trichlorethylene. This step is very important for perfect bond between epoxy and beryllium.
- 5. Teflon was used as a mold to form the epoxy plate with its side covered with mold release agent (Dow Corning 20/Naphtha) attached to the polished surface.

Since the performance of the image coupler is essentially determined by the epoxy plate and the microhorn structure, the epoxy was prepared in accordance with two specific purposes, namely the minimization of the attenuation coefficient and the homogeneity of the mixture which implies that all gaseous impurities were to be removed from the mixture. The following steps yielded the best results for casting the epoxy.

- 1. National Led Vorite 689 and curing agent Polycin 876 were degassed separately in vacuum at 5 to 10 mm of mercury absolute pressure and at room temperature.
- 2. The degreased beryllium plate with the teflon mold attached to the polished surface was leveled on a plateau of an opened vacuum chamber, and the polished surface of the beryllium was brushed with a primer (Cromox #13-R-50 by Mobil) for improved adhesion.

²In order to achieve quarter-wave resonance (or odd-multiple of quarter-wave) for mechanical resonator, one of its radiating faces must be rigidly clamped (zero velocity), which is difficult to achieve in practice. An approximate (since sound velocity is a function of frequency) solution is to tune the resonator at twice the operating frequency as half-wave resonance (or odd multiple of half-wave).

- 3. Equal parts (by weight) of the resin, mentioned on page 107, and curing agent were then carefully and throughly mixed by hand using a metal spatula and a plastic cup at ambient pressure and temperature.
- 4. The mixed components were then poured at ambient pressure on the leveled beryllium plate. The amount of epoxy cast resulted in a final thickness which is about 0.5 mm (≈ 20 mils) greater than the required thickness.
- 5. The mixture was again degassed by rapidly decreasing the pressure to 5 mm Hg allowing forth to rise and collapse, the process was continued for 25 minutes to allow for complete degassing.
- 6. The vacuum was rapidly removed eliminating some of the surface bubbles. The rest of the bubbles are removed by spraying the surface with perchlorethylene aerosol.
- The mixture was cured overnight at room temperature and 4 hours at 80°C in the following day.

After the previous steps the mold was removed from the coupler, which was then ready for the tuning procedure as follows.



Figure (5-7) Pulse-Echo Display of an Untuned plate.



Figure (5-8) Pulse-Echo Display of Tuned plate.

Preliminary Tuning of the Image Coupler

Sound velocity in beryllium is essentially independent of frequency as shown in Figure (5-2), therefore tuning the beryllium plate as half-wave resonant at twice the operating frequency can be expected to yield an accurate calibration of the plate as quarter-wave resonant at the operating frequency.

A quarter-wave epoxy plate was constructed on the beryllium plate and the complete section was tuned by the pulsed ultrasonic method (see appendix III) as half-wave resonant at the operating frequency (410 KHz). This tuning was accomplished by grinding the epoxy to its proper thickness till maximum transmission was achieved as shown previously in Figure (5-7) and Figure (5-8). From the previous step the thickness of the quarter-wave epoxy plate was determined very accurately. Using this quarter-wave thickness value for the epoxy a full-wave coupler was constructed from the tuned quarter-wave beryllium plate and a three-quarter-wave epoxy layer plus grinding allowance. Figure (5-2) shows that sound velocity in thin plates is less than the longitudinal sound velocity in bars for most materials, therefore it was expected that the second quarter-wave section of the microhorn structure would be longer than the first quarter-wave.

In order to achieve the highest velocity amplification and for ease of machining a stepped microhorn structure with square cross section was fabricated. A 32×24 elements structure was constructed for operation at 410 KHz to demonstrate the feasibility of the image coupler. The preliminary tuning for the full-wave coupler was accomplished using the pulsed ultrasound method (Appendix III).

The coupler was immersed inside the water tank as shown in Figure (5-9), and the frequency of maximum sound transmission through the full-wave resonant coupler was recorded (f_0'). As a consequence of the previous precaution of making the epoxy layer thickness larger than the design thickness, the desired frequency of operation was greater than the measured resonance: $f_0 > f_0'$.

110



Figure 5-9 The pulsed sound, immersion technique for determining the half-wave resonant frequency of thin plates.

Referring to Figure (5-6), and from the preceding discussion the thickness of the beryllium plate, the first and second quarter-wave epoxy plate in the coupler was considered to be fairly accurate, only the last quarter-wave in the micro horn section was then tuned by grinding the epoxy micro horn tips. By repeating the grinding process in small steps, the resonant frequency of the coupler as full wave resonant was increased gradually till maximum transmission was achieved at $f_0 = f_0$. With the above tuning procedure the coupler could be tuned to within 5% of the desired operating frequency. Final tuning, however, was performed under actual loading conditions; that is, with the micro horn structure bounded by air.

Step-biased holographic interferometry was used for the final tuning procedure. Implementation of the step-biased technique requires the coupler to move as a piston with a calibrated step motion. Referring to Figure (5-10), in order to achieve this calibrated step motion, the image coupler (IC) rested on three piezoelectric crystals (Px) bonded to the back plate (P), which in turn was bolted to the water tank (T). The image coupler aperture was sealed by RTV to the back plate window, therefore the coupler was free to move as a piston by applying D.C. voltages to the piezoelectric crystals.

The voltage required to obtain a quarter-wave displacement can easily be computed, the d_{33} constant gives the required voltage to be applied to the crystal electrodes for a specific displacement Δt

$$d_{33} = \frac{\text{strain developed}}{\text{applied field}} = \frac{\frac{\Delta t}{t}}{\frac{V}{t}} = \frac{\Delta t}{V} \quad \text{meter/volt}$$

therefore the required voltage to produce a displacement Δt is given by

$$V = \frac{\Delta t}{d_{33}} \quad \text{volts} \quad (5-24)$$



Figure 5-10 ACOUSTIC IMAGE COUPLER (IC)

where

V = Applied voltage in volts

- Δt = Required displacement in meter
- t = Crystal thickness in meter
- d₃₃ = Crystal constant in meter/volt

for lead titanate zirconate $d_{33} = 270 \times 10^{-12} \text{ m/v}$ and the voltage to be applied is therefore 580 volts. Since the d_{33} constant varies from one crystal to another due to manufacturing tolerances, actual calibration of the step bias was achieved by optical means as follows.

First a hologram of the image coupler in the stationary state was taken without any excitation to the three piezoelectric crystals. Then the coupler was viewed through this hologram in accordance with standard real time holographic interferometry techniques. This showed a bright image of the coupler. Then the calculated voltages (580 volts) were applied to the three piezoelectric crystals and these voltages were varied slightly until the image coupler appeared dark. This indicated the achievement of the calibrated quarter-wave step motion as given before by equation (3-27).

Testing and Final Tuning of the Image Coupler

The performance of the acoustic image coupler as a tuned resonant system may be determined from the frequency response of the relative vibration amplitude of the microhorn structure surface. Two different test procedures can be used to obtain the frequency response. An arrangement permitting both procedures, is diagramatically shown in Figure (5-11). The actual laboratory implementation is illustrated in Figure (5-12).

Referring to Figure (5-11), the partially tuned image coupler "IC" is mounted, as previously described on the water tank wall. A broad band transducer "So", mounted





Figure (5-12) Setup used for tuning and evaluating the image coupler performance.

inside the water tank "T" on a movable carriage to provide a vernier adjustment of the distance between the transducer and the coupler generates a continuous plane sound wave which propagating in the water medium, is normally incident on the beryllium surface. The transducer output is kept constant by using step attenuator "A" at the transducer input. The optical system consists of a laser "L", a beam splitter "BS" for splitting the laser beam into an object beam "Bo" and a reference beam "B_R", two spatial filters "SF" to filter both optical beams and the real time plate holder "PH".

In the first technique a photo multiplier "PM" is used for optical detection, and the reference beam " B_R " is blocked. B_R is used for the second technique only. The object beam " B_0 " which is reflected from the vibrating microhorn structure surface, suffers a periodic lateral displacement which is converted to an amplitude modulation by the knife edge "K". The resultant amplitude modulated wave is detected by the photomultiplier tube and is converted to an electrical signal whose frequency is that of the incident sound wave. This signal is then amplified and displayed on an oscilloscope. Assuming the microhorn tips vibrate as a piston, the electrical signal amplitude is proportional to the microhorn surface vibration amplitude. Figures (5-13) and (5-14) show the displayed signal for a partially tuned coupler and a completely tuned coupler respectively.

Referring to Figures (5-11) and (5-12) in order to increase the sensitivity of the optical system and to average the vibration amplitude over a few microhorn elements, the angle of incidence of the laser beam on the coupler was made large (quasi-tangential incidence). Also a lens "L" was placed between the point of reflection and the knife edge. The knife edge was positioned at the focal point of the lens. It is worth noting that the method described above detects the vibration amplitude A_0 of the microhorn structure surface, not directly the displacement amplitude transmission coefficient td. Since $td = \frac{A_0}{A_1}$ it is imperative for our measurement, that the acoustic intensity of the incident sound wave be constant with frequency throughout the test. This can be accomplished by using the step attenuator. A small disc transducer (microprobe) was used to measure



Figure (5-13) Detected signal from partially tuned acoustic image coupler.



Figure (5-14) Detected signal from tuned acoustic image coupler.

the incident acoustic intensity and was placed at the same distance from the source transducer as the image coupler's first surface. By sweeping the frequency of the drive voltage to the transmitting transducer, a correction curve to compensate for the attenuation of the acoustic energy with increasing frequency was obtained and therefore the correct setting of the step attenuator at any operating frequency was determined.

With the experimental arrangement shown in Figure (5-11), the following general procedure was used to determine the frequency response of A_0 .

- 1) In order to minimize diffraction effects, particularly at low frequency, the distance between the coupler and the transducer was kept as large as possible.
- 2) The transducer was first aligned so that the acoustic radiation impinged perpendicularly on the beryllium plate. Pulses were sent from the transducer and their echo received as in the pulsed echo method and the amplitude of the first echo was maximized by adjusting the step-bias coarse adjustment screws.
- The optical system, especially the position of the knife edge, was adjusted to yield the highest signal to noise ratio.
- 4) Having aligned the acoustical and optical system, the transducer was excited with a sinusoidal voltage from a variable frequency generator. For each frequency the transducer's distance was adjusted to yield maximum output signal. Finally, each measurement was corrected to account for the variation with frequency of both the transducer output and the gain of the electrical amplifier.
- 5) The amplitude of the received signal should peak at the transducer's resonant frequency " f_0 ".

Finegrinding of the microhorn structure tips was performed till final tuning was achieved.

The second tuning technique utilized the step-biased real time holographic interferometry described in Chapter III. In this technique a calibrated quarter-wave step motion was applied to the coupler. An exact quarter-wave displacement was obtained using the procedures of real time holographic interferometry as previously described in some detail (see page 114.) Now, by irradiating the coupler with the acoustic energy, the interference patterns with reversed brightness distribution was produced by step biased real time holographic interferometry. By analyzing the fringe patterns quantitative information about the vibration amplitude was obtained. With the high sensitivity of the step bias interferometer (25Å), final tuning of the image coupler was achieved. Notice that now fine tuning can be performed on each and every point of the coupler's surface. Comparison with the results of the previous tuning was also performed. Figure (5-15) illustrates the tuned image coupler with the biasing crystals arrangement, and Table (5-5) gives the tuning data for the beryllium epoxy system.



Figure (5-15) Image coupler with the biasing crystals arrangement.

