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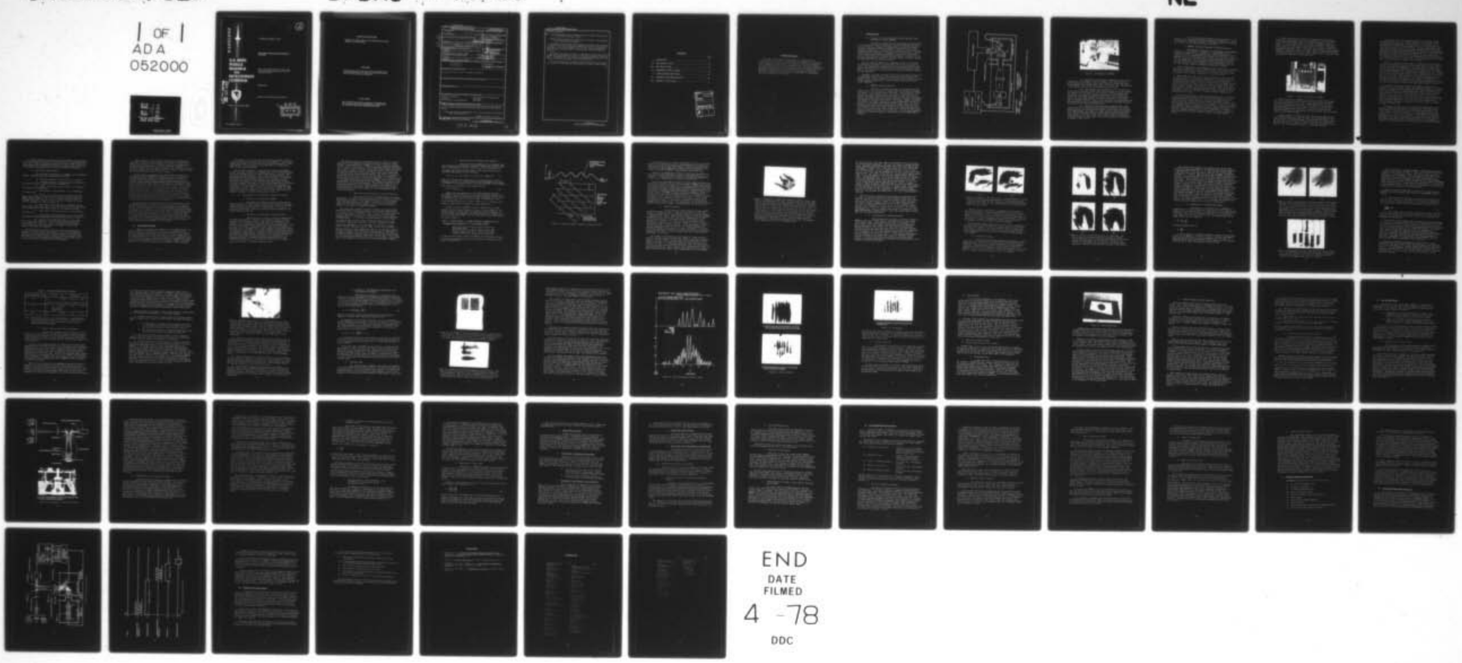

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TECHNICAL REPORT T-78-10

REAL-TIME ACOUSTICAL HOLOGRAPHY SYSTEMS

Virgil G. Irelan, Bobby R. Mullinix, and John G. Castle
Ground Equipment and Missile Structures Directorate
Technology Laboratory

October 1977

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Redstone Arsenal, Alabama 35809

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The existing system for Acoustical Real Time Holographic Image Reproduction is described, together with operating instructions. Its novel features include:

(1) Large diameter (approximately 4 in.) ultrasonic beam and correspondingly large image area.

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ABSTRACT (Continued)

cont (2) High intensity of the ultrasonic beam and therefore improved penetrability for thick test objects.

(3) Excellent damping in the water tanks and therefore less background noise during real time viewing.

Preliminary nondestructive testing measurements indicate that the system resolution is close to the theoretical diffraction limit for the acoustical wavelengths (in the water medium) of 0.3, 0.5, and 1.5 mm. For discerning flaws in samples with high internal scattering, the real-time feature is necessary.

For highly reflecting test objects, an improvement in penetration has been demonstrated using a coating to reduce the reflection coefficient of the test object. Preliminary data are presented using 3-MHz beams through ceramic and foam test plates with the images recorded photographically.

The Acoustical Real Time Holographic Image Reproduction system is ready to be tested as a nondestructive testing method for flaws in silica radomes.

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The authors would like to acknowledge the competent aid of Mr. Michael E. Casciolo of the Sperry Services Corporation in the design of the electronics system within the acoustical real-time holographic image reproduction system and the preparation of a detailed operation and maintenance manual on the electronics system. The authors appreciate the advice received early in the design phase from Dr. Robert Kurtz of NASA/MSFC and Dr. Martin Fox of the Electrical Engineering Department of the University of Connecticut for assistance in establishing the design criteria for the system.

I. INTRODUCTION

A. History of the Acoustical Real Time Holographic Image Reproduction System (ARTHIR)

The Army's pervasive need for nondestructive testing (NDT) for the strength of missile components includes seeking improved means for flaw detection. Imaging the transmission of acoustical energy at ultrasonic frequencies holds the promise of adequate resolution and reasonable penetration of optically opaque test objects such as missile radomes and other components. Imaging of acoustic patterns on a liquid-to-air surface gives reasonable sensitivity and permits large image size and real-time optical viewing and/or recording. Therefore, it was decided to demonstrate the utility of liquid surface acoustical imaging for the Army's NDT flaw detection program.

When the acoustic image on the liquid-air surface is a hologram, its detection and display by optical means can be done with high contrast. The commercially available units for real-time acoustical holographic display are made as an exploratory medical diagnostic tool. As such, they do not have the high acoustical power needed to penetrate ceramic missile components.

Therefore, the choice was made to start with the general concept of the commercial systems but to incorporate higher power acoustics and possibly better acoustic damping to extend the state-of-the-art of liquid surface acoustic imaging NDT of ceramic composite and metal missile system components.

B. ARTHIR'S Internal Functions

Each burst of acoustical energy that penetrates the test object travels to the liquid-air surface where its reflection produces an elevation of the surface a short time later. That elevation includes the desired ripple (holographic grating) when a reference burst of coherent ultrasonic energy arrives coincident with the burst from the object. The area containing the ripple scatters light into "diffraction" side bands for filtering, and viewing or recording. ARTHIR is arranged to accomplish all these functions as shown schematically in Figure 1. Figure 2 is a photograph which shows the test object water tank in the foreground, the rubber tube coupling and the ripple tank at the left, the electronics power and control system in the right background, and part of the optical system on the extreme left. The white, saw-toothed covering in the object tank serves as damping for water waves especially needed during real-time imaging. These functions are accommodated as follows:

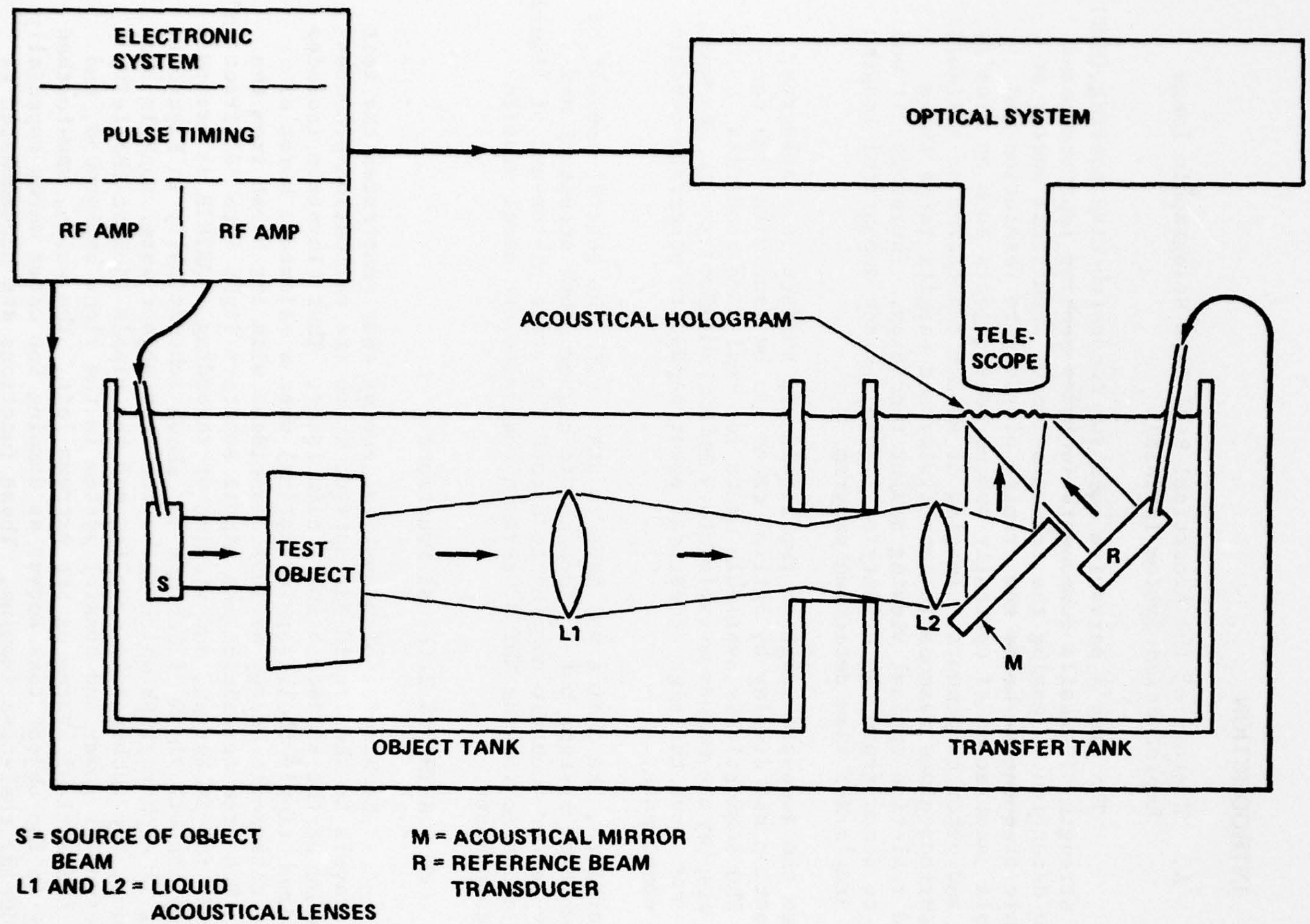


Figure 1. Schematic arrangement of existing ARTHIR system.

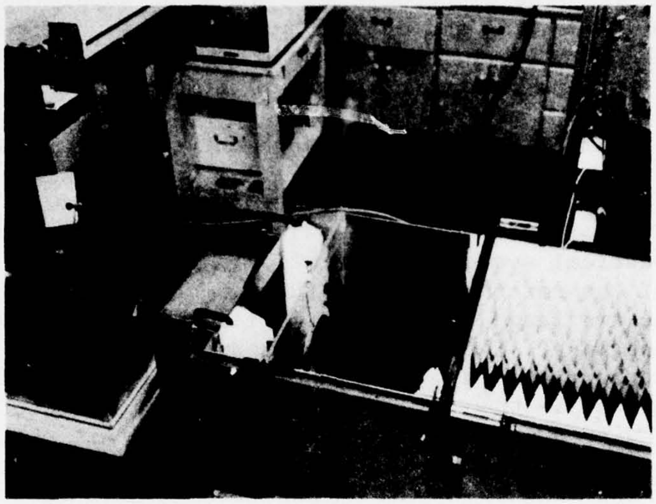


Figure 2. Arrangement of ARTHIR.

1) The object tank of water, measuring 60 × 30 × 24 in., contains the 5-in. diameter source transducer, space and holders for positioning the test object, and a liquid lens for focusing the transmitted pattern from the test object into the transfer tank. The function of insonifying a test object is discussed in Section I.D.

2) The transfer tank, measuring 23 × 23 × 24 in. contains a second (optional) liquid lens and an acoustic mirror for locating the image of the test object on the liquid-air surface, together with a reference 5-in. diameter transducer suitably driven and directed to deliver the coincident overlapping coherent pulse over the same image area of the air-liquid surface. Provision is made for a mini-ripple tank for holding a special liquid in the image area and thereby permitting more sensitivity, that is, deformation per incident sound power density. The acoustics are discussed in Section II.

3) The optical bench assembly illuminates that image surface area with a suitably delayed pulse of collimated light from an argon-ion laser, and then forms the desired optical image of the rippled air-liquid surface. The image of a single pulse is readily recorded on film. Regular repetition of this pulsed image formation permits real-time viewing on a diffuser screen or a TV camera chain with real-time recording directly on video tape. The optical subsystem is discussed in in detail in Section III.

4) The electronic subsystem for supplying power to and control of the acoustical and optical subsystems is described in detail in Reference 1. Section IV contains a brief description of the function and operation of the electronic system of ARTHIR.

C. ARTHIR's Internal Arrangement and Typical Operation

The existing arrangement of the components within ARTHIR (Figure 2) is the result of a succession of improvements over the originial acoustical system configuration. The key improvements are in orientation of the reference beam with respect to the optical system, damping in the two large tanks, and the isolation of the imaging surface from the object tank. The high radio frequency (RF) power available from the electronic system to generate a high power density beam over the test region of 3- to 4-in. diameter is the prime feature by which the system attains superior penetration of thick test objects.

Further improvements to the ARTHIR are known to be readily available. The imaging advantages of specific changes in the optical system are discussed in Section III. Adaptation of the acoustic system to accept nonimmersible test objects is discussed in the next section.