TUNING DATA FOR THE BERYLLIUM EPOXY SYSTEM

d ₁ mm	d ₂ (λ/4) Mm	d ₂ (3λ/4) Mm	f _o KHz	f _o KHz	Comment
8	0.0	0.0	820	410	Single Br. Plate
8	1.419	4.239	401	400	Full & Half wave resonat
8	1.406	4.23	403	402.5	
8	1.402	4.206	405	404	
8	1.4	4.202	407	406	
8	1.398	4.197	408	409.5	Tuned System
8	1.38	4.18	413	411.5	
8	1.37	4.12	416	413.6	

 d_1 = Thickness of Beryllium Plate

 $d_2(\lambda/4)$ = Thickness of Epoxy Plate for the Velocity Transformer

 $d_2(3\lambda/4)$ = Thickness of Epoxy layer for the whole coupler including microhorn structure

 f'_0 = Frequency at which $|r_p|$ nulls (max. transmission) using pulsed ultrasound (Appendix II).

 $f_o =$ Frequency at which $|t_d|$ or A_o is maximum using final tuning arrangements.

CHAPTER VI

PERFORMANCE OF THE TUNED ACOUSTIC IMAGE COUPLER AND THE INSONIFYING TRANSDUCERS

The acoustic image coupler described in Chapter V responds to a wide angular spectrum of incident acoustic plane waves. This is of great importance since it allows off axis holograms to be obtained without extreme restrictions. Variation of the sensitivity of the coupler with angle of incidence is also minimized. This basic advantage is mainly due to the use of beryllium which has minimum mode coupling and to the unique construction of the microhorn structure.

Sensitivity to Angle of Incidence

The frequency response of the tuned acoustic image coupler to different angles of incidence was experimentally measured using the same arrangement used for the final tuning [see Figure (5-11)] the result of the experiment is given in Table (6-1) and is plotted in Figure (6-1). It is shown that an off-set of 15° from normal incidence reduced the gain of the image coupler by only 20%, while the same off-set reduces the gain of a conventional image coupler by more than 60%.

Interelement Cross-Coupling

As seen minimum angle sensitivity for the system depends on minimum mode coupling in the structure and on minimum inter-element acoustic cross-coupling. A simple experiment was conducted to evaluate the cross-coupling between different microhorn elements in the structure. Interelement cross-coupling can be measured by measuring the relative amplitude of vibration induced in edge elements by excitation of a central area. This measurement can be performed using either the step-biased real time holographic interferometer described before or the photo multiplier detector as in the arrangement shown in Figure (5-11) (See Note 1).

¹Since detection of vibration induced in edge elements due to excitation of a central area is desired, the lens in the arrangement of Figure (5-11) was removed to allow optical detection from small areas on the coupler surface.

TABLE 6-1

ANGLE SENSITIVITY OF THE ACOUSTIC IMAGE COUPLER

a' i	td	$\Delta {f f}$
Incident angle of Acoustic Energy	Gain $\frac{A_0}{A_i}$	Bandwidth (KHz)
0	40	8.2
15°	32	10.25
20°	19	12.8
25	12	27.2
30	9	36.3



Figure 6-1 FREQUENCY RESPONSE OF A TUNED ACOUSTIC IMAGE

Coupler for a) Normal Incidence

15° off-set from normal incidence 20° off-set from normal incidence b)

c)

In order to excite only a central area of the structure, a sheet of styrofoam with a hole (¹/₂" diameter) was placed between the transmitting transducer and the image coupler, in water and next to the coupler. As a result only the energy passing through the hole irradiated the coupler, while the rest of the acoustic energy was reflected back. In accordance with the holographic interferometry method, by counting the number of interference fringes "n" between the two points on the perifery of the structure and using equation (3-12), the relative displacement between the two points, and so the cross coupling can be determined.

By using the photomultiplier detector, interelement cross coupling was measured directly. By illuminating the different elements and detecting the reflected moduleted beam, the displayed output voltage corresponding to the coupling level was recorded. Figure (6-2) shows coupling levels to edge elements due to excitation of central area (see Note 2).

Insonification Pattern

For transmission (shadow) imaging in order to realize as high resolution as possible the object and therefore the image coupler must be irradiated uniformly by the transmitting transducer. On the other hand it is also $known^{(3, 42)}$ that owing to diffraction effects, the resolution diminishes rapidly as the image coupler-to-object distance is increased. In order to optimize the results it is fundamental at this stage to study and visualize the pattern of energy propagation from an ultrasonic disc transducer.

² Due to the difficulty of exciting a single element in the microhorn structure Figure (6-2) was plotted for coupling levels, referred to the central four elements.


Figure 6-2 Coupling levels to edge elements due to excitation of central four elements.

Sound beam propagation from flat transducer is influenced by three design parameters, namely the transducer size, shape, and operating frequency. Consider a radiating circular disc (piston) with radius a, the normalized intensity distribution is given by (74, 75),

$$I/I_{O} = \left\{ \left\{ \sin \frac{\pi}{\lambda} \left[\sqrt{r^{2} + a^{2}} \cdot r \right] \right\} \quad \left\{ \frac{J_{1} \left(\frac{2\pi a}{\lambda} - \sin \theta \right)}{\frac{2\pi a}{\lambda} - \sin \theta} \right\} \right\}^{2}$$
(6-1)

where

r = Distance from disc center (range)

 θ = Is the angle between radius vector and the axial axis

 λ = Wave length of sound in the medium

 $I_0 = Acoustic intensity at r = \theta = 0$

= Axial intensity next to the transducer.

Equation (6-1) can be broken into two equations yielding the normalized axial intensity distribution and the directivity function

Relative Axial Intensity =
$$\sin^2 \frac{\pi a}{\lambda} \left[\sqrt{r^2}/a^2 + 1 - \frac{r}{a} \right]$$

= $\sin^2 \pi/\lambda \left[\sqrt{r^2 + a^2} - r \right]$ (6-2)

Directivity Function =
$$\left[\frac{J_1(Z)}{Z}\right]^2$$
 (6-3)

where $Z = \frac{2\pi a}{\lambda}$ Sin θ

Equation (6-2) and (6-3) were plotted by computer and are shown in Figure (6-3) and Figure (6-4).



Figure (6-3) Axial intensity distribution for disc transducer $\frac{a}{\lambda} = 5$.



Figure (6-4) Lateral intensity distribution for disc transducer.

The radiation pattern from any driven element is composed of two regions or zones of energy, known respectivly as:

- The Fresnel Zone (or near field) extending from the transducer to the last peak in the energy pattern, as shown in Figure (6-3).
- 2) The Fraunhofer Zone (or Far field) extending from the last peak of the energy pattern to greater axial distances.

In order to understand the acoustic energy distribution in the near field zone, Huyghen's principle of radiation field analysis can be applied to the sound field propagation from a piezoelectric element, in a manner similar to its use in analyzing electromagnetic wave and optical propagation. Huyghen's principle states that any wave phenomenon can be analyzed by summing the contributions from a distribution of simple point sources of proper intensity and phase to represent the physical situation. When this principle is applied to the mechanical energy propagated from a plane piston acoustic radiator, the contributions consist of compressions and rarefaction of wave energy emitted from small area elements of a piezoelectric transducer excited with an alternating voltage. A point source (one whose dimensions are small compared with a wave length), radiates in a spherical pattern. With a sufficiently large number of small sources acting in a single plane with the same phase, the radiated energy tends to form plane wavefronts of compression, rarefaction vibrations in the far field due to the constructive interference from the elements, while in the nearfield both destructive and constructive interferences occur. This situation is sketched in Figure (6-5). As in optics or electromagnetic radiation, the propagation pattern is a function of the number of wavelengths contained in maximum linear dimension of the driving element. For this reason, it is desirable to measure the transducer diameter in units of wave length of sound. The energy divergence to be expected from a radiating element with a diameter of one wavelength is approximately ± 45 degrees. For a larger diameter of four wave lengths it is approximately ± 10 degrees. If an essentially plane sound-beam pattern is to be maintained over a long range, the beam divergence must be kept to a minimum. The driver diameter should, therefore, be great enough to prevent excessive beam divergence over the useable portion of the energy propagation pattern. Figure (6-6) shows the beam divergence as influenced by crystal diameter.



Figure (6-5) Wavefront propagated from multiple source emitter (using Huyghen's Analogy).



Figure (6-6) Beam divergence as influenced by crystal diameter.

For $\frac{a}{\lambda} > 5$ equation (6-2) simply reduces to

$$I/I_{o} = \sin^{2} \quad \frac{\pi a^{2}}{2\lambda r}$$
(6-4)

Using equation (6-4) it is clear that the last axial maximum in the nearfield occurs at $\frac{a^2}{\lambda}$. In order to minimize the diffraction effects and to achieve as high resolution as possible the image coupler was placed at the last axial maximum with respect to the transducer (experimental verification is given later in this chapter).

It was expected that under practical experimental conditions the distance of the last axial maximum in the near field from the transducer would differ from the theoretical value (a^2 / λ) , due to damping and boundary conditions. Therefore a measurement was performed, accurately to determine this distance experimentally. A small sensor transducer was used to scan the near field of the radiating transducer and its output was directly displayed on an oscilloscope. The last axial maximum was found at $(r = 9/16 \ a^2/\lambda)$. This experimental result agrees with previous work (76, 77, 74).

It must be noticed that the size of the sensor transducer (microprobe) may affect the result since the introduction of the measuring probe into the transmitted beam may distort and alter the beam by reason of its interaction with the transmitted energy, therefore its size must be kept at a minimum.

An air backed lead titanate zirconate disc transducer was designed to operate as a radiating transducer at 410 KHz with a dimension of 2.5" diameter and 0.2" thickness. Using the previously described measurement technique, the last axial maximum of the acoustic intensity in the nearfield was found at 6.26" from the radiator in close agreement with $(9/16 a^2/\lambda)$. The transducer was therefore placed at 6.26" from the image coupler. This yields a satisfactorily uniform insonification of the image coupler since operation is still in the nearfield uniform distribution and the transducer is as far as possible from the radiator minimizing diffraction effects. It is well known (78) that in the nearfield of a transducer the field is uniform over a cross section of the order of the transducer's radiation area, as shown in Figure (6-7). In order to extend this region a novel transducer design was employed. This design yields a uniform lateral distribution and permits beam focusing. The details of the design are described in Appendix (IV).

In order to evaluate the imaging system's performance, the dynamic range of the system must be calculated. Referring to Figure (6-8), the intensity reflection coefficient α_r at the boundary of two media with acoustic characteristic impedances of Z_1 and Z_2 is

$$\alpha_{\mathbf{r}} = \frac{\mathbf{I}_{\mathbf{r}}}{\mathbf{I}_{\mathbf{i}}} = \left(\frac{\mathbf{Z}_{2} \cos \theta_{\mathbf{i}} - \mathbf{Z}_{1} \cos \theta_{\mathbf{t}}}{\mathbf{Z}_{2} \cos \theta_{\mathbf{i}} + \mathbf{Z}_{1} \cos \theta_{\mathbf{t}}}\right)^{2}$$
(6-5)

where

 $I_r = Reflected acoustic intensity$

 $I_i = Incident acoustic intensity$

 θ_i , θ_t = Angle of incident and transmission respectively.

Similarly the intensity transmission coefficient is

$$\alpha_{t} = \frac{I_{t}}{I_{i}} = \frac{4 Z_{2} Z_{1} \cos^{2} \theta_{t}}{(Z_{2} \cos \theta_{t} + Z_{1} \cos \theta_{t})^{2}}$$
(6-6)

For the case of normal incidence $\theta_i = \theta_t = 0$ and α_t , α_r reduce to \cdot

$$\alpha_{\mathbf{r}} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 , \quad \alpha_{\mathbf{t}} = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2}$$
(6-7)

Referring to Figure (6-8) and applying the transmission line analogy to determine the transmission loss caused by inserting the object in the acoustic path, we obtain (79)







$$\alpha_{r} = \left(\frac{Z_{2} - Z_{1}}{Z_{2} + Z_{1}}\right)^{2} \qquad \alpha_{t} = -\frac{4 Z_{1} Z_{2}}{Z_{1} + Z_{2}}$$

Figure (6-8) Reflection losses at interfaces

$$\alpha_{t_{2}} = \frac{I_{t_{2}}}{I_{i_{2}}} = \frac{4}{4 \cos^{2} K_{2}^{\ell} + \left(\frac{Z_{2}}{Z_{w}}\right)^{2} \sin^{2} K_{2}^{\ell}}$$
(6-8)

where

 Z_2 = Acoustic impedance of object Z_w = Acoustic impedance of water ϱ = Object width $K_2 = w$ = Operating radian frequency

$$C_2 = \frac{W}{C_2} = \frac{Operating radian requery}{Speed of sound thru object}$$

Equation (6-8) is derived considering the object as an infinite baffle, therefore in practical cases

Transmission loss
$$\leq 10 \log \frac{1}{\alpha_t}$$
 db (6-9)

referring to Figure (6-8) the total transmission loss for the system (i.e., the dynamic range) is

Total Transmission loss = $10 \log_{10} \frac{I_{i_1}}{I_{t_3}}$

$$= 10 \log_{10} \left(\frac{I_{i_{1}}}{I_{t_{1}}} + \frac{I_{t_{1}}}{I_{i_{2}}} + \frac{I_{i_{2}}}{I_{t_{2}}} + \frac{I_{t_{2}}}{I_{i_{3}}} + \frac{I_{i_{3}}}{I_{t_{3}}} \right)$$

$$= 10 \log_{10} \frac{I_{i_{1}}}{I_{t_{1}}} + 10 \log \frac{I_{t_{1}}}{I_{i_{2}}} + 10 \log \frac{I_{i_{2}}}{I_{t_{2}}}$$

$$+ 10 \log \frac{I_{t_{2}}}{I_{i_{3}}} + 10 \log \frac{I_{i_{3}}}{I_{t_{3}}}$$
(6-10)

The second and fourth term in equation (6-10) represents the absorbtion losses in the water medium. For viscous liquids the attenuation coefficient is given by (80, 67)

$$\alpha = \frac{2\omega^2 \xi}{3\rho_{\circ} C^3} \qquad \text{neper/meter} \qquad (6-11)$$

where

Radian frequency of sound wave = ω Liquid density = ρ С Speed of sound in liquid. = = Coefficient of viscosity ξ For fresh water $\alpha = 8.24 \text{ x f}^2 (\text{Hz}) \text{ x } 10^{-15}$ (Theoretical) (6-12) $\alpha = 24 \text{ x f}^2 (\text{Hz}) \text{ x } 10^{-15}$ (Experimental)

for 410 KHz operating frequency in water $\alpha = 0.004$ neper/meter, which is negligable considering the propagation distances involved.

To test the imaging capability of the device an object is interposed between the radiator and the image coupler, creating acoustic conditions equivelent to gabor hologram formation. The object used was made of 0.1" thick aluminum sheet and was placed at 1.875" from the image coupler by using equations (6-7), (6-8), (6-9), (6-10) the following numerical value are obtained

$$10 \log \frac{I_{i_2}}{I_{t_2}} = 14.6 \text{ db}$$

$$10 \log \frac{I_{i_1}}{I_{t_1}} = 7.5 \text{ dbs}$$

$$10 \log \frac{I_{i_3}}{I_{t_3}} = 7.5 \text{ dbs}$$

total transmission loss = 29.6 dbs

Therefore the system must have a dynamic range of at least 30 db = to accomodate the transmission losses (it must be noted here that since the object is not an infinite baffle its transmission loss will be less than 14.6 dbs).

Assuming the object's absorbtion to be 10dbs, by using equation (4-2), we conclude that, in order to ensure a detectable amplitude of vibration of $A_0 = 30 \text{ A}^0$, the transducer radiation intensity must be $I_{i_1} = 1.13 \times 10^{-3} \times 10^2 = 113 \text{ mW/cm}^2$

Experimental Results

In accordance with the previous discussion the transducer was placed at 6.28" from the acoustic image coupler and was also aligned so that the incident acoustic energy impinged perpendicularly on the image coupler. Real time optical holographic interferometry was used so that the image coupler was viewed through a hologram of the coupler in its stationary state. The transducer excitation power was increased till visual detection of the fringe patterns on the output surface of the image coupler took place. The acoustic intensity level at the interface between the acoustic image coupler and the water required for visual detection was then measured by means of a microprobe as previously described and calibrated. Figure (6-9) shows the fringe patterns observed at an incident intensity level (at the imaging plane, i.e., beryllium - water interface) of 520 mW/cm².

Referring to Figure (6-9) it is clear that the maximum incident intensity level is at the center of the coupler. Information about the vibration's amplitude distribution can be calculated as discussed in Chapter III. The parallel dark bands appearing on the mounting plate are due to step rotation and can be eliminated by applying the step bias technique as will be explained in Chapter VII with increase in the detection sensitivity.



Figure (6-9) Real time holographic interference image of tuned acoustic image coupler subjected to $520 \,\mathrm{mW/cm^2}$ incident acoustic intensity.

CHAPTER VII

IMPLEMENTATION OF THE STEP-BIASED HOLOGRAPHIC INTERFEROMETRY FOR ACOUSTICAL HOLOGRAPHY

The discussion of Chapter VI has introduced the acoustic image coupler which matches acoustic impedance from water to air and provides further velocity advantage for the acoustic signal. The image coupler, used in conjunction with holographic interferometry, can constitute a simple and sensitive acoustic image detector system, which does not require scanning. In this chapter we further investigate the implementation of the step-biased holographic interferometry technique for recording the converted acoustic hologram, or for displaying in real time the object shadowgram. In particular we shall consider the contribution of the new technique in reducing the threshold acoustic intensity required for imaging⁽⁸²⁾.

The relative ease of adjusting the optical parameters (see equation [3-27]) of the step-biased holographic interferometer as well as its high sensitivity and its ability to detect the displacement amplitude of every point of a vibrating, diffusely reflecting object makes this technique well suited for detecting vibrational motions induced by acoustic waves with amplitudes as small as 20 A°. Referring to Figure (5-10), which shows the details of construction of the acoustic image coupler including the arrangement to obtain the calibrated quarter-wave step motion, it is clear that by applying an appropriate DC voltage (given by equation 5-24) to each of the biasing piezoelectric crystal the image coupler can be made to move as a piston by any desired displacement. As shown in Figure (5-10) the image coupler has two degrees of rotational freedom around two axes in the imaging plane. Consequently, in practice, before applying the calibrated bias, a step rotation usually takes place, which produces dark and bright parallel fringes during the imaging. This regular sequence of bright and dark lines is described by (44, 51, 83)

$$\begin{vmatrix} g(0) \\ mr \end{vmatrix}^{2} = \frac{1}{2} \left[1 + \cos\left(\frac{4\pi D}{\lambda}\right) \right]$$
$$= \frac{1}{2} \left[1 + \cos\left(\frac{4\pi \theta y}{\lambda}\right) \right]$$
(7-1)

where

 θ = Step rotation y = Distance of corresponding point from axis of rotation D = θy = Point displacement $g_{mr}^{(0)}$ = Modified degree of coherence

Equation (7-1) gives the brightness distribution of the displaced points on the image coupler and is plotted in Figure (7-1).

Referring to Figure (7-1), it is shown that dark strips occur at $[D = (2n+1)\lambda/4]$, i.e., at odd multiples of quarter-wave step motion, which is in agreement with equation (3-26) for A = 0 and D = $(2n+1)\lambda/4$. This regular sequence of stripes can be eliminated by biasing the image coupler to compensate for the step rotation and to introduce any desired step motion as described previously in Chapter V.

Experimental Results:

The object chosen for imaging was a letter A of aluminum 2.5 inches in height, 1.75 inches wide at the base and 0.1 inch thick, placed at 1.875 inches from the image coupler and was insonified by an air backed lead zirconate titanate disc transducer of 2.5 inches in diameter, 0.2 inch thick, and was placed at 6.26 inches from the image coupler, which corresponds to the last maximum in the near field zone.



Figure 7-1 Brightness distribution in the reconstruction of step motion.

Figure (7-2) shows the transducer and transducer housing used in the experiments, and Figure (7-3) shows the aluminum object chosen. Figure (7-4) is the reconstruction of a time average hologram of the image coupler without step bias (i.e., DC excitation) or any insonification from the water medium. Figure (7-5) is a photograph of the face of the image coupler superimposed in space with the virtual holographic image of Figure (7-4), in accordance with the technique of real time holgoraphic interference. We shall henceforth refer to such pictures as "real time holographic interference images". In Figure (7-5) the coupler was stationary without step bias or acoustic insonification from the water medium. Notice the regular sequence of bright and dark lines described by equation (7-1) due to the step rotation of the coupler. Figure (7-6) is the real time holographic interferometric figure of the image coupler without step-bias but with acoustic insonification from the water medium and without insertion of the object between the transducer and the coupler. Notice the circular fringes on the face of the coupler due to the transfer of the vibratory motion from the water medium to air, also the dark and bright lines on the mounting plate due to the step rotation as discussed before. The brightness of any point on the coupler face is given by equation (3-26). The incident acoustic intensity at the water beryllium interface was measured using a microprobe as previously described, and was found to be 84 mW/cm^2 . For this set of conditions the incident acoustic power can also be calculated using equation (3-12) to obtain the peak amplitude of vibration from Figure (7-6) and then substituting into equation (4-1). This agrees with the experimental value obtained using the microprobe method.

Figure (7-7) is the real time holographic interference image of the image coupler without step-bias but with object inserted in place and with acoustic insonification. For this situation the transducer excitation was increased till clear detection of the object shadowgram on the coupler face was possible. Notice the circular fringes on the coupler face due to the vibratory motion, and the sequence of dark and bright lines on the mounting plate due to the step rotation, also the shadow of the letter A, one can identify the outline of the object with some difficulty, even at this high intensity level. Actually, in order to obtain a clear image of the object, the distance between the object and the image coupler

145



Figure (7-2) Transducer used in the imaging system.



Figure (7-3) The object "Letter A" used for imaging.



Figure (7-4) Reconstructed time average hologram of the image coupler. No step-bias motion or acoustic insonification were applied.



Figure (7-5) Real time holographic interference image of the image coupler, with free step rotation and without acoustic insonification.



Figure (7-6) Real time holographic interference image of the acoustic image coupler, with acoustic excitation level of 84 mW/cm² and without step-bias motion.



Figure (7-7) Real time holographic interference image of the acoustic image coupler, with object inserted in the imaging tank and with acoustic intensity of 370 mW/cm^2 . No step-bias motion applied.

was varied till the clearest acoustic shadowgram image was obtained at a distance of 1.875 inches ¹, which correspond to an incident acoustic intensity of 370 mW/cm^2 . This was verified by direct measurement using the same microprobe method. In this case the picture of Figure (7-7) was optimized for use as a direct shadowgram. A better image, and a three dimension one, can be obtained by using the information of Figure (7-7) as a gabor hologram, as discussed in Chapter IV. Optical reconstruction requires, of course, appropriate scaling techniques.