Test objects are held in the object tank, shown in the foreground of Figure 2, by one of two types of holders, each of which allows for smooth adjustment of position and firm location during inspection. One type of holder suspends the test object from the bar across the top of the object tank as shown. The other supports the test object from the bottom of the tank. Sharp imaging of the test object on the air-liquid surface requires the accurate positioning of the test object and both lenses to within increments much smaller than the depth of focus. Increments of 0.25 in. were found to make noticeable differences in image clarity at 3 MHz.

With the reference beam incident at approximately 45° in the plane of the optical system and the argon laser light collimated by a telescopic lens with a focal length of F = 30 in., the ripple in the hologram forms the optical diffraction pattern vertically with the first order located approximately 0.5 mm from the central of zero order. With this separation being as large as 0.5 mm, the task of optically filtering out background light is manageable with fairly simple masks stuck to a stage with x-y micrometer drives for smooth adjustment to the best position. Remnant background light can readily be held at least 10 dB below the intensity from the rippled portion by the image optical filters.

Setting the electronic controls for appropriate pulse lengths, delay times, and RF power level is accomplished at the control panels of the electronic system shown in the right background of Figure 2. Figure 3 is a photograph of the control panel in ARTHIR. From left to right, the control knob functions are choice of ultrasonic frequency, pulse repetition rate, width of ultrasonic pulse, delay of light pulse, and delay of reference pulse. The second chassis houses the extra tuning capacitors required for tuning at 1 MHz. The third and fourth chasses are the RF power amplifiers. The fifth (lowest) chassis houses the high voltage power supplies for these amplifiers.

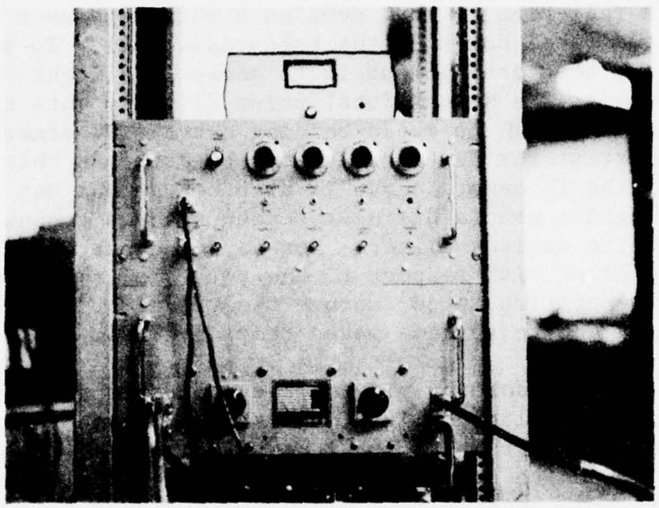


Figure 3. Tuning control panel in ARTHIR.

Typical operation of ARTHIR at 3 MHz involves pulse lengths near 100 μsec, the reference burst delayed approximately 1500 μsec behind the source transducer, and the laser delayed approximately 300 μsec behind the reference transducer drive. The 1500 μsec corresponds to the time required for the source burst to travel the length of the object and transfer tanks to the mirror, because the mirror and the reference transducer are approximately the same distance from the target area on the air-liquid surface.

Typical operation of ARTHIR with the transfer tank separated by a 5-in. diameter rubber boot from the object tank involves water as the liquid forming the surface hologram. The principal advantage to using the mini-imaging tank around the target surface area is to keep most of the dust out. Use of a special liquid in the mini-ripple tank, such as Freon 113 may allow improved contrast for thick test objects.

The effective size of the acoustic image on the rippled surface measures between 3 and 4 in. across, depending on the choice of the acoustic lens configuration. The portion of a test object which is insonified by the source beam measures close to 4 in. across when the test object is within 1 ft of the source. Acoustic magnification near unity gives the best sensitivity (the best penetration of a thick test object) but acoustic resolution of detail in a thin object can apparently be improved at 1 MHz by using acoustic magnification up to four or more. The choice is made by the operator's selection of lens location(s). The photographs discussed in this report demonstrate the clear resolution of a 2.0-mm bar pattern at 3 MHz using an acoustic magnification of near unity and a field-of-view (FOV) of 4-in. diameter.

Viewing in real-time is best done on a white opaque screen placed beyond the second focal point of the telescopic lens. To view remotely in real-time, the best arrangement is to accept the light beyond the optical filtering at the second focal point directly into the TV camera lens. Caution is required to avoid burning out the TV camera photosensor, but the best contrast for TV recording can be attained this way. Viewing with the aid of the TV camera chain is also convenient but at a considerable loss in contrast when a diffuser screen such as ground glass is inserted beyond the optical filter. For asynchronous operation of the TV camera and monitor with respect to the pulses of the acoustical system, higher repetition rates improve the visual brightness but degrade the image clarity due to surface waves remaining from pulse to pulse.

Recording is best done by placing the camera so that its lens aperture accepts the filtered light. Photographic recording of a single pulse in this manner is then accomplished with the optical magnification controlled by the choice of camera lens focal length. Several single shot photographs have been so recorded using a camera lens whose focal length is 5 in., giving an optical magnification of 1/6 from water surface to photographic film. An additional (intermediate) lens can be used to increase this value without any sacrifice in image quality. The laser source in ARTHIR puts out so much light (approximately 65 W) that the optical contrast is limited by stray light. This is covered in detail in Section III.

In summary, the NDT function of the existing ARTHIR system is to present the pattern representing the transmission of coherent sound waves through a selected area of the test object approximately 3 to 4 in. across) for real-time viewing or for recording by TV or photographic film. To do this, the operator of the ARTHIR system must set the electronic timing and RF (ultrasonic) power controls, confirm the alignment of the optical system, align the acoustical system with the test object immersed so that the desired plane in the test object is focused on the liquid surface, and choose the mode of viewing/recording.

It is the purpose of this report to aid the operator in these tasks and to present the information in sufficient detail to expedite decisions as to how to improve the signal-to-noise in any given image. Before the three subsystems within ARTHIR are discussed in detail, the next section will present a few comments on the modes for sample insonification.

D. Test Object Insonification

The ultrasonic beam available in ARTHIR is its outstanding feature. Specifications may be summarized as follows:

1) Ultrasonic frequency — Choice of 1, 3, or 5 MHz.

2) Tranducer diameter — Effectively 4.8-in. diameter for the source and 4.6-in. diameter reference transducers.

3) Medium — Water where speed of sound is 1.49 mm/μsec and the mode is longitudinal.

4) Beam diameter — Approximately 4 in. in midsection of object tank.

5) Beam profile — Central region contains many sharp peaks, characteristic of the near-field Fresnel pattern of the disc-shaped source transducer, the choice of frequency and of the specific distance downstream. One mode of exposing the test object in the far field is suggested for 1 MHz in Section II.

5) Beam power — High. The quartz transducer crystals can be driven during each pulse as high as 5 kV across the 50-ohm coaxial cable leading from the RF power amplifier to the resonant crystal.

6) Pulse length — Typically 100 μsec; can be adjusted up to 850 μsec.

7) Liquid lenses — Nominal aperture of 8 in. Focal lengths with Freon 113 fluid are adjustable but are currently 11 and 8 in. in water.

8) Space for Immersible Test objects — 22 in. wide, 2.5 ft long, and the water is 22 in. deep with the beam centered at 10.5 in. above the tank floor. Plans for imaging with these beams should reckon with their high degree of coherence as well as the effects of the near field pattern.

The normal modes of mounting the test object involve immersion. Mounting in a stable position when support is from the tank bottom is aided by using flat rubber sheets within the mount, still permitting adjustment of the object position in small increments typically 1/8 to 1/4 in. by hand. Stable mounting when support is from the bar across the top of the tank is attained without extra damping.

Special immersion provisions have been made for the immersion of large objects such as a silica radome. To insonify a radome that is immersed in the object tank, for example, the source transducer would be remounted from the floor of the tank so that the transducer is centrally located inside the radome. Inspection for flaws in the silica radome by transmission would then consist of a series of images recorded at successively rotated positions of the radome.

Special immersion procedures could also readily be followed for nonimmersible objects in ARTHIR as it presently exists. For example, if a silica radome were treated as a nonimmersible test object to be insonified, the source transducer would be mounted from the floor of the tank. Then the radome would be wrapped with a donut-shaped plastic bag which is contacted to the silica of the radome by a thin layer of aqua gel, vaseline, or by direct heat sealing. This is done to get a highly transmissive path for the ultrasonic beam from the water through the plastic wrap, its contact to the radome itself, and back out again to water on the other side. It is recommended that the thickness of the plastic layer be chosen to be 1/4 wavelength thick at the operating frequency of the ultrasonic beam being used for inspection; for example, at 3 MHz, the thickness of 0.30 mm in polyethylene is 1/4 wavelength. When bonded to a silica surface it serves quite well as an antireflection coating, thereby enhancing the 3-MHz transmission.

Special immersion techniques have also been demonstrated on lower powered liquid surface acoustical holographic systems for coupling to objects outside of the main tank. These techniques involve replacing the end of the main tank with a thin flexible membrane (flexible enough to conform to the surface of the dry test object) and mounting the source against the other side of the test object or in a separate source tank with its own flexible conforming wall (conforming to the other side of the dry test object). Even for this technique the dry test object must be wet with a suitable coupling medium for the transmission of the ultrasound energy through the flexible membrane into the test object itself and out again for ARTHIR to form its image.

II. THE ACOUSTIC SYSTEM

The aim of extending the capability of the ARTHIR system from readily available performance to the limit of the state-of-the-art requires care in the engineering of the optical and electronic systems within the ARTHIR system to place the limits of signal strength and of the spurious noise in the output image largely on to the characteristics of the acoustical system. This has been done with the ARTHIR now operating at the Ground Equipment and Missile Structures (GE&MS) Directorate. Therefore, the imaging performance of this ARTHIR is sample dependent.

The purpose of this section is to describe the acoustical functions so that an operator can get the most out of the ARTHIR for the particular sample being tested. The preliminary data discussed were taken on flat plate samples as representative of each small area of a larger test piece of more complicated shape.

The outstanding features of the acoustical system within ARTHIR are the high power available in the broad (4-in. across) ultrasonic beams and the well-damped response of the two water tanks. A further step in improving the acoustic signal-to-noise ratio was formulated and some preliminary test data obtained. The step involves using 1/4 wavelength thick layers of antireflection coatings on the surfaces of highly reflective test objects to improve penetration and thereby increase ultrasonic pressure delivered to the air-liquid surface where the acoustic hologram is formed. For example, a layer of 0.30-mm polyethylene on each surface of a flat plate of silica in water can increase the 3-MHz transmission from 10% to 50%. This is equivalent to raising the power output of the source transducer by a factor of five. This will be an enormous advantage for imaging through silica radomes.

A. Brief Theory of the Formation of Acoustic Holograms

1. Purpose of Hologram within ARTHIR

The reason for forming the acoustic image into an acoustic hologram on the air-liquid surface rather than using the plain acoustic image is to permit optical filtering near the back focal plane of the telescopic lens and thereby to allow viewing of the image as a bright on a dark field. This is often called optical filtering in the Fourier transform plane [2].

2. Formation of a Single-Shot Acoustic Hologram

The reflection of a pulse of ultrasonic energy which is traveling up through a liquid by the air-liquid surface is nearly complete. The reflection, however, does impart some momentum to the liquid at the air interface. Where ever the local sound pressure is sufficient to overcome thermal agitation and spurious surface waves, that portion of the surface is elevated a short time later by an amount of elevation which is dependent on the local incident sound pressure during the pulse and on the length of the pulse. Therefore, the bright portions of an acoustic image, which is focussed onto the air-liquid surface from underneath, will each produce an elevation of the local surface shortly after the pulsed image has been reflected. The time delay is a few hundred microseconds for water and typical values of the vertical displacement appear to be of the order of the wavelength of visible light for 100 mW/cm^2 of incident ultrasonic power.

The detection task is to display the acoustic image as an optical image but to avoid displaying the elevations due to spurious surface motions. The technique used in ARTHIR is to form an acoustic hologram by the coincident reflection of a second ultrasonic pulse which is coherent with the first. The two coherent waves, each several hundred wavelengths long, apply an impulse which is a maximum along those lines where the two pressure waves are in phase and a minimum along those lines where the two pressure waves have opposite phases. The minima can be made to have values close to zero by setting the amplitude of the reference pressure wave to be equal to the pressure amplitude in the bright portions of the image formed by the object beam in ARTHIR. This is done by using an adjustment on the fron panel of the high voltage power supply to the amplifier for the reference transducer. The ballistic response of the air-liquid surface is to form a ripple (grating) across each of the bright portions of the acoustic image and then for the ripple pattern to oscillate freely until the viscosity of the liquid damps out the ripple oscillations.

3. Delay in Ballistic Response of the Liquid Surface

The electronic controls in ARTHIR permit the smooth adjustment of the delay of the laser light pulse to illuminate the surface ripple (grating) during the few hundred microseconds that the maximum ripple amplitude persists. The value of the delay in the ballistic response of the liquid surface depends on the viscosity and specific density of the liquid in a complicated manner.

One theory for the ballistic ripple response of a liquid surface has been reported by Hildebrand and Brenden [3] but its basic model is open to serious question. Therefore, the way to choose the optimal properties of the liquid surface is still not clear. However, their estimated numerical values [3] for water are of interest to the typical operation of ARTHIR namely: $t_1 = 40$ msec, the time constant in their exponential damping factor for the ripple oscillation proportional to the viscosity on their model, and $1/f_R = 1.2$ msec, the period of ripple oscillation, dependent on the amplitude of oscillation on their model. Together these give $t_{delay} = 300+$ μsec for the time delay to maximum aplitude for their model. The value of the time delay measured for water is indeed several hundred microseconds but its dependence on liquid properties is not yet clear. More experiments with a variety of liquids in the mini-imaging tank remain to be done and a better model for the differential equation of motion of a volume element of the liquid needs to be developed to be assured of optimum performance of ARTHIR.

4. Image Resolution and Ripple Patch Dimension

The ripple formed in ARTHIR by the coherently modulated impulse arising from the interference between the reference beam pulse of wavelength Ω incident at angle θ_{ref} and a uniform patch of the object beam pulse arriving normal to the liquid surface may be described approximately by the expression

$$z(t, y, \theta, \Omega, p_o) = A_R(t, \Omega, p_o) \cos(2\pi y/Y_R) + B, \qquad (1)$$

where z is the vertical displacement of a surface element from its quiescent location, y is the horizontal location measured in the plane of incidence of the reference beam, p_o is the amplitude of each pressure wave, and Y_R is the period of the ripple given by

$$Y_R = \Omega/\sin(\theta_{ref}) \quad . \qquad (2)$$

Figure 4 is an illustration of this delayed ripple formation. In Figure 4, the sectional view of the plane containing the axes of the two acoustic beams, one normal and the other (reference) beam at angle of incidence, θ_{ref}, shows the points (lines of constant y) of constructive interference to be Y_R apart, where $Y_R = \Omega / \sin(\theta_{ref})$. The delay for ripple formation depends on liquid properties.

Optical contrast in ARTHIR's output is improved as Y_R is made smaller until the optical diffraction orders are well separated. For a given frequency, larger angles of incidence should be used for the reference beam. The compromise currently being struck in ARTHIR is to set θ_{ref} between 40° and 60°. For 45°, the values of the ripple period are given in Table 1.

TABLE 1. RIPPLE PERIOD, Y_R, VERSUS ULTRASONIC FREQUENCY FOR THE REFERENCE BEAM INCIDENT AT 45° TO THE WATER SURFACE.

Frequency (MHz)	1	3	5
Ripple Period (mm)	2.1	0.70	0.42

For the telescopic lens currently in ARTHIR, the 0.70-mm value of Y_R is a significant improvement over the 2.1-mm value, as discussed in more detail in Section III.

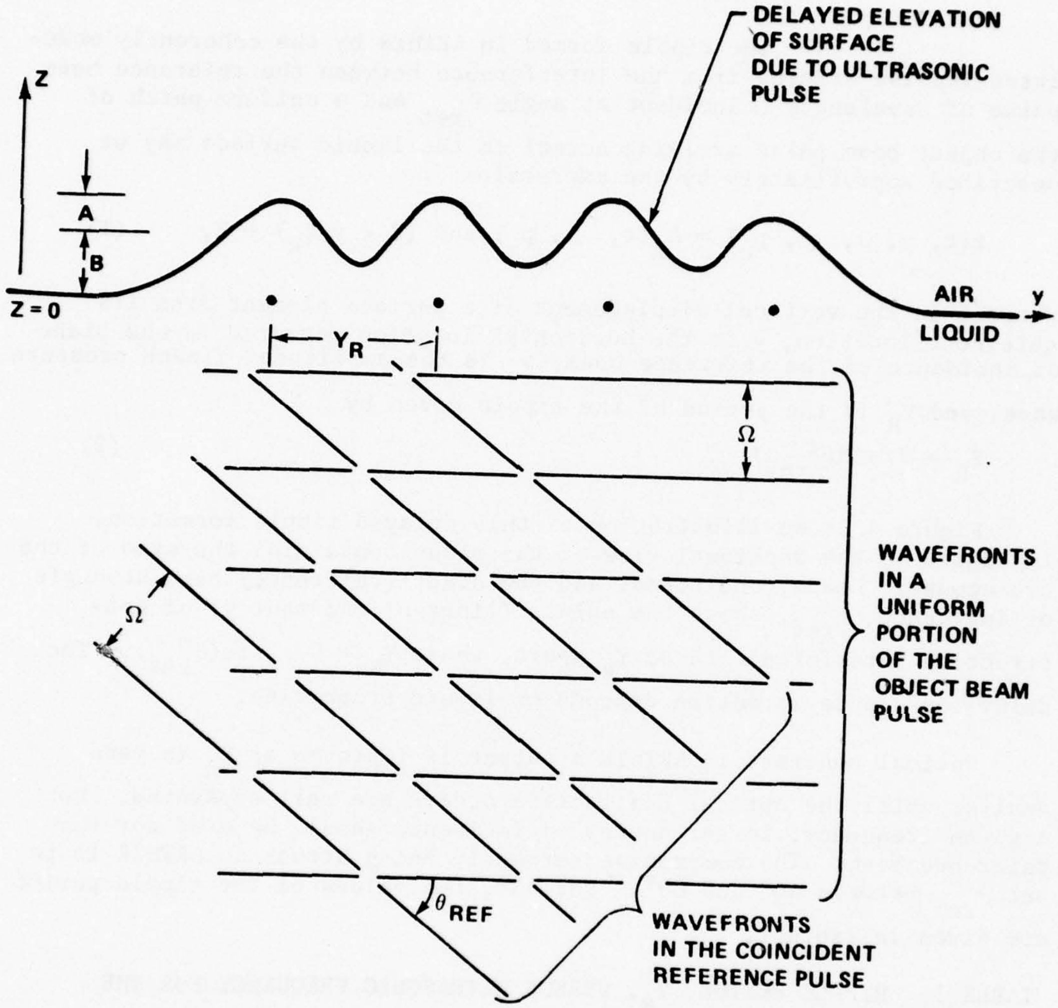


Figure 4. Ballistic ripple formation of liquid surface.

The smallest patch of rippled surface which can act as an optical grating and diffract the light into the sidebands in the second focal plane and thereby into the output image is two crests of the ripple. In other words, the minimum patch dimension along y observable in the optical side bands in ARTHIR is approximately one period, 1 Y_R.

Whether this minimum patch dimension (along the y direction) controls the acoustical resolution depends on the acoustical lens configuration. Clearly the optical system will be able to image patches as small as 0.4 mm sharply, as discussed in Section III.

In any case, the acoustics system resolution cannot be better than its diffraction limit. For the acoustic system in ARTHIR, the Rayleigh diffraction limits in the image on the air-liquid surface are calculated to be approximately 6, 2, and 1.5 mm for frequencies of 1, 3, and 5 MHz, respectively, for unity acoustic magnification. Increased magnification can improve the effective resolution values only slightly. These diffraction limits for ARTHIR's typical acoustical configuration are several times larger than the minimum dimension of a ripple patch cited previously for 45°. The overall resolution of flaws in a test object in ARTHIR is as it should be, limited by diffraction effects within the acoustical system. In particular, performance is limited by the diameter of the liquid lenses, their aberrations, and the diameter of the porthole between the two tanks. Preliminary data bear this out well.

5. Repetitive Pulses

For recording the optical image of a high contrast acoustical hologram on film, a single shot suffices with the light passing the second focal plane filter(s) directed into the lens opening of the appropriate camera. High acoustic contrast is readily available in ARTHIR for test objects which have high transparency or at least uniform transparency over resolvable portions of the object area insonified. An example of a single shot photograph taken of a high contrast test object is shown in Figure 5 where a 1.5-mm cut through a foam plastic sheet is clearly resolved. In the photograph in Figure 5, the grey background around the letters "V I" resulted because the reference transducer power was set too high. Adjustment of the ultrasonic power settings to minimize the diffraction of light from the dark portions of the acoustic surface hologram then gives a high contrast photographic film record.

For viewing or recording the optical image of a lower contrast acoustic hologram formed by transmission through a strongly scattering region of the test object, the real-time mode is needed which in turn requires repetition of the pulsed hologram formation process at many cycles per second. At a reasonable repetition rate, the operator can move the test object across the beam and "see" the image move across the speckled field-of-view. Most of the acoustic speckles in the optical output image stand still under lateral displacement of the test object,

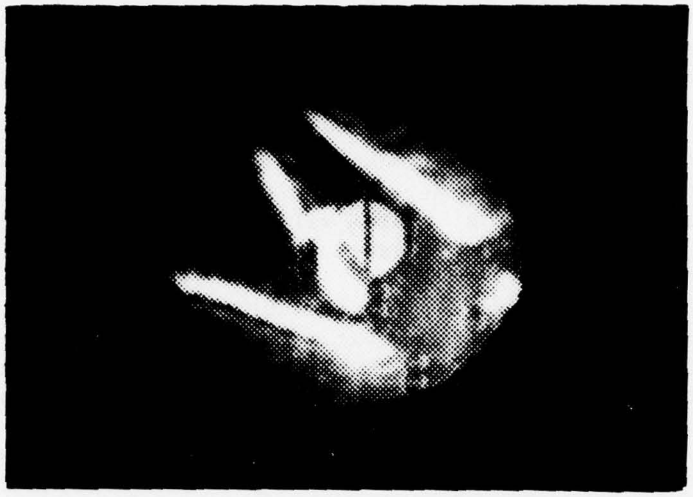


Figure 5. Photograph of single shot hologram. The test object, initials V I cut through a foam sheet, was insonified by a single 3-MHz pulse. The light passing the optical filter, a 1.0-mm wire, entered the camera lens located 4.5 in. beyond the optical filter. The upper stem of the I is 1.5 mm across; the left cut for the V is 3.5 mm across. Both are clearly shown in the photo. The circle with the dark line through it is light reflected from the Mylar film at the bottom of the water in the mini-imaging tank and shadowed by the optical filter; a procedure for removing that circle is discussed in Section III. The laser pulse power was reduced for this photo to avoid overexposing the 3000 Polaroid film. Acoustic magnification was approximately 1.3 and optical magnification was 0.15. The aperture on the telescopic lens was 3-in. diameter mask.

so the pattern due to the test object is discerned by its motion across the static speckle background. The real-time effect of moving the test object laterally across the object beam can be seen by the lapsed time photographs in Figure 6 and 7. The test object is a 1-in. thick sheet of Plexiglas in which a void was formed by drilling a 3/16-in. hole part way in from one side and plugging the hole with an Allen head steel machine bolt. Two liquid lenses were used to get acoustic magnification close to 2.0. The repetition rate was near 200 per second; the RF at 3 MHz. The photograph shows the TV monitor output with a 4-in. diameter mask on the telescopic lens. Figure 6 shows the bolt head in water displaced between Figures 6(a) and 6(b) by approximately 1/4 in. Most of the fringe pattern remains fixed between (a) and (b). Another example is shown in Figure 7 where the portion of the test object seen includes the end of the drilled hole in the plastic sheet. The comparison between Figures 7(a) and 7(b) shows the same TV monitor output exposed for 0.5 and 1.5 sec, respectively. The succession of Figures 7(b), (c), and (d) shows the change due to two 1/4-in. displacements of the void.

Caution should be exercised against raising the repetition rate too high. If the waves created by a given pulsed hologram have not died out before the arrival of the next ultrasonic pulse, the surface grating will be distorted and contrast in the output image diminished. With water surfaces in ARTHIR, repetition of several hundred hertz can still give reasonable contrast; for 60 Hz, the excellent contrast appears little changed from a single shot. According to the numerical calculations [3], a wait of several times 40 msec is necessary to avoid such interference in a water surface. This cast further doubt on their model for the ripple information.

6. Noise Sources in Surface Holograms

The principal form of noise in the output images of ARTHIR is the static speckle pattern associated with the use of near field coherent beams. Beam patterns are given in some detail in the next section. The static speckle from the beam profiles themselves can be minimized for test objects with high contrast transmission patterns by keeping the acoustic power level low. The static speckle from apertures in the water tank system can be minimized by appropriate care in alignment and in avoiding spurious edges within the beams. Strong diffraction patterns will develop in high contrast test patterns from the coherence in the object beam seeing the boundaries between regions of different transmission coefficients as effective edges, leading to the usual edge diffraction patterns being superimposed on the pattern of transmission changes.

(a)

(b)

Figure 6. Succession of TV monitor views. The test object, a 3/16-in. steel bolt, was displaced approximately 1/4-in. between the photographs in Figures 6(a) and (b). Conditions include acoustic magnification of 2 at 3 MHz, a 4-in. diameter mask on the telescope, and repetition over 200 sec.

Another source of noise which is independent of the sample is spurious surface waves. These are generated by a variety of sources, such as air currents in the room, vibrations from the floor due to walking in the building, trucks outside, and remnant surface waves from operator motion of the test object during real-time viewing. Damping and isolation features in ARTHIR have reduced these noise levels considerably, as discussed in the following paragraphs.

The background sample dependent noise can be due to those defects and scattering centers within the test object which are not clearly resolved. This noise will move with motion of the test object and discrimination against it may require sophisticated image processing based on the sharp field of focus of the acoustical imaging system within ARTHIR.

B. Ultrasonic Imaging

Focussing the ultrasonic transmission pattern of a thin test object onto the air-liquid surface below the telescopic lens in ARTHIR serves to present the acoustic image where it can be detected optically. Obtaining sharp focus is the most critical acoustical adjustment required within ARTHIR for clear optical imaging. It is the purpose of this section to present an outline of several satisfactory ways of focusing the acoustic image of a thin test object.

(a)

(b)

(c)

(d)

Figure 7. Views of a void moving across the 3-MHz beam. The test object, a 1-in. Plexiglas sheet containing a plugged 3/16-in. diameter hole, is displaced by successive 1/4-in. steps between the photographs (b), (c), and (d). The photos (a) and (b) show the same TV monitor output with different camera exposures. Conditions were otherwise the same as for Figure 6.

The difficulty of handling thick objects to get useful images results from the superposition of diffuse patterns from those regions of the test object that are out of focus on the focused image of those portions of the test object that are in focus. The special difficulty in a coherent imaging system, such as ARTHIR's acoustics, is that the out-of-focus pattern usually has many sharp diffraction lines as sharp as those diffracted from the in-focus portion of the thick test object. One satisfactory way to accomplish controlled focusing of a thick object is to place a thin, high contrast pattern of known design adjacent to the thick test object and focus initially on the known design; subsequent small displacements of the thick test object will translate the plane of focus through the thick object in steps. Figure 8 shows the appearance of the image on the ground glass screen of a high contrast test object, the 10-mm bar pattern in foam plastic as photographed in Figure 9, with and without a silica plate in the beam next to the foam plate. The only change in the settings of ARTHIR that accompanied the insertion of the silica plate was turning up the power to the source transducer slightly to restore the brightness of the image on the ground glass screen. It is concluded that several voids in the silica are visible, as in the photo of Figure 8(b).