As discussed in greater detail in the following, Figure (7-8) is the real time holographic interferometric picture of the image coupler obtained with full implementation of the step-bias method, thereby obtaining a one-order of magnitude increase in sensitivity of the holographic interferometer. As a result the transducer excitation could be reduced till the object image was still clearly detected, and the incident acoustic intensity at the hologram plane was measured by the microprobe method as 47 mW/cm^2 . Referring to Figure (7-8), notice that the brightness distribution on the coupler face is reversed due to the implementation of the step-biased method and is proportional to $[1 - J_0 (4\pi A/\lambda)]^2$, as a result the object shadowcast appears dark with essentially no image distortion as in Figure (7-7), and with clear outline, one can also resolve the center hole in the aluminum letter A at this low threshold intensity of 47 mW/cm^2 which is almost one order magnitude lower than the threshold intensity required previously for conventional imaging. Also, due to the step-bias implementation one can notice that the sequence of the dark and bright lines on the mounting plate has disappeared, since the coupler was moved as a piston by a displacement of exactly one quarter-wave by means of the three biasing crystals as previously described.

Again, for the purposes of this experiment, the parameters of the physical arrangement (distances from radiator to object, from object to acoustic image coupler etc.) were chosen to optimize the system's performance in generating an acoustic shadowgram. This

¹Owing to diffraction effects, the resolution diminishes rapidly as the receiver-to-object distance is increased. Where it is not practical to position the transducer this close to the surface of interest, high resolution shadowgrams can still be obtained with the use of a focused transducer.



Figure (7-8) Real time hologrpahic interference image of the acoustic image coupler, with full implementation of the step-bias method and with threshold acoustic intensity of 47 mW/cm^2 .

mode of operation, as discussed in greater detail elsewhere, is itself very interesting, permitting real time optical visualization of a two-dimensional image (shadowgram) of an insonified object. As indicated, this can be achieved by implementing the technique of acousto-optical holographic interferometry, previously shown in Figure (4-2) up to and including step 2 (obtaining of the converted acoustic hologram H_4). Indeed, under proper choice of physical experimental parameters, as seen, H_4 is itself a shadowgram of the object. Obtaining the shadowgram of Figure (7-8) not only proves the capability of the system to generate shadowgrams. It also demonstrates the operational qualities (in particular the sensitivity) of the holographic interferometry acousto-optical converter, proving the feasability of operating the system for true three-step holographic imaging as described in Chapter IV.

Full implementation of the three-step method of acoustic holography permits, of course, three dimensions imaging of the insonified object. In this application the transparency of Figure (7-8) is interpreted as the converted acoustic hologram H_4 rather than as a shadowgram. This constitutes step 2 in the proposed three step acoustic holography discussed in Chapter IV. In order to reconstruct the three dimension image of the originally insonified object, the converted acoustic hologram H_4 must further be reconstructed by conventional optical holography techniques. This in turn raises several problems. If proper corrective steps are not taken, the image so reconstructed suffers from major distortions due to the difference in wavelength between the acoustic waves used to form the acoustic hologram and the optical radiation used for reconstructing the converted acoustic hologram H_4 . Scaling of the converted acoustic hologram by photoreduction will eliminate depth distortion resulting from the fact that longitudinal magnification and lateral magnification are no longer the same. As a consequence, the reconstruction displays longitudinal (perspective) aberrations similar to those encountered in high magnification microscopy.

This scaling problem has been investigated by many authors (3, 84, 85). Recalling the results of Meier⁽⁸⁵⁾ and following his notation, let U be the ratio of the wavelength of the reconstructing radiation to the wavelength of the radiation used during hologram recording. With reference to Figure (7-9), if the dimension of the hologram and object are small com-

153



Figure 7-9 Typical geometry for the holographic recording and reconstruction process.

pared to Z_0 , Z_r and Z_c , then it can be shown that (84, 85, 3)

$$M_{Lat} = \frac{M}{\frac{1 \pm m^2}{U} \frac{Z_o}{Z_c} - \frac{Z_o}{Z_r}}$$
(7-2)

$$M_{\text{Long}} = \pm \frac{1}{U} M_{\text{Lat}}^2$$
(7-3)

where the upper sign corresponds to the virtual image, the lower sign corresponds to the real image and

 M_{Lat} = Lateral magnification of the reconstructed image

$$M_{Long}$$
 = Longitudinal magnification of the reconstructed image

- m = The ratio of the linear dimensions of the hologram used in the reconstruction process to the analogous dimensions of the hologram obtained in the recording process (hologram dimension scaling).
- Z_0 = Radius of curvature of the object beam
- Z_r = Radius of curvature of the reference beam
- $Z_c = Radius$ of curvature of the reconstructing wave

In optical holography neither hologram nor wavelength scaling is usually necessary. With m = U = 1, an undistorted image ($|M_{Lat}| = |M_{Long}|$) of unit magnification is readily obtained by chosing $Z_c = Z_r$. The situation is quite different in acoustical holography since U is commonly of the order of 10⁻⁴. Without any scaling of the hologram dimension (m = 1), the longitudinal magnification of the reconstructed image usually exceeds the lateral magnification by several orders of magnitude. It is possible to obtain an undistorted image only if, $|M_{Lat}| = |M_{Long}|$, referring to equations (7-2) and (7-3), this condition can be satisfied if

m (1 - mZ₀/Z_c) = U (1 - Z₀/Z_r) (7-4) which results in $|M_{Lat}| = |M_{Long}| = U.$ In particular, if the reference and reconstructing waves are both plane ($Z_c = Z_r = \infty$), an undistorted image results when m =U. Hence, for this case, the hologram dimensions must be reduced by a factor of 10⁴. Another special condition arises when $Z_r = Z_o$ (Fourier hologram), in which case $|M_{Lat}| = |M_{Long}| = U$, when m = Z_c/Z_r . Demagnifying the hologram by a factor equal to the wavelength ratio (U) before optical reconstruction may decrease the hologram area to the point where resolution may suffer and proper hologram illumination for reconstruction may become difficult to achieve. In practice, with our dimensions of the acoustic hologram, this process would result in an optical transparency of the order of 0.1 mm square. A compromise can be made in which the hologram is reduced in size to about 5 mm square and the reconstruction is viewed through a low power microscope or an eyepiece. Appropriate scaling can also be achieved by computer processing. Under proper conditions this solution may permit extremely short time delays between the formation of the acoustic hologram and the reconstruction of the final image therefore allowing quasi-real time operation.

The above experiments prove the capability of the new imaging system to obtain acoustic shadwograms (two-dimension imaging) in real time. Since, by placing the object close to the acoustic image coupler, the acoustic shadowgram cast (rather than the true reconstructed image) can be viewed in real time. Any motion or deformation undergone by the object under investigation will be portrayed in the shadowgram in real time. As a result of this later characteristic the new system offers a potential application for cardiac acoustic imaging or moving target classification.

On the subsequent photographic manipulations required to obtain an optical transparency of the converted acoustic hologram H_4 , suitable for true holographic optical reconstruction prevent the present acoustic holography system from providing three dimensions real time visualization. This difficulty can in part be overcome by using either Kalmar type or photoresist techniques, or by proper computer processing. By such means the time delay between acoustic hologram formation and the final image reconstruction can be decreased to less than a second, thereby extending the system ability for quasi-real time operation.

Referring to Figure (7-8) one can see that the image resolution was limited by the microhorn output cross section and the aperture size as indicated before by equations (5-20), (5-21) and (5-22). This can easily be improved upon in future design, therefore the proposed imaging system has a potentially higher resolution capability which is not affected by any decrease in resolution due to the display system, a scanning electron beam diameter or detector aperture. The resolution of the visual image is directly proportional to the aperture area and inversly proportional to the microhorn output cross section area. Therefore, by proper construction of the microhorn structure elements (i.e. higher velocity amplification factor), the conversion sensitivity that can be achieved in practice may reach one mW/cm^2 at 400 KHz.

Generally speaking, the "holographic acoustic image converter" combines some of the characteristics of both linear and non-linear ultrasonic detectors discussed in Chapter II due to the use of a coupler and the "Step-biased holographic interferometer", respectively. As a result, this device is a simple, relatively sensitive, frequency selective, non scanned image converter whose receiving aperture is not limited to any particular size, especially if beryllium is used for constructing the first quarter-wave matching plate. For any operating frequency this will result in a plate twice as thick as that obtained by using any other metal. This property, coupled with the higher rigidity of beryllium relative to other metals, ensures improved mechanical support for the microhorn structure. A one meter square aperture size appears feasible for construction without excessive worrying about buckling or deforming, which makes it suitable for different underwater imaging applications and will result in great image resolution even at lower frequencies as usually practiced for sonar applications.

As mentioned before it is to be expected that a threshold sensitivity of the order of 10^{-3} Watt/cm² or better can be achieved easily with the present system, however it must be remembered that this threshold sensitivity obtained for normal sound incidence (for which threshold intensity is usually reported) and as demonstrated in Chapter VI, an angle of 15° off-axis will reduce the sensitivity by only 20% due to the unique construction of the acoustic image coupler. It must be noted here that under the same angle of incidence, conventional image couplers sensitivities would be reduced by more than 60% from maximum as reported by several authors (42, 69).

157

The interdependence between the angular sensitivity, threshold intensity, and resolution of the acoustic image coupler is due essentially to the use of a coupler whose receiving surface (the beryllium water interface) is a part of a full-wave mechanical resonant device. The angular sensitivity of the present acoustic image coupler is most readily determined experimentally as shown in Chapter VI. Its interdependence with the threshold intensity and resolution is evaluated using equation (4-1) and equation (5-22). As a result of the unique characteristic of its low angluar sensitivity, the new acoustic image coupler permits the recording of conventional off-axis (split-beam) acoustic holography, therefore effectively separating the true image from the conjugate image during reconstruction.

Finally by comparing the performance of the new acoustic imaging system with the performance of scanned and non-scanned ultrasonic detectors as discussed in Chapter II, the proposed acoustic imaging system compares favorably, since it combines most of the desired characteristics of both categories, as follow:

- 1. Its simplicity and economy.
- 2. Its ability to simultaneously detect a quantity related to incident acoustic energy at each and every point of the acoustical diffraction pattern.
- 3. The elimination of the need for scanning, therefore increasing the information handling rate of the system.
- 4. Its frequency selectivity due to the use of mechanical resonance property.
- 5. The ease with which amplification can be achieved, especially in the microhorn structure stage.
- 6. The processing time delay to obtain the final image can be decreased to less than a second, therefore allowing quasi-real time operation.
- 7. Real-time acoustic shadowgram operation is achievable by using real time holographic interferometry.
- 8. High conversion sensitivity, and low threshold intensity of the order of mW/cm^2 at 400 KHz.
- 9. High resolution, due to essentially unlimited aperture size, high spatial sampling rate by using miniture step horn elements. The system is unrestricted by display system limitation such as frame rate or scanning electron beam diameter.

With further development of the present system, such as better microhorn structure and efficient solutions of the scaling problems such as appropriate computer processing, acoustic holography may fulfill its promise as a means for three-dimensional visualization.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

A novel holographic acoustic image converter is developed. The converter constitutes a fundamental device in the three step method of acoustic holography proposed and described in this dissertation (see Chapter IV) and consisting of:

- 1. The generation of an acoustical hologram and its transference from one medium (water) to another (air) using the acoustic image coupler.
- 2. The optical recording of the acoustical interference pattern using the real time step-biased holographic interferometer to obtain the converted acoustical hologram.
- 3. The reconstruction of the converted acoustical hologram.