1. Ideal Acoustic Beam With Thin Lenses

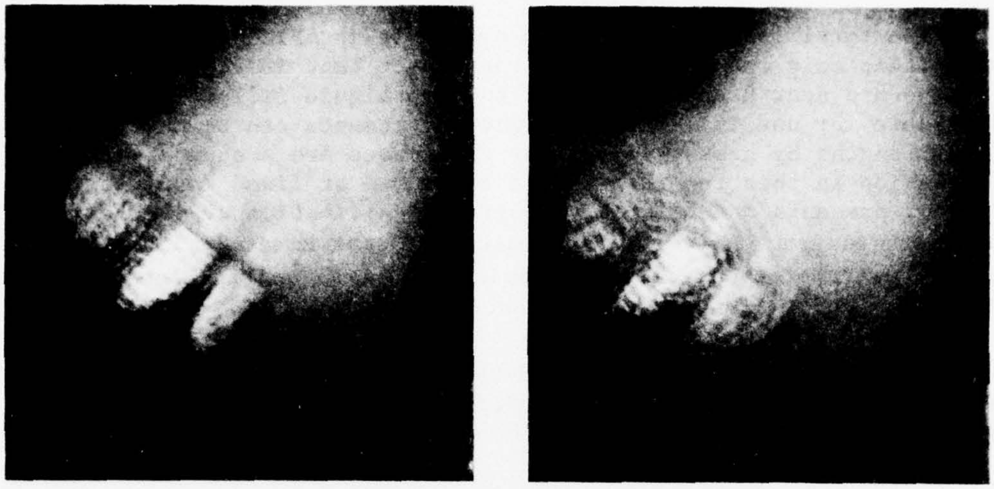
The function of an acoustic lens in ARTHIR is to collect some of the waves scattered off axis by the voids, defects, and edges of the test object and to focus those waves into an image farther downstream. The thin lens formula for paraxial rays is useful here. For a single lens with focal length F, the object distance DO and the image distance DI are related by

$$\frac{1}{F} = \frac{1}{DO} + \frac{1}{DI} \quad . \tag{1}$$

The lateral magnification is

$$M = \frac{DI}{DO} \quad . \tag{2}$$

To use a single lens focusing the acoustic image on the air-liquid surface within ARTHIR, it is useful to refer to paraxial ray diagrams. The beam axis and each lens axis are presumed to be collinear, the distances DO, DI, and F are measured along the beam axis. The acoustic mirror serves to rotate the beam axis to the vertical.



(a) (b)

Figure 8. Views of a test pattern, with and without a silica plate in the beam. The superposition of a silica test plate in the 3-MHz beam next to the foam test plate with 10-mm wide slots cut through it on a 20-mm period is shown in (b) to add gray patches to the appearance of the foam test plate alone in (a). The acoustic man-magnification was 1.2 with the plane of incidence of the reference beam not optimum but at approximately 60° from the plane of the optical bench. The gray patches show voids in the silica which move with the silica test plate in the real-time mode of viewing.

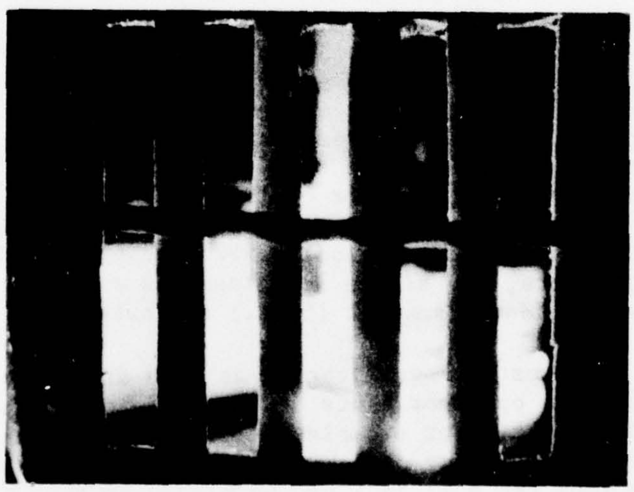


Figure 9. Photograph of the foam test plate with the 10-mm slots in it. The test plate is 1-mm thick foam plastic through which five slots cut from the 1-mm foam plate and can be seen well-resolved in the ARTHIR output such as in Figure 8.

The total length of the beam available in ARTHIR when the source beam makes only one pass through the object tank is 100 in. The focal lengths are near 8 and 11 in. for the two liquid-filled lenses now available for use in ARTHIR. Slight adjustments can be made to the focal lengths by pressurizing, but the lenses are adequate. The discussion in this report presumes their use at fixed focal lengths. Table 2 presents the value of acoustic magnification available in ARTHIR which range from unity to large values of approximately 5, as determined by the operator's choice of the object location and the location of the acoustic lens or lenses for a given water level.

Operation near unity (DI) and the choice of the object location. Operation near unity acoustic magnification is recommended for two reasons:

a) Sharp focus is attainable on the transfer tank surface with less precision required in the longitudinal positions of lenses and the test object at unity magnification. It should be noted that the derivative, d(DI) / d(DO), is given from Equations (1) and (2) as

$$\frac{d(DI)}{d(DO)} = M^2 \quad . \tag{3}$$

b) Unity magnification with two lenses permits nearly full beam power to pass through the port channel between the two tanks into the transfer tank and therefore should give the best resolution and best penetration simultaneously.

The geometry of the transfer tank, with the beam axis approximately 10 in. below the surface and the center of the target surface area under the telescope 16 in. from the face of the port, is quite well suited for the two-lens focusing at unity acoustic magnification as illustrated in the ray diagram of Figure 1. For larger test objects, the operator might prefer to use only one lens at unity magnification. It is clear that the 5-in. diameter of the port forms the limiting aperture. Therefore, the effective limiting resolution should be somewhat larger than with the 8-in. diameter lens being the effective aperture. Furthermore, the single lens case has somewhat less beam power available due to the smaller (5-in.) aperture.

Operation at acoustic magnification as high as 4 or 5 may be advantageous when the operator wants a blown-up view of the insonified area of the test object. For example, better resolution has been found at M = 4 at the low frequency of 1 MHz than at M = 1 at the same low frequency. One lens (FL = 11 in.) can be placed to give M = 4 and still have the effect of the 5-in. port over the central portion of the acoustical hologram.

TABLE 2. ACOUSTIC MAGNIFICATION IN ARTHIR

Acoustic Magnification	One Lens		Two Lenses		
M	DO	DI	DO1	L1 to L2	DI2
	Use F1 = 11 in.		Use F1 = 11 and F2 = 8 in.		
1.0	22	22 just inside ripple tank	22	38	16
2.0	16	33	16	49	16

Note: Symbols are defined in text and in Figure 2. Focal lengths of the liquid lens are assumed to be F1 = 11 in. and F2 = 8 in. Final acoustic image is to be focused on the air-liquid surface below the telescope.

2. Actual Ultrasonic Beam and Its Adjustment

Imaging with a coherent beam is difficult at best. Imaging in the near field of the radiator (or any subsequent aperture) is made even more complicated by the irregularities in the near-field Fresnel patterns involved. Both the coherent scattering and the near-field irregularities result in speckle in the final acoustic image on the liquid surface.

One real-time viewing technique for reducing the coherent contributions has been described recently in the literature as multifrequency insonification. It involves rapidly varying the frequency at which the transducers are being driven over a sufficient range to wash out the speckle in the image due to coherent scattering from edges and other nonuniformities in the beam path. Because this frequency range is large with respect to the resonance width of the 5-in. quartz crystals being used as transducers in ARTHIR, such rapid frequency sweep is difficult if not impractical at the high powers used in ARTHIR for thick or highly reflecting test objects.

The only beam configuration within ARTHIR which permits far-field operation is to add a mirror in the large object tank in the usual position of the source transducer and run the source beam two or three lengths of the tank to get the object position into the far field. This will work only with the 1-MHz frequency when using the large (5-in.) transducer. At the higher frequencies, the far transition point requires too many passes up and down the length of the object tank to get to the transition point. The attenuation of ARTHIR's acoustic beam is no more than 50% traversing the length of the object tank. The irregularities of the near-field beam of the 5-in. source transducer operated at 3 MHz have been measured with a small 0.03-in. diameter probe. For high contrast flaws in the test object, the beam near-field amplitude fluctuations which are as large as 30% will not confuse the output image. However the output contrast for small, low contrast flaws will be degraded by these irregularities and the operator of ARTHIR will need real-time viewing or recording, even computer processing to discern such flaws.

Beam adjustments can produce a well-focused acoustic hologram under the telescope when they are made in the following sequence:

a) Without lenses and with reference beam off, the source transducer is aligned with the aid of a small acoustic transducer receiver to have:

1) The beam center coincident with the center of the port to the ripple tank, typically approximately 10 in. above the tank floor, and 10 in. below the water surface.

2) The beam level, oriented at the desired angle with respect to the plane of the optical system, typically 90°.

b) The height and location of the acoustic mirror, mounted at a fixed 45° with the vertical, are adjusted to reflect the source beam centrally into the surface area viewed by the telescope.

c) Coarse focusing can be accomplished by setting the lenses in the location expected for the thin lens formula in Equation (1), while marking the approximate plane of focus in the object space. For example, if the operator chooses to get an acoustic magnification of $M = 1$ using two lenses, then the lens L2 with 8-in. focal length is placed in the transfer tank so that its center is on the beam axis, its plane is perpendicular to the beam axis, and its center is 6 in. (2F - 10 in.) from the acoustic mirror reflection point. Continuing the example the other lens (L1, with the focal length of 11 in.) is then placed in the object tank, centered on and aligned with the beam axis and the distance of $2(F1 + F2) = 16 + 22 = 38$ in. from the lens in the transfer tank. The approximate plane of focus in the object space is then 22 in. farther upstream from the center of this L1 lens.

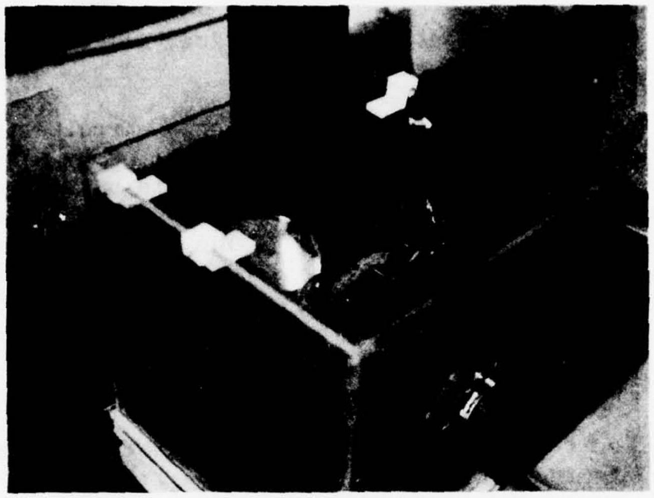


Figure 10. Transfer Tank. The 2 × 2 × 2-ft transfer tank is shown without water for a better view of its contents. The black cylinder reaching down to the tank holds the 6-in. diameter telescopic lens within 1 in. of the water surface. The three white clamps hold the mini-ripple tank when it is in place. The 45° acoustic mirror reflects the ceiling lights in the photograph. The ring to the upper right of the mirror is the reference transducer 5-in. diameter face. The rubber coupling to the object tank is in the lower right of the photograph.

d) Covering the target surface area under the telescope with the reference beam can readily be done by visual alignment when the beam is aimed directly at the surface of the transfer tank without striking the acoustic mirror. The recommended orientation of the reference beam is either to be within the plane of the optical system or perpendicular to it. For the present mounting of the optical system, the alignment within the optical system plane is the more convenient. The recommended angle of incidence is in the range from 45° to 60°, as a compromise between a small value of the ripple period Y_R and a uniform reference beam.

e) Power controls need to be set low enough to avoid overdriving the liquid surface. Evidence for overdriving is the formation of ripple patterns by one beam alone; such patterns are correlated near the threshold with the near-field beam irregularities. Their presence reduces the contrast available in the final output image.

f) Final focusing is done with both beams on; the ARTHIR in the real-time viewing mode. Trimming adjustments of lenses for a thin test pattern as the test object will permit optimal focusing of the acoustic holographic image on the surface. Lateral motions and orientation changes should be kept small at this stage; steps no larger than 0.25 in. are recommended.

3. Resolution: The Theoretical Diffraction Limit and Observed Performance

The diffraction pattern of a circular aperture of diameter D which is illuminated or insonified uniformly with wavefronts flat across the aperture, that is, by the far-field pattern of the source of the waves, has a central maximum of intensity along the axis surrounded by a succession of dark and bright rings. The radius of the first dark ring at distance DS along the beam axis from the aperture is given by the Airy disc formula [4] as

$$r = 1.2 \times \text{wavelength} \times \frac{DS}{D} \quad . \qquad (4)$$

This can be applied to both the acoustical and optical systems in ARTHIR to calculate their effective diffraction limits.

In applying the Airy formula of Equation (4) to the acoustical system in ARTHIR, the wavelength in the water is used at 0.5 mm at 3 MHz; for DS, the distance to the liquid surface along the object beam from its limiting aperture D is substituted. Therefore, the radius of the Airy disc on the liquid surface may be estimated at 3 MHz for unit magnification to be approximately

$$r_A = 1.2 \times 0.5 \times \left(\frac{22}{8}\right) = 1.7 \text{ mm} \quad .$$

A conservative criterion for resolution of two points in the object plane into their separate Airy discs, called the Rayleigh criterion, is to set the minimum resolvable separation of the image centers equal to the Airy radius.

It has been found the ARTHIR displays (Figure 5) 1.5-mm wide bar very clearly at 3 MHz. Using the test object shown in Figure 11, good resolution of the 2-mm bar pattern was obtained as shown in the TV monitor photograph in Figure 12. The clarity in high contrast images indicates that the acoustic system in ARTHIR is operating very close to the theoretical diffraction limit for far-field and that the degradation due to the actual near-field beam conditions shows up only in low contrast images.

C. Reference Beam

The reference beam in ARTHIR is generated by a transducer of the same geometry and electrical design as the source transducer discussed previously. The 5-in. diameter quartz crystal is air backed and contacted around its front surface with approximately 1/16 in. of its periphery by a conducting, silver impregnated, rubber gasket in each case.

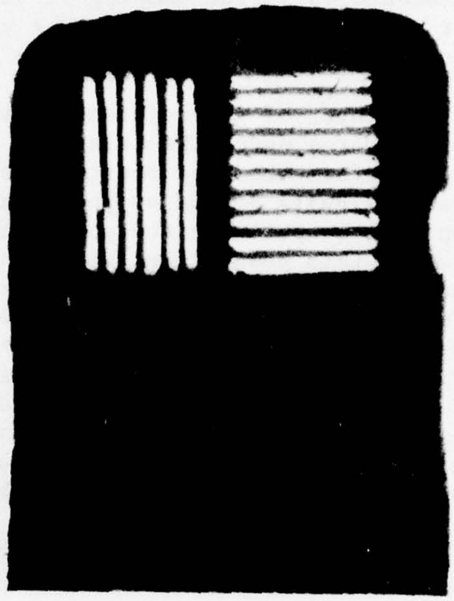


Figure 11. Photograph of the foam test plate with the 2.0-mm slots cut cut through it. The 1-mm thick foam plate was cut through, leaving 2.0-mm bars on 4.0-mm period. Many of the irregularities seen in this photo could be seen in the acoustic holograms in ARTHIR.

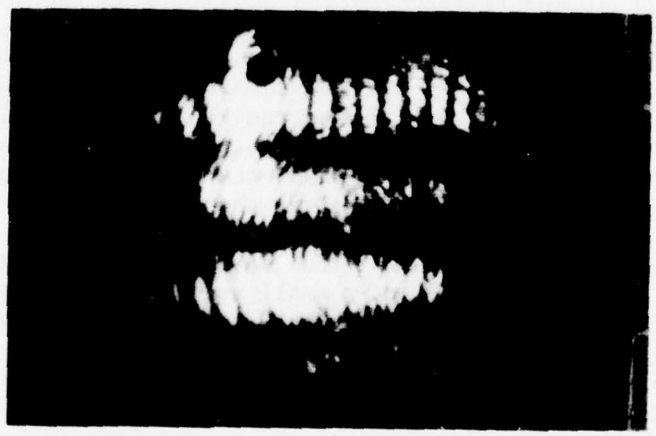


Figure 12. Resolution of a 2-mm bar pattern on the TV monitor. The 2-mm horizontal bar pattern in the test object shown in Figure 11 was insonified at 3 MHz with acoustic magnification of 3.6 in the surface holograms. Three of the 2-mm openings are shown here with a superimposed diffraction pattern due to the irregularities.

The reference transducer is supported from the transfer tank bottom on a rubber-padded plastic frame which has an adjusting screw to control the elevation in the region around 45°. The damping of soft plastic or rubber at each point of contact is apparently useful to the generation of reliable holograms. The exact angle is not critical.

The distance from the center of the reference transducer and the center of the target surface area under the telescope is approximately 8 in. or 1.5 diameters downstream from the source crystal. So the near-field irregularities are quite severe as shown in Figure 13. They become evident in the optical output when the power setting is high as used for initial alignment. This power level is too high for hologram service; it degrades the contrast in the ripple pattern, and therefore in the output image. The alignment, while viewing the surface of the liquid with the reference beam set at rather high power but with the source beam off, is accomplished by incremental positioning of the reference support until the splash pattern from the reference beam is centered on the surface under the telescope as seen through the TV monitor. After alignment is satisfactory, the power setting is turned down to a level to be selected by the nature of the object transmission pattern.

Matching the ultrasonic pressure arriving at the liquid surface from the reference beam to the pressure in that part of the test image which is of most interest will produce the maximum ripple amplitude for that portion of the test image. Several examples of the contrast obtained are given in Figures 14 (a), (b) and (c).

For test objects which have holes completely through them (ultrasonic transmission without any reflection) the amplitude of the reference beam should be set to give maximum output brightness in those clear areas of the corresponding test image. Several standard test patterns of this type were made from foamed plastic sheets, giving bright bars, circles, or dark background, when the source beam amplitude is set to avoid splashing the liquid surface in these bright areas, the reference transducer amplitude is then set to match the source amplitude in these bright areas. If either is set too high, the contrast will be reduced.

For more typical test objects which have considerable reflections at their two surfaces and relatively small variations in transmissivity, the power setting procedure is not so well defined. The goal is the same; namely, to match the amplitudes of the pressure waves from the two beams over the portions of the output image which are being most closely scrutinized. This is straightforward for flat regions of a test object. The strong variation of reflections of the source beam with angle of incidence on the test object makes this setting procedure arduous for a test object of arbitrary shape. However, if the portion of the test object under close inspection were a section of a cylinder or a large cone, then the mapping by rotation of the test object could use constant

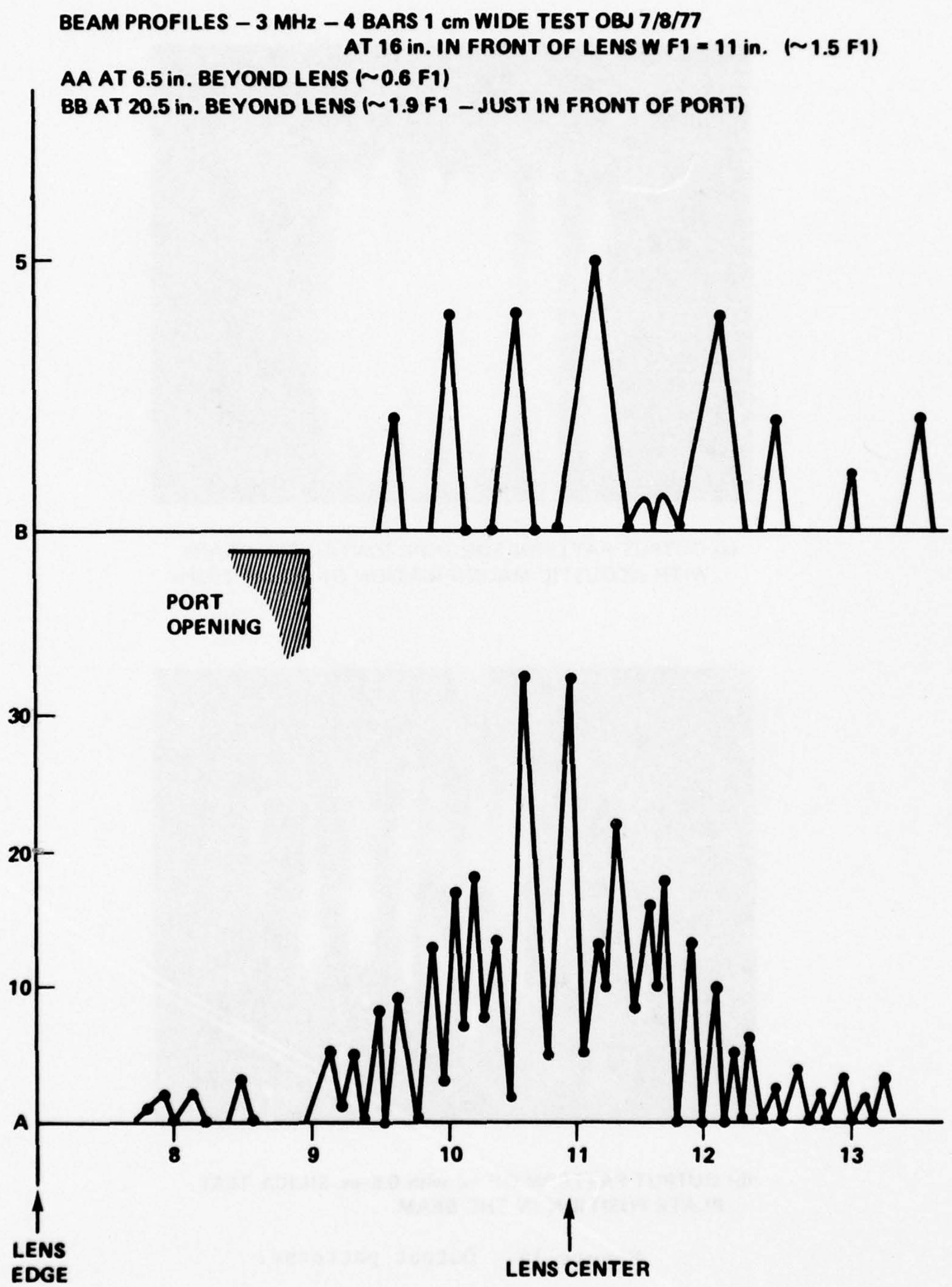
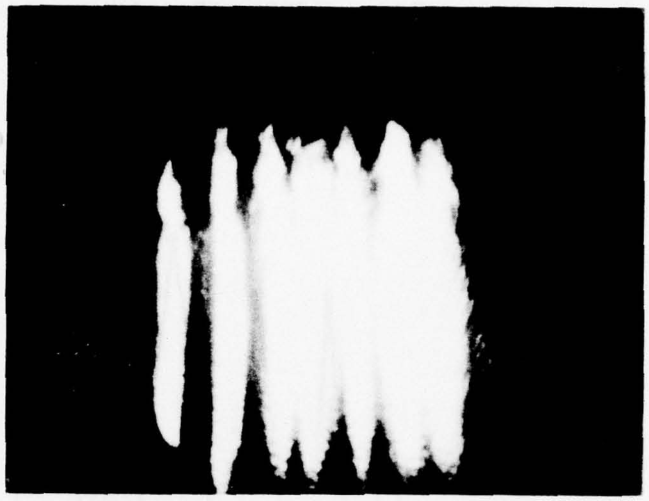
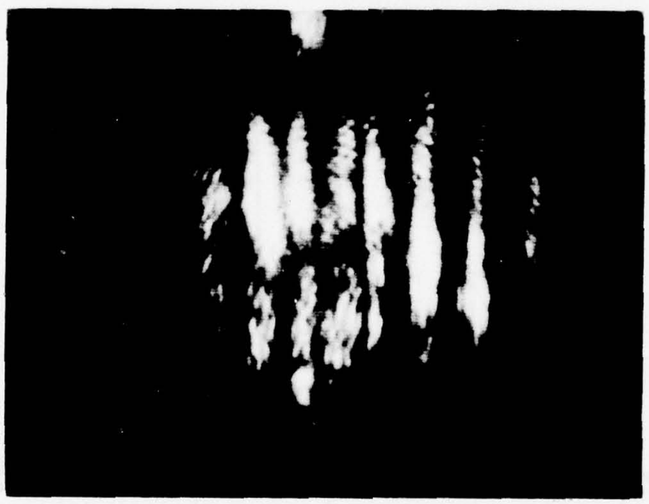


Figure 13. Near field beam profile at 3 MHz.

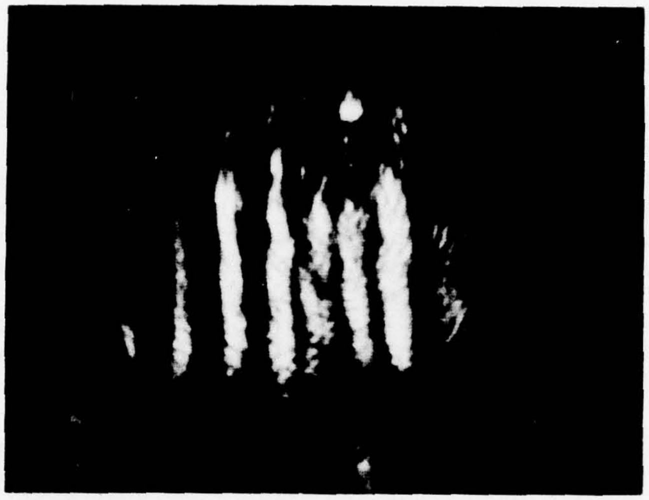


(a) OUTPUT PATTERN FOR HORIZONTAL 2-mm BARS WITH ACOUSTIC MAGNIFICATION OF 1:1 AT 3 MHz



(b) OUTPUT PATTERN OF (a) with 0.5-in. SILICA TEST PLATE POSITION IN THE BEAM.

Figure 14. Output patterns.



(c) OUTPUT PATTERN OF (b) WITH THE SILICA PLATE MOVED 0.25 in.

Figure 14. (Concluded).

settings of the source and reference transducer power which were set to maximize ripple for that portion of the image derived from the axial region of the cone or cylinder. It would be interesting to try this on a silica radome, coated to keep the voids in the silica dry during the immersion in the object tank.

D. Acoustic Mirror(s)

The function of the acoustic mirror located in the ripple tank is to rotate the object beam axis so that it strikes the liquid surface under the telescope at normal incidence. The mirror should do this without adding any phase variations to the object beam and without much loss in energy. Plate glass serves well. A plate of stainless steel would give approximately a 20% increase in the delivered power over the plate glass mirror now in ARTHIR. If stainless steel is to be used, the plate should be ground flat and polished to an optical finish of 1/4 wavelength. A fixed 45° mount with rubber padding improves the reliability of the holographic image output of ARTHIR.

Acoustic mirror(s) placed in the object tank should permit a long enough source beam to reach the far field at 1 MHz before impinging on the test object. Actually the stainless steel end wall is observed to perform fairly well as a mirror for this service, even though at an inconvenient angle.

E. Transfer Tank

As noted in the introduction, the separation of the liquid surface where the acoustic hologram is to be formed from the object tank where real-time usually means motion of the object through the water into a separate transfer tank (Figure 8) reduces spurious surface waves in the hologram area. The present arrangement of a separate transfer tank coupled to the object tank by a 5-in. diameter 6-in. long water channel whose wall is a soft rubber tube, provides a large factor in this reduction. Should further isolation be required, a thin Mylar membrane can easily be mounted across one end of the channel under one of the existing collars which hold the connecting rubber tube.