The feasability of a three-step acoustical holography system utilizing the new acoustic image converter has been proved, and several means for its implementation have been analyzed both theoretically and experimentally. This has resulted in proof of feasability of quasi-real time operation for three dimensional imaging. Real-time acoustic shadowgram (two-dimensional) operation has been demonstrated.

The holographic interferometry acousto-optical image converter offers the great advantage of displaying the intensity distribution of the acoustic energy on the whole first surface of the image coupler (beryllium plate) as a visual image, the converted acoustic hologram which, in turn, by conventional optical holographic reconstruction yields the three dimensional image of the originally insonified object. The complete device consists of (1) the acoustic hologram generating system, (2) an appropriate acoustic image coupler whose primary function is to transfer the acoustical energy from a surface bounded by water to a surface bounded by air and (3) the real time optical holographic interferometer with mechanical step bias. The holographic interferometry acousto-optic image converter appears to be the first-to-date that exhibits the favorable characteristics of both scanned and non-scanned imaging systems discussed in Chapter II. These characteristics are:

- 1. Real time operation for two dimensional imaging (acoustic shadowgram).
- 2. Quasi-real time operation (less than a second delay) for three dimensional acoustic imaging (acoustic holography).
- 3. High sensitivity (1 mW/cm^2 can be achieved).
- 4. Frequency selectivity (high signal to noise ratio).
- 5. Easier amplification by using the microhorn velocity amplifiers.
- High resolution (at 20 cm range, angular resolution = 0.056° and range resolution = 0.2 cm).
- 7. Simplicity.
- 8. Non-scanned type, high information transmission rate.
- 9. The ability to detect a quantity related to the vibration amplitude at each and every point of the acoustical diffraction pattern and convertes it to optical form.

Some of the improvements and innovations introduced in each of the three parts of the image converter are summarized in the following:

The Real Time Optical Holographic Interferometry System

The above study has yielded the new technique of step-biased holographic interferometry (see Chapter III). This technique (51, 52) affords an improvement of the sensitivity of conventional, optical holographic interferometry methods by more than one order of magnitude (that is, from 330Å to 20Å). The technique is based on the superposition of a calibrated quarter-wave step motion on the motion to be detected. The sensitivity improvements derive from a reversal of the brightness distribution, so that vibrating points appear lighter, nodal points darker in the converted image. Experimental verification of this technique was provided in Chapter III, and was implemented in the imaging system (see Chapter VII). The step-biased holographic interferometry technique has proved to be easily implemented in practice, and is readily applicable to all conventional holographic interferometry methods, particularly to real time interferometry.

The Acoustic Image Coupler

A particularly detailed study was conducted on the development and testing of an acoustic image coupler. This device is made up of two parts: a velocity transformer consisting of two quarter-wave plates, and a velocity amplifier consisting of a half-wave microhorn structure. A theoretical and experimental study of the two quarter-wave velocity transformer was conducted in some detail. To this end, the theoretical relations describing the behavior of the two section were developed (Chapter V and Appendix II). This study resulted in a practical, working system which proved to be capable of augmenting the displacement amplitude of the acoustical diffraction pattern as it is transferred from a surface bounded by water to a surface bounded by air. It was also proved that the overall system performance is governed by the attenuation losses in the epoxy section. It therefore became important to develop a usable practical method to measure accurately the attenuation coefficient of different epoxy compounds and their other acoustical characteristics of interest. The method devised is described in Chapter V. Finally a specific epoxy (NL System 88) was chosen since it offered the lowest attenuation coefficient (see Table 5-2).

In the formation of the first matching plate of the acoustic transformer, the novel use of beryllium with its unique acoustic characteristics, greatly upgraded system performance by minimizing lateral coupling. In order to achieve higher gain and less lateral
coupling, a mosaic of velocity amplifiers in the form of stepped microhorn structure was added to the velocity transformer. The complete coupler then forms a full-wave mechanical resonator. In **order** to avoid the reflection losses between the two half-wave sections, the microhorn structure was fabricated from the same epoxy compound (system 88) used to form the second matching plate in the first half-wave section.

In the course of this experimentation, two useful methods for tuning and testing the angular sensitivity of the acoustic image coupler were devised. As described in Chapter V, coarse tuning was accomplished with a pulsed sound, water immersion technique (see Appendix III), while final tuning was achieved by two optical methods. In the first method [see Figure (5-11)] a laser beam reflected by one point of the vibrating output surface of the coupler is intercepted by a knife edge and then received by a photo multiplier tube, the amplified output of which is linearly proportional to the vibration amplitude and is displayed by the oscilloscope. By this method tuning of the image coupler surface is performed one point at a time. This point by point technique is very precise, but very time consuming. In the second method tuning is achieved using the real time step-biased holographic interferometer, which gives simultaneous quantitative information about the vibration patterns over all the output surface of the image coupler. Both methods were used in "tuning" and testing the performance of the acoustic image coupler.

Experimental verification of the obtained, theoretical relations describing the behavior of metal epoxy construction was provided (see Chapter V). In particular, a velocity augmentation of 40 at 410 KHz has been achieved with beryllium-epoxy construction the resultant gain (32 db) in the power actually transmitted across the water-air interface represents a significant improvement.

The Acoustic Hologram Formation System

Included in the dissertation is a theoretical and experimental investigation of a transducer with uniform intensity distribution (see Appendix IV). This transducer design allows focusing by simply driving the disc and ring electrodes on the transducers with 180°

163

out of phase voltages (88). As a result high resolution transmission imaging of an object close from the image coupler is made possible (real time application).

Finally the techniques described on the previous pages, theoretical developments and experimental results indicate that a holographic interferometry acousto-optical image converter of the above description having a threshold intensity of the order of 10^{-3} W/cm² at 410 KHz appears feasible. The various studies conducted and described in this dissertation have resulted in a number of recommendations pertaining to further work.

- 1. As indicated in Chapter VII the time delay between acoustic hologram formation and the final reconstruction prevents the present system from producing instantaneous acoustic holograms for real time visualization, it would be useful to further investigate different approaches to overcome this problem. Computer processing seems to be the most promising, since it will not only minimize the time delay problem but it will also have the advantage of automatically taking care of all scaling problems caused by the wavelength discrepancy between acoustic and optical radiation.
- 2. The experimental results of Chapter V and Chapter VI indicate that a further increase of the displacement amplitude transmission coefficient is primarily limited by the acoustic losses of the epoxy section. It would seem, therefore, that a study of the loss mechanism of epoxy or of any other suitable material and the subsequent reduction of its attenuation coefficient, by using different curing and mixing processes, can greatly increase the gain of the acoustic image coupler. For the purpose of such an investigation, the attenuation coefficient, the velocity of sound and therefore the specific acoustic impedance of the material could be conveniently determined with great accuracy using the testing method shown in Figure (5-4).
- 3. The experimental results of Chapter VII and the numerical value corresponding to equations (5-19) to (5-22) given in Chapter V indicate that the detail and resolution of the acoustic image would be directly proportional to the detector

164

aperture and is inversely proportional to the microhorn output cross section area. Consequently, two different regions in the incident acoustic field separated by less than the spacing between the microhorn structure elements cannot be easily resolved as separate entities. Therefore for improving the image resolution, larger couplers, with a higher density of microhorn elements should be investigated.

- 4. As indicated in Chapter VII, the present system permits real time viewing of the acoustic shadow cast by the object when placed in the immediate vincinity of the image coupler. This is of great importance for many applications that require real-time operation. In order to improve the resolution of this process the implementation of focused image acoustic holograms should be further investigated, either by using an acoustic lens to focus the image into the hologram plane or by using focused transducers to insonify the object, thereby circumventing the need to place the object very close to the image coupler in order to avoid disturbing diffraction effects. A focused transducer design is given in Appendix (IV), this design should be further developed and extended to obtain Fresnel pattern transducers with better focusing capability.
- 5. It should be pointed out that although the use of **continuous** waves has been implied throughout this dissertation on the holographic image converter, acoustic shadows and acoustic holograms can be formed just as well with pulsed acoustic waves. Appropriate choice of pulse duration and repetition rate and the use of a pulsed laser synchronized with the acoustic pulser for recording the converted acoustic hologram will eliminate multiple reflections of incident waves, and ringing in the object.
- 6. Finally, a new piezoelectric material has recently been introduced $(^{86})$. It has been shown $(^{87})$ that PVF₂ polymer plastic films can be rendered relatively strongly piezoelectric by a simple poling process, opening the way to new design of ultrasonic transducers. Table (8-1) gives the PVF₂ acoustic character-

165

TABLE (8-1)

ACOUSTIC CHARACTERISTIC OF PVF2

Acoustic Impedance	$3.7 \times 10^6 \text{Kg/m}^2 \text{sec}$
Electro Acoustic Coupling Coefficient	20%
Attenuation Coefficient	0.45 N/meter
Unloaded Q	14
Sound Velocity	2100 m/sec.
Relative Dielectric Constant	4
Density	$1.76 g_{\mathrm{m}}/\mathrm{cm}^{\mathrm{3}}$

istics. The new material offers potential applications in imaging system since as shown by Table (8-1) its acoustic characteristic impedance (3.7 $\mathrm{Kg/m^2}$ sec) closely matches that of the human body and of water consequently minimizing reflection losses. It could be used for either detection or transmission of acoustic waves. A half wave microhorn structure of PVF_2 seems feasible and can be fabricated better than with system 88, bearing in mind that PVF_2 has lower losses than any material we tested for constructing the present acoustic image coupler, which could result in sensitivity improvement. A potential application for the new material is for constructing a piezoelectric mosaic-amplifier-mosaic detector as discussed previously in Chapter IV. As shown in Figure (4-5), a mosaic of PVF_2 can be constructed to vibrate at half-wave resonance in their fundamental thickness mode at the frequency of the incidence sound wave. The voltage generated piezoelectrically at the other face of each crystal element is amplified electronically and then applied to the corresponding element in the output mosaic. As a result the incident amplitude vibration pattern is faithfully transferred to the output mosaic with great amplification, which is then converted to visual image by optical holographic interferometry methods. It should be noted here the ease of simulating the acoustic reference wave electronically which can be added in the middle stage of this electro-acoustic transducer. This potential application offers the advantages of yielding real gain in the conversion process and high sensitivity which is limited only by the electronic amplification stage, also might have the disadvantages of higher cost and complexity in fabrication and maintenance.

The general applications and advantages of acoustic holography have been discussed in the literature. Medical diagnosis, short-range underwater imaging and non-destructive testing are some areas where the application of acoustic holography can afford distinct advantages over present imaging methods. With reference to the above applications, it is expected that the proposed three-step acoustic imaging system using the real time holographic image converter can perform these in a simpler manner, and providing a real time or quasi-real time image of superior quality than those obtained from present acoustic holographic imaging systems.