Isolation of the transfer tank from vibrations is very adequate using the soft rubber tube around the water channel and several layers of polyethylene foam under the tank floor. The two principal sources of external vibration noise in the transfer tank are the heavy coaxial power cable to the reference transducer and air currents across the water surface. The latter can be effectively shielded by a tank cover which could also serve to keep off most of the dust. It is anticipated that, if a satisfactory way can be found for damping the vibrations coming through the reference cable (clamping to the side of the transfer tank seems to provide a temporary fix), then the principal sources of random noise in the acoustic holograms will arise from:

1) Dust on the liquid surface.
2) Surface waves driven by air currents.

Surface waves in the $2 \times 2 \times 2$-ft transfer tank are quite well damped by the 2-in. thick batts of rubberized hair mounted along two of the sides to protrude through the surface of the liquid and cover most of the area of those sides of the tank. The measured time constant in the transfer tank is just a few seconds for the longer waves to be attenuated.

1. Mini-Ripple Tank

A mini-ripple tank is provided (Figure 15) so that the operator of ARTHIR may use a special liquid, other than water, for the surface hologram if he chooses. The literature [3] predicts using a questionable model, that a larger ripple amplitude per unit power density input can be obtained by choosing a liquid having different viscosity and different density than water. Freon 113 has been used in the minitank to obtain acoustic holograms but has not yet been able to show any significant advantage in ARTHIR. An advantage may exist for those test objects that have low transmission.

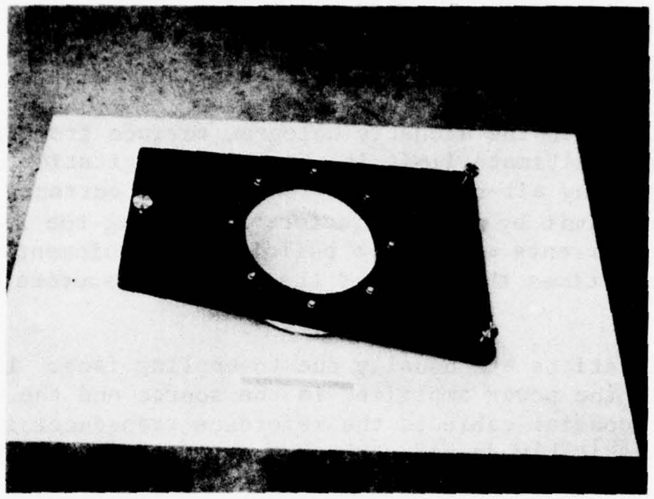


Figure 15. Mini-ripple tank.

Combating dust is sure to be a continuing battle for the operator when testing objects with low contrast flaws. A quick fix for the dust problem in a short run is to use clean water in the mini-ripple tank. For production-type inspections, an air cover which includes a dust precipitator will probably be required eventually.

Damping of the surface waves generated in the minitank is aided by a saw toothed sponge ring placed around inside the periphery of the 7.5-in. diameter tank. The sponge is thick enough to protrude above the liquid surface. The sponge material absorbs the liquid involved so that the surface wetting aids in the damping as well as the surface shape.

To avoid acoustic distortion from any strain patterns in the Mylar film stretched over the bottom of the mini-imaging tank, the operator should adjust the thickness of the liquid in it to be an odd integral number of half wavelengths thick over the area being viewed. Three thumb screws are provided and three Teflon support bearings, visible in Figure 2, permit the levelling and the setting of the absolute height of the minitank to coincide with that in the ripple tank itself. The thickness is controlled by adding liquid a few drops at a time until the optical background of the Mylar membrane indicates no curvature. Because the Mylar film is only 0.001-in. thick and its acoustic interactions are therefore very small, an alternative procedure has been found to be satisfactory. On occasion, the liquid level has been adjusted to curve the Mylar membrane sufficiently to form the light reflected from the Mylar membrane into a reasonably small image; for example, one-fourth to one-tenth of the size of the water surface hologram. Then tilting the minitank moves this small image of the membrane out of the field-of-view corresponding to the surface hologram; therefore, it contributes no light to the background of the hologram image.

F. Acoustic Damping for Noise Reduction.

Noise is present in the acoustic hologram surface from several sources. The lowest ultimate limit is the thermal agitation of the water surface itself. In any air-conditioned room the air currents will always exceed the thermal limit by a large factor. Shielding the liquid surface from the room air currents will leave building and equipment vibrations, which are also many times thermal, and the principal sources of random acoustic noise.

Equipment vibrations are usually due to cooling fans. In ARTHIR the cooling fan in the power amplifier is the source and the coupling is through the stiff coaxial cable to the reference transducer in the transfer tank. A suitably damped cable support is needed to reduce this source.

Building vibrations are quite significant even in a building where the floor is a concrete slab on the ground. Significant isolation was obtained for the object tank by using 0.4-in. thick rubber pads under the leveling feet of the tank support. More rubber padding may be advisable to realize the full potential of the system's ability to view low contrast flaws.

After all the isolation steps are taken, damping within each of the liquid bodies involved is still needed. The discussion of the target surface area where the pulsed ripple hologram is formed begins here.

If a mini-ripple tank is used, each pulse of ultrasonic energy generates surface waves of several wavelengths. The surface wavelengths correspond to the ripple period (2 mm at 1 MHz to 0.4 mm at 5 MHz) and to the width of the bulge associated with each bright portion of the image (from the resolution limit of a fraction of a millimeter to the full field-of-view of 3 to 4 in.). These waves must be dissipated before the next pulse in repetitive (real-time) operation. The saw toothed sponge and the natural viscosity seem to give a damping time contant as large as several milliseconds for water. This may be adequate for much of the real-time operation planned for the ARTHIR system because the present light source is so bright that single shot camera exposures give excellent contrast. The ultimate performance may require more damping in the minitank but the next improvements would seem to be in order for the larger tanks.

The transfer tank needs a cover for isolation against room air currents in addition to the present internal damping from the batts of rubberized hair. Given such a cover, the existing support foam layers are sufficiently isolating to have the principal source of spurious surface waves be either the power cable to the reflector or pressure waves coming through the water channel from the object tank. The telescope itself serves to isolate the liquid surface of the minitank from room air currents.

The object tank might benefit from a partial cover, but the normal real-time testing operation involves the operator moving the test object either by sliding the object holder through the water or moving his arm through the water to slide the test object across the tank floor. The present damping seems adequate; it includes the following:

1) Masking, for antireflection, the case of the source transducer to reduce the reflected pulse reflected by the test object which would arrive at the target surface before the light pulse does and thereby reduce output contrast.

2) Rubber pads for covering the tank floor and for each of the supports that rest on them.

3) Saw-toothed foam liners for two of the side walls, protruding through the surface and covering most of the side area.

Again the observed time contant is down to a few seconds and appears to be adequate for real-time viewing of test objects with flaws of reasonable contrast.

G. Enhancement by Antireflection Coatings

Increased penetration means more ultrasonic power in the beam transmitted through the test object; it results in the ability to test thicker objects. One of the more promising techniques to accomplish this is using antireflective coatings on each side of the test specimens. Any layer of a material with an acoustic impedance intermediate between that of the test object and that of water will reduce the beam reflection and thereby increase the beam transmission where the layer is made one quarter of an acoustic wavelength thick and bonded well as a coating to the test object. Polyethylene has been tested as an antireflective coating for silica. At 3 MHz a quarter wave plate is 0.30-mm thick.

Markedly enhanced transmission was found through a silica test plate where a quarter wave layer of polyethylene was stuck on one face with aqua gel. The acoustic impedance of polyethylene is approximately $2.7 \times 0.9 = 2.5$ gm mm/cm^3 μsec. The acoustic impedance of silica ranges from $5.7\ (2.2) = 12.7$ gm mm/cm^3 μsec for optical grade fused silica to $4.0\ (1.92) = 7.7$ gm mm/cm^3 μsec for the porous silica used in missile radomes. Therefore, the 2.5 value for polyethylene is very close to the ideal intermediate impedance of $(1.5 \times 7.7)^{1/2} = 3.4$. Polyethylene is close enough to the optimum value for an antireflective coating between radome silica and water to give an enhancement factor greater than five in transmitted power through a silica radome.

III. THE OPTICS SYSTEM

The purpose of the optics within ARTHIR is to detect and to display and/or to record the liquid surface acoustic hologram formed on the surface of the transfer tank. The requirements for detection of the acoustic image include the following:

a) Illumination of the entire hologram with light of one wavelength having sufficient coherence to form a well-defined diffraction pattern from the surface ripple.

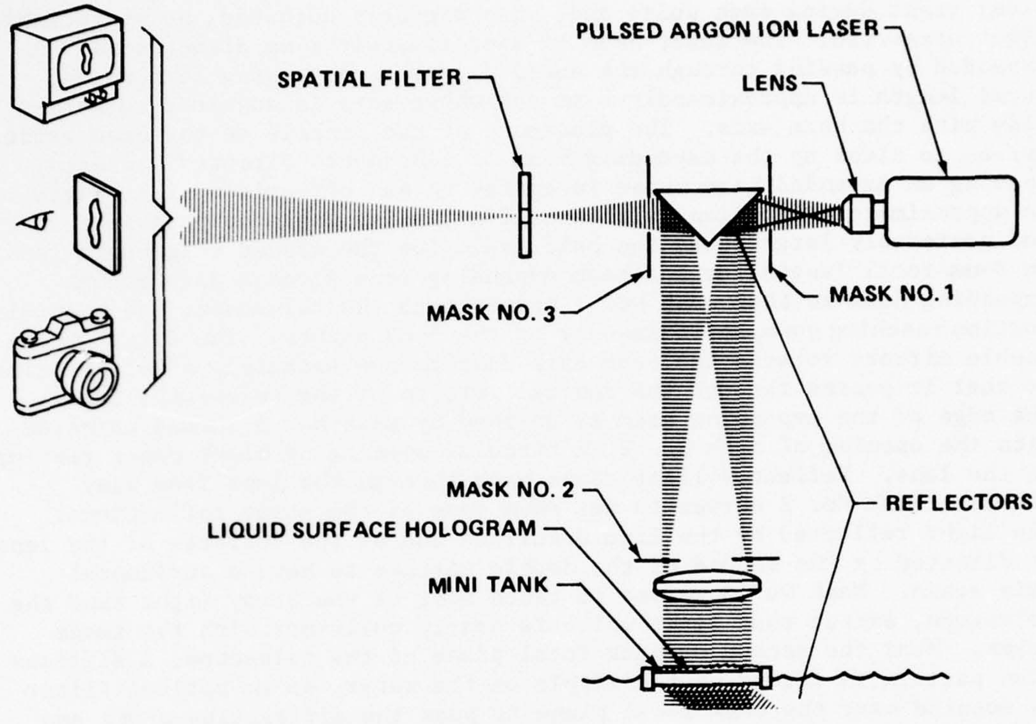
b) Viewing of the entire hologram through the desired optical filters with a camera appropriate to the mode of output; real-time or single shot and recording or viewing.

The quality of the optical elements needs to be high enough to permit the illumination, filtering, and recording or viewing to be done without contributing much to the noise level in the image of the test object formed in the acoustic hologram. Specifics are discussed in this section with the aim of guiding the operator through successful alignment and operations and of guiding the engineer responsible for making the next improvements to the optics system of ARTHIR through economical steps toward better contrast.

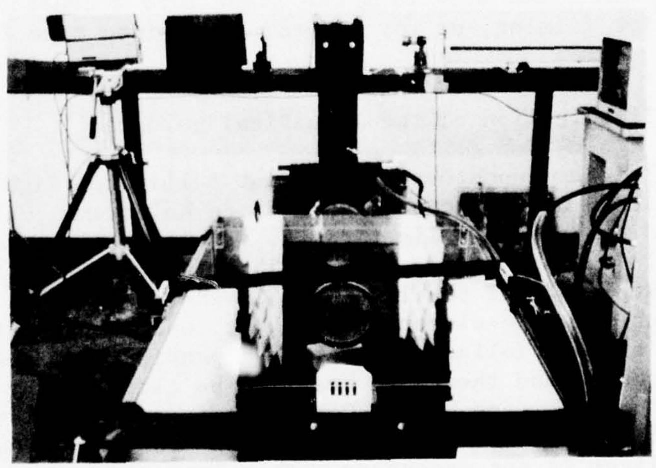
A. Elements of the Optical System

The arrangement of the optical elements of ARTHIR is shown in Figure 16 (a) schematically and in Figure 16 (b) photographically. Adjustments and other specifics are discussed in the following sections. The functions of these optical elements are discussed here.

The overall functions of detecting, displaying, and/or recording the acoustic ripple hologram in ARTHIR are done in real-time or with a single shot by choice of the operator. The detection process starts with illumination of the hologram, continues by the collection of the reflected light aimed through an appropriate optical filter, and ends with imaging the filtered light onto the detecting surface — TV camera, photosurface, viewer's eye, or the photographic film in a recording camera. Display for real-time is most easily accomplished by viewing the filtered image on a white paper screen. Display for real-time is also readily accomplished, with the option of remote viewing, by use of the TV camera and monitor. Photographic recording is readily accomplished by passing the filtered light directly through the camera lens to the photographic film, for single shot records or for lapsed time simulation of real-time acoustical inspection.



(a) SCHEMATIC



(b) OPTICAL ARRANGEMENT VIEWED ALONG THE DIRECTION OF THE ULTRASONIC OBJECT BEAM.