APPENDIX I

ACOUSTIC IMPEDANCE MATCHING BETWEEN TWO MEDIA

Consider the propagation of a plane sound wave through three different media under conditions of normal incidence. Assume that the mismatched medium 1 and medium 3 have known acoustic impedances Z_1 and Z_3 , and that the matching layer medium 2 has an unknown impedance Z_2 . Referring to Figure (I-1), for the transmission of sinusoidal plane acoustic waves from one medium to another at normal incidence along the plane interface of the two media, the sound power transmission coefficient is defined for media 1 and 2 as

$$\alpha_{t_{12}} = \frac{I_{t_2}}{I_{t_1}} = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2}$$
(I-1)

and for the three media 1, 2 and 3 it is

$$\alpha_{t_{13}} = \frac{I_{t_{3}}}{I_{t_{1}}} = \frac{I_{t_{2}}}{I_{t_{1}}} \frac{I_{t_{3}}}{I_{t_{1}}} = \frac{I_{t_{2}}}{I_{t_{1}}} \frac{I_{t_{3}}}{I_{t_{2}}}$$

$$= \frac{16 Z_{1} Z_{2}^{2} Z_{3}}{(Z_{1} + Z_{2})^{2} (Z_{2} + Z_{3})^{2}}$$
(I-2)

where

$$I_{t_i}$$
 = Transmitted acoustic power in medium i

 Z_i = Acoustic impedance of medium i and i = 1, 2, 3



Figure (I-1) Sound transmission between three media.

For maximum acoustic power transmission the first derivative of equation (I-2) with respect to Z_2 is set equal to zero, i.e.

$$\frac{\partial \left(\frac{\mathbf{I}_{t_3}}{\mathbf{I}_{t_1}}\right)}{\partial \mathbf{Z}_2} = 0$$
 (I-3)

$$32 Z_1 Z_2 Z_3 (Z_1 + Z_2)^2 (Z_2 + Z_3)^2 - 32 Z_1 Z_2^2 Z_3 [(Z_1 + Z_2) (Z_2 + Z_3)^2 + (Z_1 + Z_2)^2 (Z_2 + Z_3)] = 0$$

which yields

$$Z_2 = \sqrt{Z_1 Z_3} \tag{I-4}$$

i.e., the "best matching" layer acoustic impedance equals the geometric mean of the acoustic impedances of the two mismatched media 1 and 3.

APPENDIX II

DETERMINATION OF THE AMPLITUDE TRANSMISSION COEFFICIENT "td" FOR MULTILAYER FILMS

Consider the propagation of a plane sound wave through three different media under the condition of normal incidence. Assume that the initial wave is propagating in medium "W" in the positive X direction, that the boundary between media "W" and "1" is located at x = 0, and that the boundary between media "1" and "a" is located at x - d as shown in Figure (II-1). Assume further that medium "a" extend to infinity. Due to the transmission and reflection of sound at each boundary, a wave propagating in the positive and negative x directions will result in each medium except medium "a" which will only contain a transmitted wave (see Figure II-1). Under steady state conditions, the pressure of each of these waves may be represented as follows (42, 65)

$$P_{W} = P_{W} \exp [i (\Omega t - K_{W}x)]$$

$$P_{W}^{*} = P_{W}^{*} \exp [i (\Omega t + K_{W}x)]$$

$$P_{1} = P_{1} \exp [i (\Omega t - K_{1}x)]$$

$$P_{1}^{*} = P_{1}^{*} \exp [i (\Omega t + K_{1}x)]$$

$$P_{a}^{*} = P_{a} \exp i [\Omega t - K_{a}(x - d_{1})]$$
(II-1)

where

P is the respective complex amplitude of the pressure of waves travelling in the positive x direction

 \mathbf{P}^* is the respective complex amplitude of the pressure of waves travelling in the negative \mathbf{x} direction



Figure (II-1) Sound transmission from medium "W" to medium "a" through an intervening layer "1".

K is the magnitude of the propagation vector in each respective medium.

 Ω = Angular frequency of the incident sound wave.

 d_1 = Thickness of medium "1"

t = Time

The boundary conditions require that both the pressure and the velocity be continuous. The velocity u can be expressed in terms of the pressure P and the acoustic impedance Z in the following manner

U = + P/Z for waves propagating in the positive x direction.

 $U^* = -P^*/Z$ for waves propagating in the negative x direction.

The boundary condition at x = 0 yield

 $P_w + P_w^* = P_1 + P_1^*$ pressure continuous

$$\frac{P_{w}}{Z_{w}} - \frac{P_{w}^{*}}{Z_{w}} = \frac{P_{1}}{Z_{1}} - \frac{P_{1}^{*}}{Z_{1}} \quad \text{velocity continuous} \quad (\text{II-2})$$

While the boundary condition at $x = d_1$ yield

 $P_1 \exp(-i \gamma_1) + P_1^* \exp(i \gamma_1) = P_a$ Pressure continuous

$$\frac{P_1}{Z_1} \exp(-i\gamma_1) - \frac{P_1^*}{Z_1} \exp(i\gamma_1) = \frac{P_a}{Z_a} \qquad \text{Velocity continuous} \quad (\text{II-3})$$

where $\gamma_1 = K_1 d_1$ (a complex quantity)

and Z_w , Z_1 and Z_a are the acoustic impedances of media "W", "1" and "a", respectively. Solving simultaneously for P_1 and P_1^* from equation (II-3) yields

$$P_{1} = \frac{(Z_{a} + Z_{1})}{2 Z_{a}} \qquad P_{a} \exp(i\gamma_{1})$$

$$P_{1}^{*} = \frac{(Z_{a} - Z_{1})}{2 Z_{a}} \qquad P_{a} \exp(-i\gamma_{1})$$
(II-4)

Substituting (II-4) into (II-2) and using the following definitions

$$r_p = P_w^* / P_w = Pressure reflection coefficient$$

 $t_p = \frac{P_a}{P_w} = Pressure transmission coefficient$

the relations of (II-2) become

$$1 + r_p = (\cos \gamma_1 + i \frac{Z_1}{Z_a} \sin \gamma_1) t_p$$
 (II-5)

$$\frac{1}{Z_{w}} - \frac{r_{p}}{Z_{w}} = \left(\frac{\cos \gamma_{1}}{Z_{a}} + i - \frac{1}{Z_{1}}\sin \gamma_{1}\right) - t_{p} \quad (\text{II-6})$$

which can be expressed in matrix form as follows

$$\begin{bmatrix} \mathbf{1} \\ 1/Z_{w} \end{bmatrix} + \begin{bmatrix} 1 \\ -\frac{1}{Z_{w}} \end{bmatrix} [r_{p}] = [M_{1}] \begin{bmatrix} 1 \\ 1/Z_{a} \end{bmatrix} [t_{p}]$$
(II-7)

where the transfer matrix of medium "1" is

$$[M_{1}] = \begin{bmatrix} \cos \gamma_{1} & i Z_{1} \sin \gamma_{1} \\ \frac{i \sin \gamma_{1}}{Z_{1}} & \cos \gamma_{1} \end{bmatrix}$$
(II-8)

Referring to Figure (II-1), if media "W" and "a" are separated by more than one layer, for instance N layers, then each layer may be described by a unique transfer matrix of the form (II-8). Furthermore, with an analysis similar to that described on the preceding pages, one can obtain an equation of the form (II-7), where M_1 is replaced by the overall, equivalent transfer matrix Meq. This equivalent transfer matrix is the product of all the individual transfer matrices M_1 , M_2 , $M_3 - - M_n$, i.e.

$$[Meq] = [M_1] [M_2] [M_3] - \cdots [M_n]$$

$$= \begin{bmatrix} m_1 & m_2 \\ m_3 & m_4 \end{bmatrix}$$
(II-9)

Once Meq has been determined, the pressure transmission and reflection coefficients of the overall system can be determined. With reference to equations (II-5) and (II-6), simultaneously solving for r_p and t_p yields

$$r_{p} = \frac{m_{1} Z_{a} + m_{2} - m_{3} Z_{w} Z_{a} - m_{4} Z_{w}}{m_{1} Z_{a} + m_{2} + m_{3} Z_{w} Z_{a} + m_{4} Z_{w}}$$
(II-10)

$$t_{p} = \frac{2 Z_{a}}{m_{1} Z_{a} + m_{2} + m_{3} Z_{w} Z_{a} + m_{4} Z_{w}}$$
(II-11)

where m_1, m_2, m_3 and m_4 are the elements of the equivalent matrix as defined in relation (II-9).

Other reflection and transmission coefficients may be determined from \mathbf{r}_p and \mathbf{t}_p as follows

for velocity

$$r_{\mu} = -r_{p}$$
 $t_{\mu} = (Z_{w}/Z_{a}) t_{p}$ (II-12)

for displacement

$$r_{d} = -r_{p} = r_{\mu}$$
 $t_{d} = \frac{Z_{w}}{Z_{a}} t_{p} = t_{\mu}$ (II-13)

Therefore the amplitude transmission coefficient is

$$t_{d} = \frac{2 Z_{w}}{m_{1} Z_{a} + m_{2} + m_{3} Z_{w} Z_{a} + m_{4} Z_{w}}$$
(II-14)

As an example of the application of this theory, consider the case of a two-layer system in which Z_1 and Z_2 , and γ_1 and γ_2 are the respective characteristic impedances and phase angles of the two intervening media, (e.g. between water and air). Then the equivalent transfer matrix for the over all system is

$$[Meg] = [M_1] [M_2] = \begin{bmatrix} \cos \gamma_1 & i Z_1 \sin \gamma_1 \\ \frac{i \sin \gamma_1}{Z_1} & \cos \gamma_1 \end{bmatrix} \begin{bmatrix} \cos \gamma_2 & i Z_2 \sin \gamma_2 \\ \frac{i \sin \gamma_2}{Z_2} & \cos \gamma_2 \end{bmatrix}$$
$$= \begin{bmatrix} m_1 & m_2 \\ m_3 & m_4 \end{bmatrix}$$
(II-15)

Substituting from equation (II-15) into equation (II-14), the displacement amplitude transmission coefficient is

$$t_{d} = 2Z_{w} / [(A \cos \gamma_{1} \cos \gamma_{2} - B \sin \gamma_{1} \sin \gamma_{2} + i (C \cos \gamma_{1} \sin \gamma_{2} + D \sin \gamma_{1} \cos \gamma_{2})]$$
(II-16)

wh**er**e

$$A = Z_a + Z_w$$

$$B = Z_1 Z_a / Z_2 + \frac{Z_w Z_2}{Z_1}$$

$$C = Z_2 + Z_a Z_w / Z_2$$

$$D = Z_1 + Z_a Z_w / Z_1$$

APPENDIX III

LIQUID IMMERSION PULSED SOUND TECHNIQUE FOR MATERIAL TESTING

The design and tuning of the quarter-wave resonant plates discussed in Chapter V requires knowledge of the speed of sound in the plates; or, in other words, their quarter-wave resonant frequency.

Figure (III-1) shows the arrangement used for measuring the speed of sound in thin plates. The same arrangement can be used directly for tuning the coupler. Referring to this figure, a gated, sinusoidal voltage whose frequency can be controlled, is applied to a piezoelectric crystal and monitored with an oscilloscope. If normal incidence is maintained, the voltage pattern on the CRT will show the initial sound pulse and its echoes which, for the geometry indicated $(d + x_2 < x_1)$, arrive in the following sequence:

- 1) Pulse reflected from the front surface of the plate, (this pulse has travelled a distance equal to $2x_1$).
- 2) Pulse transmitted through the plate, almost totally reflected from the tank wall, and transmitted a second time through the plate, [this pulse has travelled a total distance equal to $2(x_1 + d + x_2)$].
- Further echoes due to multiple reflections with arrival times depending on the relationship between x₁, d and x₂.

It is assumed that the duration of each pulse is sufficiently long to establish steadystate conditions within the plate and that the pulse repetition rate is low to acquire all the echoes. The frequency at which the reflected echo is a minimum and, at the same time, the transmitted pulse is a maximum indicates that the plate is in resonance so that its thickness d is an integer multiple of $\lambda/2$ where λ is the wavelength of sound in the material.