Figure 16. Arrangement of the optical system

The pulsed laser source emits a well-collimated beam of green (or blue) light during each pulse and, when properly adjusted, no appreciable light otherwise. The laser beam of approximately 2-mm diameter is expanded by passing through the small diameter converging lens whose focal length is approximately 8 mm and whose axis is adjusted to coincide with the beam axis. The placement of the pinhole at the beam waist serves to clean up the expanding beam of components directed off axis, leaving an expanded beam whose intensity versus off-axis conical angle is approximately Gaussian, with a half-intensity angle comparable to and preferably larger than the half angle for the masked telescopic lens. An 8-mm focal length for the beam expanding lens gives a wide enough expanding beam so that mask No. 1 passes into the telescope, the central portion reaching down, approximately to the 3-dB points. The first of the double mirrors rotates the beam axis down to approximately 4° off vertical so that it passes through the central portion of the telescopic lens. The edge of the expanding beam as defined by mask No. 1 should coincide with the opening of mask No. 2, a circular opening of black paper resting on the lens. Reflected light comes back through the lens from many sources; mask No. 2 serves to cut down some of the stray reflections. The light reflected by the liquid surface and by the surfaces of the lens is directed by the second of the double mirrors to have a horizontal axis again. Mask No. 3 serves to catch most of the stray light from the telescope, except that light which is nearly collinear with the image beams. Near the second or back focal plane of the telescope, a diffraction pattern is formed by the ripple on the water, so an optical filter is mounted near the back focal plane to pass the diffraction spots and to block the zero order and as much of the stray light as is feasible. Viewing then calls for a screen or the TV camera chain. Recording, on the other hand, calls for directing the light into a camera for still shots, lapsed time filming, or for recording on video tape from the TV chain.

B. Illumination of the Acoustical Hologram

Bright monochromatic coherent collimated light is desirable for the illumination of the acoustical surface hologram. Collimation is readily obtained by forming a light source at the focal point of the telescopic lens. The present compromise is to form this apparent light source approximately 4° off the lens axis in the front focal plane. The existing lens is a two-element telescopic lens with D = 6 in. and F = 30 in. The pinhole following the beam expanding lens serves as the apparent light source and therefore needs to be close to the front focal plane of the telescope lens. Coherence is sufficient with a rather large pinhole; 10-μm diameter pinhole has been found to be satisfactory. Monochromatic filter is not necessary with a laser source.

Brightness is a compromise. If high brightness were inexpensive, the adjustment would be to spread out the pulsed beam from the laser with a very short focal length lens and allow only a small portion of the uniform center to pass through mask No. 1 into the telescope. However, brightness is expensive, so the beam is expanded only a small factor (such as two-times larger than the angle of acceptance of the telescope.

For the existing lens with a 4-in. mask, this half angle of acceptance is 4/60 or 0.066 rad, so the choice of 8-mm focal length for the beam expanding lens spreads out the beam to where it has fallen to approximately half intensity (3 dB) at the edges of masks No. 1 and No. 2. If a more uniform illumination of the hologram surface is needed, then brightness will have to be sacrificed and a shorter focal length beam expanding lens used in front of the pinhole source.

Timing of the light pulse consists of setting the delay of the light pulse beyond the reference drive pulse. Values for apparently the best contrast are typically near 300 μsec. The length of the light pulse is presently fixed at approximately 300 μsec. It is possible that some improvement can be attained by adjusting this width.

Alignment starts with leveling the optical bench and the laser beam, before its expansion. To do this, it is recommended that the holders for the beam expander lens and for the double mirror be lifted off the optical bench so that a long length of the narrow beam can be leveled. After leveling, the double mirror mount should be restored so that the angles of the mirror and the level of the mirror carriage can be set to give a horizontal laser beam out of the second mirror, while striking very near the center of the lens in the telescope. After the narrow laser beam in the region of the back focal plane is reasonably close to level, the beam expander and pinhole are inserted and adjusted so that the axis of the beam out of the laser and the pinhole is centered on the focal point or beam waist following the beam expanding lens.

The final adjustment for illumination is then to choose the size and set the position of mask No. 1 in front of the first mirror so that its edge allows a slight amount of light to fall on the edge of mask No. 2 resting on the telescope lens. Mask No. 2 should be no more than a 5-in. diameter for the existing lens and preferable not more than 4-in. diameter to keep down the astigmatism of the inexpensive spherical lens being used. For acoustical magnification near unity, the hologram intensity falls off severely at the periphery of the 4-in diameter; therefore, a diameter between 3 and 4 in. for mask No. 2 is a good match.

C. Formation of the Optical Diffraction Pattern from the Surface Hologram

The surface of the liquid is essentially flat and reflects only a small fraction of the incident light. For water, only 4% is reflected. Of this reflected light, a small fraction will be organized into a simple diffraction pattern provided that the illumination is sufficiently monochromatic and coherent. When there is no test object in place and the two acoustic beams are set to have equal amplitudes below the saturation of the liquid, the uniform ripple pattern on the liquid surface is expected to produce a single row of bright spots in the plane containing the angle of incidence of the reference beam, θ_{ref}. The first order spots are separated from the central, zero order spot by the spacing, s, given by

$$s = \lambda \frac{F}{Y_F} \quad . \tag{5}$$

For the argon laser beam λ = 514.5 nm and the values of s range, for the F = 30-in. = 760-mm telescope lens, from 0.18 mm for 1 MHz, 0.53 mm at 3 MHz, to 0.90 mm for 5 MHz. If the ripple is sinusoidal, the two first-order spots will be the only ones generated.

The light intensity in these first-order spots from a uniform ripple grating may reach several percent of that in the central bright spot. When a test object is in place, the transmitted image will have patches of ripple of the same ripple period, Y_R, but the diffraction pattern will be a lower intensity corresponding to the smaller fraction of rippled area. The detection problem is to reform the image information contained in these diffraction spots in the face of stray light and spurious light which is much brighter than the whole image.

1. Optical Filtering and the Influence of the Astigmatism of the Telescope on the Diffraction Pattern

The spherical astigmatism of the existing telescopic lens is more severe as the opening in cover mask No. 2 is made larger. The effect of spherical astigmatism is to defocus the diffraction pattern spots in the back focal plane and to form them into the shape of short narrow bars oriented radially (sagittal) just beyond the back focal plane and oriented tangent to the circumference just short of the back focal plane. A clear explanation is given in many optics textbooks [4].

The spherical astigmatism of the present lens is sufficiently severe with the 4-in. diameter opening to produce the narrowest bars at approximately 0.3 in. off the back focal plane. The operator must therefore locate the back plane filter to exclude the zero spot, which is itself a bar due to the 4° offset being used, and pass the first-order bars. The shape of optical filters found to be convenient is a straight wire stretched across a small circular opening in a large disc. It is convenient to form the filters by gluing a section of wire across the opening in a metal washer and spraying the assembly black. Often the addition of opaque straight edges parallel to the line of centers of the diffraction pattern is a significant aid in reducing stray light when passing the tangential bar pattern. Typical values are an optimum wire diameter around 0.04 to 0.05 in. for 3 MHz and a separation of the opaque straight edges of 3 mm.

The primary adjustment of the filter is to place the wire across the central spot (bar) and between the two first-order bars to exclude the bright background light from the flat water. This is easily seen during the TV viewing of the reconstructed image of the hologram. The preferred orientation is to have the wire parallel to the length of the bars. The secondary adjustment of the optical filter is then to shield the image from stray light as discussed in the next section.

2. Suppression of Stray Light

The operator of ARTHIR can readily discern the presence of stray light in the output image of the transmission of a thin test object from the gray appearance of the areas in the pattern that should be black on the TV monitor or in the single shot photos. This stray light should be reduced to the point where the contrast in the output image for one of the foamed plastic test objects is controlled by the surface of the water or other liquid, and not by stray light in the optical system.

Contrast is usually defined in terms of the light intensities in the output image by the visibility, V as

$$V = \frac{(I_b - I_d)}{(I_b + I_d)} \qquad (6)$$

where I_b and I_d are the intensities in the bright and dark areas of interest. By using a thin test object such as the wide bars cut through foamed plastic sheets for which the acoustical contrast is high (V near unity), the operator can seek high visibility in the output image by reducing stray light that may be present.

This stray light comes form from many different sources. Suggestions for suppressing the light from each identified source are discussed separately here.

a. Stray Light from Dust

Perhaps the ultimate source of stray light in any large optical system is dust. Dust particles are particularly effective in reducing contrast in a coherently illuminated optical system such as the one in ARTHIR. Every particle on the edge of an aperture stop and every dust particle anywhere that gets illuminated will spread its diffraction pattern all across the exit of the optical system. Dust and other particles are particularly disturbing in ARTHIR when they are on the liquid surface or on the surfaces of the telescopic lens. Care must be taken to reduce their populations in ARTHIR initially and during operation.

b. Stray Light from Spurious Water Waves

Assuming that the liquid surface is free of dust and can be kept free, the next limit of stray light should be the light from spurious surface waves on the liquid in the hologram area that gets around the zero stop filter. Effort to preserve the isolation and damping is appropriate, as discussed in Section II. The two steps that would appear to pay immediate benefits in image contrast are as follows:

1) To use a cover over most of the transfer tank primarily as a windshield. Such a cover could also be useful in keeping out dust.

2) To use a vibration absorbing support for the power cable to the reference transducer.

c. Stray Light from Surfaces of the Telescope

The existing lens is comprised of two elements. Each of the four surfaces has a broadband antireflection coating which reduces the normal 4% reflected intensity down to approximately 0.5%. The reflection from the top convex surface is not particularly troublesome, except for the dust. Reflections from the other three coated surfaces add up to strong background light. To improve the output contrast by reducing this stray light requires the replacement of the present lens by another whose antireflection coating has been specialized to blue-green, and therefore will have reflected intensity from each surface down to 0.1%; the cost of such coating should be small. The present compromise coating allows operation of ARTHIR with an He-Ne laser as a source.

Stray light can also be scattered off the black inside surface of the 7-in. diameter telescope housing. Adequate reduction can apparently be attained by masks No. 1, 2, and 3, where appropriately positioned.

d. Stray Light from the Room

Dark walls adjacent to ARTHIR plus black cardboard covers for most of the optical bench should reduce the stray light from the room down to a negligible level. This is especially important when the TV camera is focused on a diffusing screen. It may even help eventually to shield most of the water system of ARTHIR from room light during operation at the best contrast sensitivity.

e. Stray Light from the Membrane on the Minitank

As discussed in Section II, the Mylar membrane on the minitank reflects a noticeable amount of the laser light. To minimize the effect of this stray light, i.e., to keep it out of the dark areas of the desired image, it has been found useful to raise the level of the liquid in the minitank above that of the ripple tank so that the image of the membrane is small and then tilt the minitank so that this membrane spot is outside the desired image.

D. Optical Reconstruction of the Image

The usual form of the output of ARTHIR is an optical image of the acoustic surface hologram, bright where the ripple is strong, dark where there is no ripple, and shades of grey in between. To adjust the optical output configuration (filter and camera), it is useful to start with a view of the diffraction pattern magnified.

1. Setting the Filter by Viewing the Diffraction Pattern

A useful way of setting the position of the back-plane optical filter and of deciding on any refinement to its shape is to form the image of the diffraction pattern by placing a short focal length lens behind the optical filter at slightly more than one focal length downstream. Viewing the output image will show the enlarged diffraction pattern with the edges of the optical filter clearly defined. Once the best position and shape are attained, removal of the short focal length lens without moving the optical filter will permit viewing of the reconstructed image.

The reduction of stray light by the circular aperture stop of mask No. 3 can perhaps best be judged while viewing the magnified diffraction pattern. The final check is its influence on the final contrast in the holographic image.

2. Optical Magnification

The light coming through the back-plane filter has been focused by the telescopic lens, whose focal length is F = 30 in. If the black cover on the optical bench were sufficiently light tight, an enlarged image could be recorded directly on film at locations farther than 30 in. beyond the back focal plane. Using a camera set for focus at infinity gives a reduced size image on the filter. Using a camera lens with a focal length of 8 in. located at 8 in. beyond the filter will produce the image at a magnification of 8/30 or 0.27.

Care must be taken to preserve the contrast of the hologram while seeking a convenient optical size of the output image.

3. Viewing on the TV Monitor

Each pulse of light that passes through ARTHIR's optical system is approximately 300 μsec long. The normal scan of a single TV line takes approximately 60 μsec. Therefore, the TV camera will see only five TV lines or approximately 1% of the field-of-view during each pulse. Asynchronous operation of the TV scan requires that many hundreds of pulses are scanned before the scanning will cover the whole image. This effect becomes clear in the operation of ARTHIR with TV viewing by the strong increase in the brightness and contrast as the pulse repetition rate is increased over the rate of 60 Hz.

Contrast can be improved with TV viewing by directing the filtered beam into the TV camera lens without an intermediate screen. The large improvement available in direct viewing is probably worth the effort required in avoiding burnout of the TV camera. The most convenient real-time recording is by means of video tape output of the TV camera.

4. Image Enhancement by Means of the Computer Controlled Fringe Reader

The output images that ARTHIR produces from high contrast test objects have high contrast and are usable for analysis of the test object as produced. For test objects with lower contrast — for example, flaws with smaller reflection coefficients — the output images of ARTHIR will still have a speckle background from the near-field pattern used to insonify the object after all of the spurious noise is suppressed. Improvement of the flaw detection should be attained for these cases by recording the output images with and without the test object and using the Optical Fringe Reader as controlled by the PDP 11-40 computer to subtract the background from the test object's output image.

IV. ELECTRONICS SYSTEM IN ARTHIR

The novel feature of ARTHIR is its high power wide ultrasonic beams. Supplying the RF power to the large diameter ultrasonic transducers under appropriate timing control is one of the principal functions of the electronics system. The other is to control the timing of the pulsed laser source.

The purpose of this section is to outline the procedures for operating the electronic controls of ARTHIR for the inspection of a test object. The control panel contains the following controls:

a)	Frequency of ultrasonic:	Choice of 1, 3, 5, or 7 MHz. Selection requires similar setting of switches on the rear of the RF power amplifiers.
b)	Repetition rate:	Choice of line frequency or variable frequency, from approximately 1 to 300 Hz.
c)	Width of ultrasonic pulses:	25 to 850 μsec, continuously variable.
d)	Delay for light pulse:	100 to 1000 μsec, continuously variable.
e)	Delay of reference pulses:	200 to 1700 μsec, continuously variable.