Figure (III-1) The pulsed sound, immersion technique for determining the half-wave resonant frequency of thin plates.

In order to obtain satisfactory results with this method, it is required that, with reference to Figure (III-1)

- 1) The bandwidth of the transducer be large to obtain a smooth response, and to minimize "ringing" of the crystal so that large pulse widths can be used to establish steady-state conditions in the sample without worrying about the repetition rate, water-backed crystal were used, but for constructing wideband transducer, epoxy with tungestun filling can be used to load one side of the transducer for better results.
- 2) The pulse width be sufficiently long to establish steady-state conditions within the plate under test.
- The gate should have low leakage to prevent interference between the leackage signal and the various echoes.

Figures (5-7) and (5-8) shows the echoes obtained as per Figure (III-1) for resonant and non-resonant beryllium plate. With reference to these figures, Picture (5-7) shows the initial (0) pulse, the reflected (1) pulse. Because the acoustic impedance of beryllium is much higher than that of water, the reflection coefficient is generally high, so that only the first echo was observed. Picture (5-8) corresponds to the tuned plate. In this case, the second echo (2) of the transmitted pulse was observed. Evidently, once the half-wave resonant frequency f_0 has been determined, the speed of sound C in the material at the test frequency is given by

$$C = \frac{2 f_o d}{n}$$
 meter/second (III-1)

where d = Plate thickness n = Integer

The method can also be used to obtain the attenuation coefficient of the material under test by measuring the relative amplitude of various echoes.

APPENDIX IV

DESIGN OF A TRANSDUCER WITH UNIFORM AXIAL AND LATERAL INTENSITY DISTRIBUTION AND FOCUSING CAPABILITY

Consider a flat disc transducer with radius a, the axial normalized acoustic intensity as previously discussed (Chapter VI) is

$$(I/I_0)_a = \sin^2 \frac{\pi a}{\lambda} [\sqrt{1 + \frac{r^2}{a^2}} - \frac{r}{a}]$$
 (IV-1)

and the normalized lateral acoustic intensity is

$$(I/I_{0})_{\varrho} = \begin{bmatrix} 2J_{1}\left(\frac{2\pi a}{\lambda} \sin \theta\right) \\ \frac{2\pi a}{\left(\frac{2\pi a}{\lambda} \sin \theta\right)} \end{bmatrix}^{2}$$
(IV-2)

where all variables are defined in Chapter VI, and plots of the two intensity distributions are shown in Figures (6-2), (6-3). Figure (IV-1) shows an isometric plot of the three-dimensional intensity distribution. Consider the intensity at distances of approximatly $\frac{a^2}{\lambda}$ and $\frac{a^2}{2\lambda}$. Near $\frac{a^2}{\lambda}$ the intensity decreases both axially and laterally from the central maximum value, while near $\frac{a^2}{2\lambda}$ the intensity increases away from the center.

By combining two transducers whose last axial maximum and last nearfield axial minimum coincide, it appears possible to obtain a region of uniform intensity. Instead of two transducers, a single transducer could be used by providing it with a multiple electrode configuration consisting of a common grounded electrode and two concentric electrodes to which the excitation voltage with respect to ground is applied. These two electrodes take the shape of an inner disc and an outer ring. The diameter of the inner disc electrod is chosen





so that its last axial maximum in the nearfield occurs at the required operating distance (distance between transducer and image coupler in our case), the diameter of the ring is chosen so that the last axial minimum of the combined electrodes (i.e. the two high electrodes shorted) occurs at the same distance.

In order to obtain a uniform field distribution a higher voltage is applied to the disc electrode. The main feature in this design is that by adjusting the voltage ratio rather than the geometry of the transducer one can control the beam pattern for uniformity. However, a voltage ratio which gives a uniform lateral distribution does not necessarily give a uniform axial distribution. In general the lateral uniformity is of greater importance to the acoustic imaging system, in order to illuminate a large detector aperture for higher resolution.

Voltage Drive Considerations

The two high electrodes must be driven with voltages of the same phase for uniform distribution, this may be achieved using the circuit shown in Figure (IV-2). The voltage across the outer ring is

$$V_{o} = \frac{V_{i}}{1 + \frac{C_{o}}{C_{v}} + \frac{1}{J\omega C_{v} R_{o}}}$$
(IV-3)

where

 C_0 = The clamping capacitance of the outer ring

 $C_v = Voltage ratio adjusting capacitor$

 $R_0 = Loss$ in mechanical impedance of outer ring



Figure (IV-2) Driving circuit for uniform intensity transducer

Since $R_0 >> \frac{1}{\omega C_0}$, with good approximation

$$V_{o} \approx \frac{V_{i}}{1 + \frac{C_{o}}{C_{v}}}$$
(IV-4)

Figure (IV-3) gives an isometric view of the lateral and axial intensity distribution of the present design. By varying the voltage drive ratio the lateral intensity distribution varies. Figure (IV-4) shows the lateral intensity distribution for various voltage drive ratios. It was verified (81, 88) experimentally that a voltage drive ratio $\frac{V_i}{V_0} = 3$ which corresponds to a capacitance ratio of $(\frac{C_0}{C_V} = 2)$ yielded the best lateral distribution for the present design.

Design Procedure:

Consider a 2.5" diameter (d_0) disc of 0.2" thickness PZT material (Lead Zirconate Titanate). For thickness mode resonance operating frequency = $\frac{\text{Frequency Constant}}{\text{thickness}}$

$$= \frac{82 \times 10^3}{0.2} = 410 \text{ KHz}$$

For fresh water medium at 70° F the sound velocity is 1525 meter/second, which corresponds to a wave length λ of 0.15". For the outer ring the last axial minimum should be placed at the required operating distance between the transmitting transducer and the image coupler. Conversely the same quantity should equal the distance of the last axial maximum for the inner disc transducer, therefore

$$\ell = \frac{d_o^2 \operatorname{ring}}{8\lambda} = \frac{d_i^2 \operatorname{disc}}{4\lambda}$$
(IV-5)



Figure (IV-3) Three dimensional view of the intensity distribution for the combined transducer.



using equation (IV-5), therefore

$$d_i(disc) = \frac{d_o(ring)}{\sqrt{2}} = 1.773"$$

and $\ell = 5.21$ " gives the axial location of the uniform intensity distribution region. For the present design the image coupler should be located at this distance from the transmitting transducer.

The above design approximates a plane uniform wave front at the beryllium-water interface. If a focused (point source) beam were desired in order to improve the resolution for a transmission type of acoustic imaging (e.g. Fourier transform, or focused gabor-holo-graphy) the present transducer design allows focusing to be achieved, simply by driving the two off ground (hot) electrodes with voltages V_i , V_o of opposite phase (180° relative phase). In this case the outputs of the disc and ring transducers, will interfer with each other producing a peaked or focused field.

Unless deionized water is used a problem will arise due to lack of insulation between the two hot electrodes facing the water medium. The construction shown in Figure (IV-5) in which the ground electrode faces the water medium solves this problem. Since the transducer is air backed, radiation still takes place from the ground electrode side, with same intensity distribution.



Figure (IV-5) Transducer Construction.

REFERENCES

- 1) Halstead, J., "Ultrasound Holography", Ultrasonics, April 1968, pp. 79-87.
- 2) Wade, G., "Acoustic Imaging With Holography and Lenses", <u>IEEE, Sonic &</u> Ultrasonics, Vol. SU-22 no. 6, 1975, pp. 385-394.
- Hildebrand, B.P. & Brenden, B.B. "<u>An Introduction to Acoustical Holography</u>", Plenum Press, New York (1972).
- 4) Metherell, A.F. "Acoustical Holography", Vol. 1, New York: Plenum Press, 1969.
- 5) Metherell, A.F., El-Sum, H.M.A. and Dreher, L., "Image Reconstruction From Sampled Acoustical Holograms", <u>Applied Physics Letters</u>, Vol. 10, no. 10, May 1967, pp. 277-279.
- 6) Metherell, A.F., El-Sum, H.M.A., Dreher, L., and Lamore, L., "Optical Reconstruction From Sampled Holograms Made With Sound Waves", Physics Letters, Vol. 24A, no. 10, May 1967, pp. 547-548.
- Massey, G.A., "Acoustic Holography in Air With an Electronic Reference." Proc. of IEEE, Vol. 55, no. 6, June 1967, pp. 115-117.
- 8) Metherell, A.F. and El-Sum, H.M.A., "Simulated Reference in a Coarsely Sampled Acoustical Hologram," Applied Physics Letters, Vol. 11, no. 1, July 1967, p. 20.
- 9) Preston, K. and Kreuzer, J.L., "Ultrasonic Imaging Using a Synthetic Holographic Technique", Applied Physics Letters, Vol. 10, no. 5, March 1967, pp. 150-152.
- 10) Smith, R.B., "Ultrasonic Imaging Using a Scanned Hologram Method, "IEEE Ultrasonics Symposium, Vancouver, Canada, October 1967.
- 11) Dooley, R.P., "X-Band Holography." Proc. of IEEE, Vol. 53, no. 11, November 1965. pp. 1733-1735.
- 12) Sokolov, S. "The Ultrasonic Microscope," Doklady Akademii Nauk, S.S.S.R., Vol. 64, 1949, p. 333.
- 13) Suckling, E.E., "A New Method of Transducting Ultrasonic Shadowgraph or Image for Display on an Oscilloscope, "JASA, Vol. 27, no. 2, March 1955, pp. 297-301.
- 14) Jacobs, J.E., "Performance of the Ultrasound Microscope", Material Evaluation, Vol. 25, March 1967, pp. 41-45.

- 15) Kennedy, J.A., and Muenow, R., "Practical Improvements and Applications for the Ultrasonic Image Converter", IEEE Trans. on Sonic and Ultrasonics, Vol. SU-14, no. 2, April 1967, pp. 47-52.
- 16) Jacobs, J.E., Collis, W.J. and Berger, H., "An Evaluation of an Ultrasonic Inspection System Employing Television Techniques", <u>Materials Evaluation</u>, Vol. 22, no. 5, May 1964, pp. 209-212.
- 17) Smyth, C.N., "The Ultrasound Camera-Recent Considerations", <u>Ultrasonics</u>, Vol. 4, January 1966, pp. 15-20.
- 18) Fritzler, D., Marom, E. and Mueller, R.K., "Ultrasonic Holography Via the Ultrasonic Camera", Acoustical Holography, Vol. 1, New York, Plenum Press, 1969, pp. 249-255.
- 19) Davidson, J.B. and Hull, J.F., "Recent Developments in Acoustic Imaging Systems", Litton Industries, Electron Tube Division.
- 20) Green, P.S., "High Resolution Underwater Acoustic Imaging," (LMSC), report no.
 6-77-67-42, 1967.
- 21) Massey, G.A., "An Optical Hetrodyne Image Converter", Proc. IEEE, Vol. 56, no. 12, December 1968, pp. 2157-2161.
- 22) Korpel, A. and Desmares, P. "Rapid Sampling of Acoustic Holograms by Laser Scanning Techniques", JASA, Vol. 45, no. 4, 1969, pp. 881-884.
- 23) Ernst, P.J., "Ultrasonography", JASA, Vol. 23, no. 1, January 1951, pp. 80-83.
- 24) Woodmansee, W.E., "Cholesteric Liquid Crystals and Their Application to Thermal Non-destructive Testing", <u>Materials Evaluation</u>, Vol. 24, no. 10, October 1966, pp. 564-572.
- 25) Augustine, C.F., "Microwave Holograms Using Liquid Crystal Display", Proc. IEEE, Vol. 57, no. 3, March 1969, pp. 354-355.
- 26) Petermann, L., "A New Photographic Method of Detecting Ultrasonic Radiation", JASA, Vol. 24, no. 4, 1952, pp. 416-417.
- 27) Jarman, P. "Sonoluminesence: A Discussion", JASA, Vol. 32, no. 11, 1960, pp. 1459-1462.
- 28) Bennet, G.S., "A Note on the Activation of Photographic Emulsions by Ultrasonic Waves", JASA, Vol. 23, no. 4, 1951, pp. 478-480.

- 29) Marinesco, N. and Truillet, J.J., Compt. Bend, Vol. 196, 1933, pp. 858-860.
- 30) Bennet, G.S., "On the Mechanism of the Photographic Effect of Ultrasonic Waves", JASA, Vol. 25, no. 6, November 1953, pp. 1149-1151.
- 31) Berger, H. and Kruska, I.R., "Photographic Film Detection Methods for Ultrasonic Field Visualization", JASA, Vol. 34, no. 4, April 1962, pp. 518-519.
- 32) Arkhangel'Skii, M.E. and Afanas'ev, I.A., "Investigation of the Photo Diffusion Method of Visualizing Ultrasonic Fields", <u>Soviet Physics-Acoustics</u>, Vol. 3, no. 3, 1957, pp. 230-235.
- 33) Bennet, G.S., "A New Method For the Visualization and Measurement of Ultrasonic Fields", JASA, Vol. 24, no. 5, September 1952, pp. 470-474.
- Brenden, B.B., Hildebrand, B.P., "An Introduction To Acoustical Holography", Plenum Press, New York, pp. 162-164, 1972.
- 35) Mueller, R.K., and Keating, P.N., "The Liquid Gas Interface As A Recording Medium For Acoustic Holography", <u>Acoustical Holography</u>, Vol. 1, New York, Plenum Press, 1969, pp. 49-55.
- 36) Sokolov, S. Ia., "Ultrasonic Methods for Detecting Internal Defects In Metal Products", Zavodskaia Lab., Vol. 1, 1935, pp. 1468-1473.
- 37) Sette, D., "Ultrasonic Lenses of Plastic Materials", JASA, Vol. 21, no. 4, July 1949, pp. 373-381.
- 38) Brenden, B.B., "A Comparison of Acoustical Holography Methods", Acoustical Holography, Vol. 1, New York: Plenum Press, 1969, pp. 57-71.
- 39) Gericke, O.R., and Grubinskas, R.C., "Utilization of the Liquid Surface Levitation Effect As A Means of Ultrasonic Image Conversion for Materials Inspection", Army Materials and Mechanics Research Center, Watertown, Mass., 1967.
- 40) Brenden, B.B., "Acoustical Holography as a Tool for Non-Destructive Testing", Pacific Northwest Lab., Richland, Wash., August 1968.
- 41) Green, P.S., "A New Liquid-Surface-Relief Method of Acoustic Image Conversion", Acoustical Holography, Vol. 3, New York: Plenum Press, 1971, pp. 173-187.
- 42) Fischer, W.K., "<u>Methods For Acoustic Holography and Acoustic Measurements</u>", Doctoral Dissertation, Newark College of Engineering, New Jersey, 1972.

- 43) Gabor, D., et al "Optical Image Synthesis by Holographic Fourier Transformation", Physics Letters, Vol. 18, pp. 116, 1965.
- 44) Zambuto, M., and Lurie, M., "Holographic Measurement of General Forms of Motion", Applied Optics, Vol. 9, p.2066, 1970.
- 45) Powell, R.L., and Stetson, K.A., "Interferometric Vibration Analysis by Wavefront Construction", JOSA, Vol. 55, p.1593, 1965.
- 46) Stetson, K.A., Powell, R.L., "Interferometric Hologram Evaluation and Real Time Vibration Analysis of Diffuse Objects", JOSA, Vol. 55, p. 1694, 1965.
- 47) Stetson, K.A., and Powell, R.L., "Hologram Interferometry", <u>JOSA</u>, Vol. 56, no. 9, pp. 1161-1166, 1966.
- 48) Collier, R.J., and Burckhardt, C.B., "Optical Holography", Academic Press, New York, 1971.
- 49) Archbold, E., and Ennos, A.E., "Observation of Surface Vibration Modes by Stroboscopic Hologram Interferometry", Nature, Vol. 217, p. 942, 1968.
- 50) Zambuto, M.H. and Fischer, W.K., "Shifted Reference Holographic Interferometry", Applied Optics, 1972.
- 51) Zambuto, M.H. and Hanafy, A.M., "Sensitivity Improvement by Step-Biasing In Holographic Interferometry", Optical Engineering, Vol. 14, no. 4, 1975, p. 372.
- 52) Hanafy, A.M., and Zambuto, M.H., "Step-Biased Holographic Interferometry", Paper Presented at Optical Society of America Annual Meeting, Boston, Mass., 1975.
- 53) Zambuto, M.H., Hanafy, A.M., "Interferometric Holographique Polarisee Par Deplacement en Palier", Actes de La lere reconter International Cisco - Paris, 1975, pp. 1-6.
- 54) Lurie, M., "Effect of Partial Coherence on Holography", PhD. Dissertation, Newark College of Engineering, New Jersey, 1967, p. 93.
- 55) Brooks, R.E., Heflinger, L.O., and Wuerker, R.F., "Interferometry With Holographically Reconstructed Comparison Beam", Applied Physics Letters, Vol. 7, p. 248, 1965.
- 56) Zambuto, M.H. and Lurie, M., Applied Optics, Vol. 7, p. 2323, 1963.

- 57) Fischer, W.K. and Zambuto, M., "Optical Holographic Detection of Ultrasonic Waves", Acoustical Holography, Vol. 3, New York: Plenum Press, 1971, pp. 349-362.
- 58) Fischer, W.K., PhD. Dissertation, Newark College of Engineering, New Jersey, 1972, Chapter 5.
- 59) Lurie, M., JOSA, Vol. 56, p. 1369, 1966.
- 60) Lurie, M., JOSA, Vol. 57, p. 573A, 1967.
- 61) Zambuto, M.H., Hanafy, A.M., "Sensitivity Enhancement in Real-Time Holographic Interferometry", Optics and Laser Technology, "Under Publication".
- 62) Zambuto, M.H., Hanafy, A.M., "Un Nuovo Metodo di Olografia Acustica Cinematografica", Notizie di Tecnica Cinematografica, 9, 1975.
- 63) Goodman, J.W., "Introduction to Fourier Optics", McGraw Hill Book Co., New York, 1968.
- 64) Ensminger, D., "Ultrasonics, The Low and High Intensity Applications", Marcel Dekker Inc., New York, pp. 125-135, 1973.
- 65) Kinsler, L.E. and Frey, A.R., "Fundamentals of Acoustics", New York: John Wiley & Sons, Inc., 1952, pp. 128-138.
- 66) Sittig, E., "An Acoustical Impedance Transformer Using an Inverted Solid Cone", IEEE Transactions On Ultrasonic Engineering, Vol. UE-10, no. 2, 1963, pp. 104-106.
- 67) Hueter, T.F. and Bolt, R.H., "Sonics", New York: John Wiley & Sons, Inc., 1955, pp. 86-163.
- 68) Brekhovskikh, L.M., "Waves In Layered Media", Academic Press, New York, (1960), pp. (61-66).
- 69) Mahfuz, A., Whitman, R.L., and Korpel, A., "Response of An Isotropic Acoustic Imaging Faceplate", IEEE Trans. On Sonics and Ultrasonics, 1973, Vol. SU-20, no. 4, pp. 323-330.
- 70) White, D.W., and Burke, J.E. (Editors), "The Metal Beryllium", The American Society of Metals (1955).
- 71) Nigam, A.K., "Condenser Microphone Arrays In Acoustical Holography A Review", JASA, Vol. 55, no. 5, 1974, pp. 978-985.

- 72) Marom, E. and Fritzler, "Ultrasonic Holography: A Critical View", presented at the 1968 Ultrasonic Symposium, New York, New York, 1968.
- 73) Morse, P.M. and Ingard, K.U., "Theoritical Acoustics", McGraw-Hill, New York, 1968, pp. 381-382.
- 74) Dekker, D.L., Piziali, R.L., and Dong, E., "Effect of Boundary Conditions on The Ultrasonic Beam Characteristics of Circular Disks", JASA, Vol. 56, no. 1, 1974, pp. 87-93.
- 75) Morse, P.M., "Vibration & Sound", McGraw-Hill Book Co., 1948.
- 76) Kossof, G., Robinson, D.E. and Garrett, W.J., "Design Criteria For Ultrasonic Visualization Systems", Ultrasonics, 1964, pp. 29-38.
- 77) Krautkramer, "Ultrasonic Testing of Materials", George Allen & Unwin Ltd., London, 1969, p. 227.
- 78) Mason, W.P., "Piezoelectric Crystals and Their Application to Ultrasonics", D. Van Nostrand Co., 1950.
- 79) Seto, W.W., "Acoustics", Schaum's Outline Series, McGraw-Hill Book Co., pp. 101-104.
- 80) Gray, D.E. (Editor), "American Institute of Physics Handbook", 3rd Editon, McGraw-Hill Book Co., (1972).
- 81) Zambuto, M.H. and Hanafy, A.M., "Acoustic Image Converter For Three-Step Acoustic Holography", Presented at the International Symposium of Acoustical Imaging and Holography, Chicago, Ill., August 1976.
- 82) Hanafy, A.M. and Zambuto, M.H., "Acoustic Image Converter For Three-Step Acoustic Holography", Acoustical Holography, Vol. 7, New York, Plenum Press, Edited by Kessler, L.W., 1976.
- 83) Zambuto, M.H., and Lurie, M., "A Verification of Holographic Measurement of Vibration", Applied Optics, Vol. 7, no. 11, November 1968, pp. 2323-2325.
- 84) Holt, D. and Coldrick, J.R., "Acoustical Holography and Its Applications", Ultrasonics, Vol. 7, no. 4, October 1969, pp. 240-245.
- 85) Meier, W.R., "Magnification and Third-Order Aberrations In Holography", JOSA, Vol. 55, no. 8, August 1965, pp. 987-992.

- 86) Bui, L., Shaw, H.J., and Zitelli, "Study of Acoustic Wave Resonance In Piezoelectric PVF₂ Film", G.L. Report no. 2570, Ginzton Laboratory, Stanford Univ., Calif.
- 87) Murayama, N., Nakamura, K. and Bara, H., Ultrasonics, Vol. 14, no. 1, p. 15, 1976.
- 88) Kossof, G., "A Transducer With Uniform Intensity Distribution", Ultrasonics, October 1971, pp. 196-200.

VITA

۰.

1965	B.S. Electrical Engineering, Faculty of Engineering, Alexandria University, Alexandria Egypt.	
1971	M.S. Electrical Engineering, Newark College of Engineering, Newark, New Jersey.	
PROFESSIONAL BACKGROUND		
1965-1969	Teaching and Research Assistant, Faculty of Engineering, Alexandria University, Alexandria Egypt.	
1969-1975	Research Engineer, L & R Manufacturing Company, Kearny, New Jersey.	
1975-1976	Research Fellow, New Jersey Institute.of Technology.	
1976	Research Engineer, Hewlett-Packard, Waltham, Mass.	

This research was conducted at New Jersey Institute of Technology during the years 1971 - 1977.