Typical operation of these controls for successful holographic image recording and viewing is discussed in the following paragraphs of this section. Detailed information for electronic servicing is given in Reference 1.

A. Choice of Ultrasonic Frequency

The reason for selecting one of the available electronic frequencies for the ultrasonic beams is a tradeoff between resolution and penetration. The higher frequencies generally give better resolution and worse penetration. The converse is also true. The frequencies available in the existing electronics system are 1, 3, 5, and 7 MHz. The present quartz transducers resonate at 1.0 MHz; selection of one of the higher frequencies means tuning the RF power amplifier to a harmonic of the transducer's fundamental frequency. The requisite cabling from the power amplifiers to the immersed transducers gives successively smaller power limits as the frequency is raised. The limit of the driving voltage is approximately 5000 V; the limit of the power delivered at 3 MHz before saturation of the water surface begins is well below 300 V with no test object in place.

Perhaps the strongest reason for choice of frequency is the need to separate the diffraction orders in the presence of the astigmatism and aberrations of the present telescope lens. Separation is easy at 3 MHz and above, and very difficult at 1 MHz, as noted in Section II. If the telescopic lens had a 60-in. focal length, the separation at 1 MHz would be manageable. A lower frequency is preferable for better penetration of the class of test objects which contain many microscopic scattering centers, such as epoxy filled fiber glass and slip cast fused silica. The lower frequency ultrasonic waves are scattered much less than the higher ones when the dimensions of the individual scatters is small compared to the wavelength, whereas reflection from large flaws is essentially independent of wavelength. When flaw dimensions are comparable to the wavelength, as they might be for the 1.5-mm wavelength of 1-MHz waves, there is a weak dependence on wavelength.

Another consideration for choice of frequency may be resolution. When the acoustic system is operating near its diffraction limit as it appears to be currently, then the size of the minimum flaw that can be resolved is proportional to the ultrasonic wavelength. An estimate of the diffraction limit has been given in Section II as approximately 1.7 mm for one arrangement of ARTHIR. It is clearly possible to resolve flaws closer together than this but only at reduced contrast or with computer aided image processing.

When operating at 1 MHz, additional capacity is needed in the RF power amplifier tank circuits and is supplied by the power amplifier mounted just below the control panel. At each frequency, tuning is required to attain reasonable power transfer to the quartz crystals.

B. Repetition Rate of Pulses.

For single shot recording, a slow repetition rate is chosen and the camera shutter is set for one cycle time. Line frequency is satisfactory with water as the liquid. The lower limit near 1 Hz is slow enough to be satisfactory for denser or less viscous liquids.

For real-time operation, the repetition rate is chosen which gives reasonable brightness. If care has been taken to reduce stray light as discussed in Section III, then operation at or near line frequency should be adequate to give TV viewers a full image every second or so. Brightness will increase as the repetition rate is increased, but contrast will diminish toward the high end of the control knob. The probable cause of this reduction in contrast at high repetition rate is the remnant surface waves from pulse to pulse.

For lapsed time photographic recording, the slower repetition rate is preferred because of the higher contrast in the output image. Each frame should be exposed to a single pulse of light for the test object in a new position.

C. Width of Ultrasonic Pulse

The rationale for setting the width of a low power ultrasonic pulse into the source transducer can be simply to set the pulse width larger values while the repetition rate is low until the TV monitor shows no further increase in brightness. This will be sucessful provided that the rest of the system is in reasonable adjustment.

The theoretical basis for expecting improved brightness with a longer pulse is that the ballistic response of the liquid surface to a short input pulse is slow and is proportional to the impulse, that is, the integral of the momentum transferred over the length of time the pulse is on. Therefore, in the range where the pulse length is much shorter than the ballistic response time of the liquid surface, a longer pulse will produce a larger liquid elevation in the ripple and therefore brighter image out. Experimentally, the best delay time for the light is several hundred microseconds for water; this corresponds to the effective ballistic response time to a single ultrasonic pulse. Even for low power, the best pulse length for the ultrasonic object beam will be not much over 100 μsec. The electronics is arranged with only one RF oscillator for which the two RF power amplifiers are fed, so that the pulse length for the reference beam is identical to that of the object beam.

At higher ultrasonic power, a shorter pulse will give the same impulse and thereby the same amplitude of ballistic elevation in the delayed ripple. If there is significant noise in high frequency water waves, the shorter pulses should give the acoustical image in the hologram better contrast

It is easy with ARTHIR to raise the amplitude of the ripple too high; at this threshold, the liquid surface forms ridges which emphasize the irregularities due to the near-field Fresnel patterns in the beams. Increasing the pulse length does the same thing.

It is essential to remember while adjusting under TV viewing that the contrast which is best for single shot recording will probably occur at shorter pulses and/or lower ultrasonic power levels than the settings which appear best on the TV monitor.

The width of the light pulse is normally fixed within the electronics to be approximately 300 μsec. Its optimum value will be approximately the value of the best time delay for the light pulse in quiet liquid. If the liquid surface has high frequency surface waves, then a shorter light pulse should give somewhat better contrast.

D. Delay for Light Pulse

The delay, L, of the light pulse beyond the start of the reference pulse should be adjusted when the repetition rate is low and the power settings below those for saturation of the liquid surface. With the current 300-μsec light pulse, the best delay for water is comparable to the pulse length and not critical. If the light intensity is sufficient to give adequate optical exposures with shorter light pulses and if the circuit is changed to produce a shorter light pulse, the adjustment of the delay of the light pulse may become more critical; it will produce better contrast in the output if it does become more critical.

E. Delay of Reference Pulse

The delay, R, of the reference pulse beyond the start of the object beam pulse should be adjusted to compensate for the longer path length of the object beam in the water tanks. The best ripple formation occurs when the two pulses of ultrasonic waves arrive at the liquid surface at the same time.

The tolerance on the setting of the delay depends on the pulse length being used. With the reference beam at 45° and the beam diameter of D_b = 100 mm, the time spread for the arrival of the reference beam is $D_b \tan(\theta_{ref})$ / speed = 100 × 1.0 / 1.48 = 66 μsec on the front and on the trailing edges. Therefore, with a pulse length of 120 μsec, the optimum delay would overlap the pulses so that the leading edge of the reference beam arrives approximately one half of the time spread ahead of the object pulse, approximately 30 μsec early; variations of brightness, s, in the output image from a thin test object with high contrast will appear if the delay adjustment is as much as 30 μsec off. The ten-turn potentiometer control is adequate for this adjustment; a typical value for the object beam traversing one full length of both tanks is a setting of 950 on the control where full scale of 1000 represents a time delay of 1700 μsec. The existing control potentiometer adequately takes care of the tolerance.

F. Ultrasonic Power Setting

The optimum power setting for both ultrasonic beams is strongly sample-dependent. The rationale of seeking the largest ripple amplitude by setting the reference beam intensity to be equal to the intensity of those brightest parts of the acoustic image delivered by the object beam is discussed in Section II. The procedure for setting these two power levels involves setting the two knobs on the power supply chassis (located in the bottom of the rack) in sequence while observing the hologram contrast on the TV monitor, or better yet, the diffraction pattern in the back focal plane. The fraction of light diffracted by the ripple into the first-order spots should increase as the ripple amplitude increases starting from zero. As long as the two ultrasonic beams form a sinusoidal ripple, there will be only the first-order spots in the diffraction pattern. For a given power density in the bright parts of the image, the ripple amplitude should be largest for equal reference beam intensity. As the matched beam power of both beams is raised higher order spots become bright as the surface saturates and the rib ripple becomes nonsinusoidal. This coincidence of partial saturation of the liquid surface appears to give brighter TV images but there is no evidence that such operation improves the contrast in single shot, optical, photographic recording. The rationale discussed in the section on the optical system suggests that the best optical contrast following the filter corresponds to sinusoidal ripple.

V. SYSTEM HARDWARE DESCRIPTION

The ARTHIR system consists of the following items:

a) Acoustical holography system.

b) Transducer compensator.

c) Two 500-W power amplifiers.

d) High voltage power supply.

e) Two 5-in. diameter quartz transducers.

f) Object tank.

g) Transfer and minitank assembly.

h) Optical bench.

i) Model 166-03 argon ion laser (4 W continuous wave).

j) Closed circuit TV optical accessories.

More complete details of the hardware are given in Reference 1 including wiring diagrams, schematics, and catalog data.

The real-time acoustical holography system is illustrated in Figure 17. An object to be examined is submerged in a tank of water which is insonified by an ultrasonic beam. Sound waves passing through the object are focused into a smaller, second tank and are made to interfere with another ultrasonic beam of equal or nearly equal frequency. The region of interference is covered by a plastic membrane which supports a shallow pool of Freon 113. A hologram of the submerged object appears as ripples on the upper surface; this hologram is read out optically by a properly-timed flash of coherent light from an argon ion laser. Second- or third-order interference products are passed by a spatial filter in the laser beam; an image of the object then can be recovered using a lens and a ground-glass screen or more complex imaging devices, such as a television camera.

When a submerged object is imaged in this way, it tends to become transparent; images of the whole object or any plane within the object can be observed. This facility is useful in conducting NDT of certain materials or living tissue.

The real-time acoustical holography NDT system requires two ultrasonic energy sources: the object beam and reference beam. Because the underwater acoustic path length for the object beam is generally longer than that of the reference beam, the latter must be delayed to assure the simultaneous arrival of the two beams at the liquid surface. Also, the laser readout pulse must be delayed by a period approximately equivalent to the propagation time of the reference beam plus several hundred microseconds to allow formation of liquid surface hologram. The timing relationships of these functions are shown in Figure 18.

VI. ELECTRONIC SUBSYSTEM FUNCTIONS

The purpose of the acoustical holography system is to produce and sychronize three pulse waveforms such that proper excitation is provided for two ultrasonic transducers and one laser configured to generate and read liquid-surface holograms of submerged objects. The transducer pulses consist of keyed, high-voltage RF sine waves at 1, 3, 5, or 7 MHz with continuous and independent pulse width, repetition rate, and delay controls. The laser drive consists of a fixed-width drive pulse whose delay relative to the laser transducer pulse is adjustable. The unit satisfies the timing relationships illustrated in Figure 18.

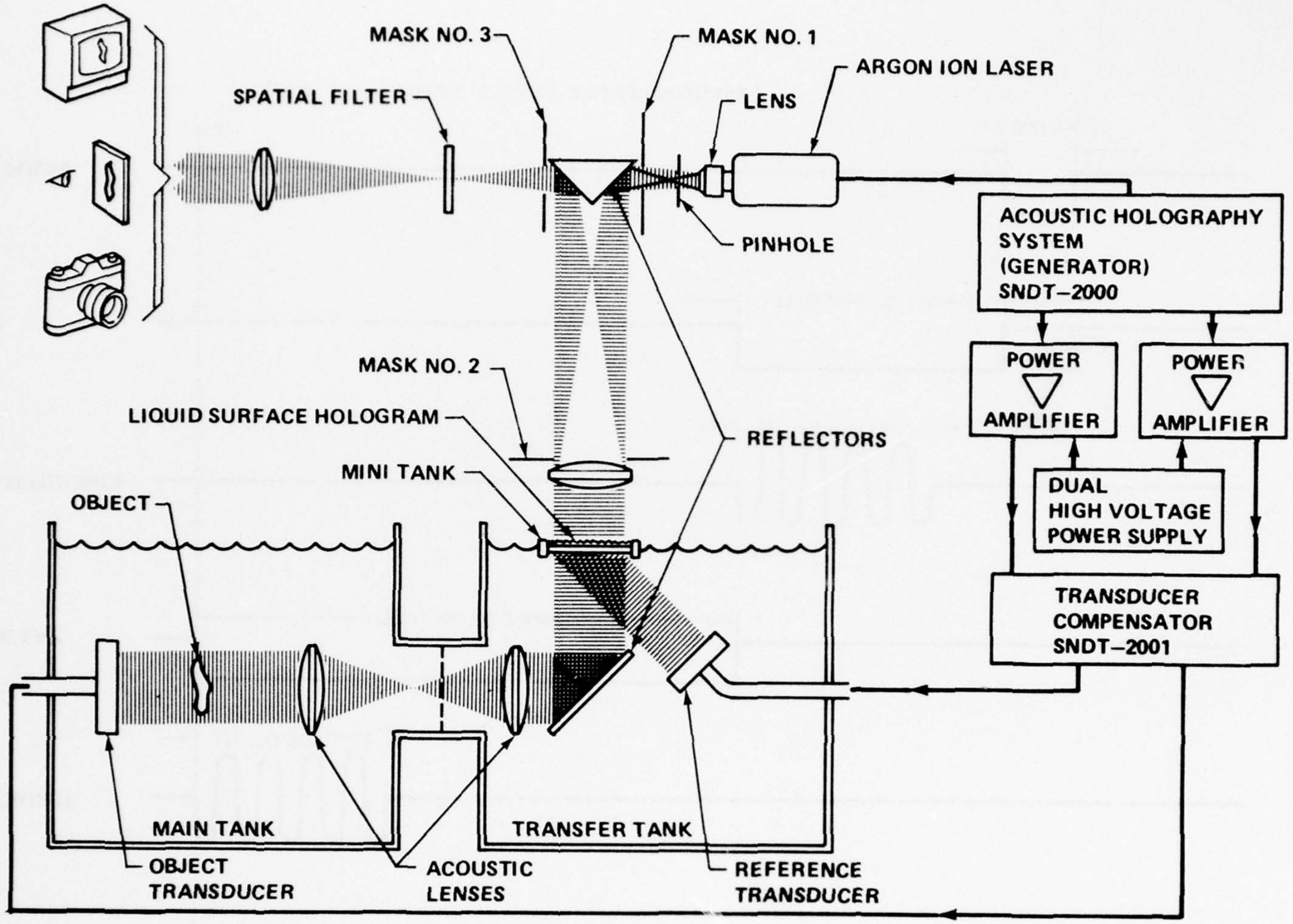


Figure 17. System configuration.

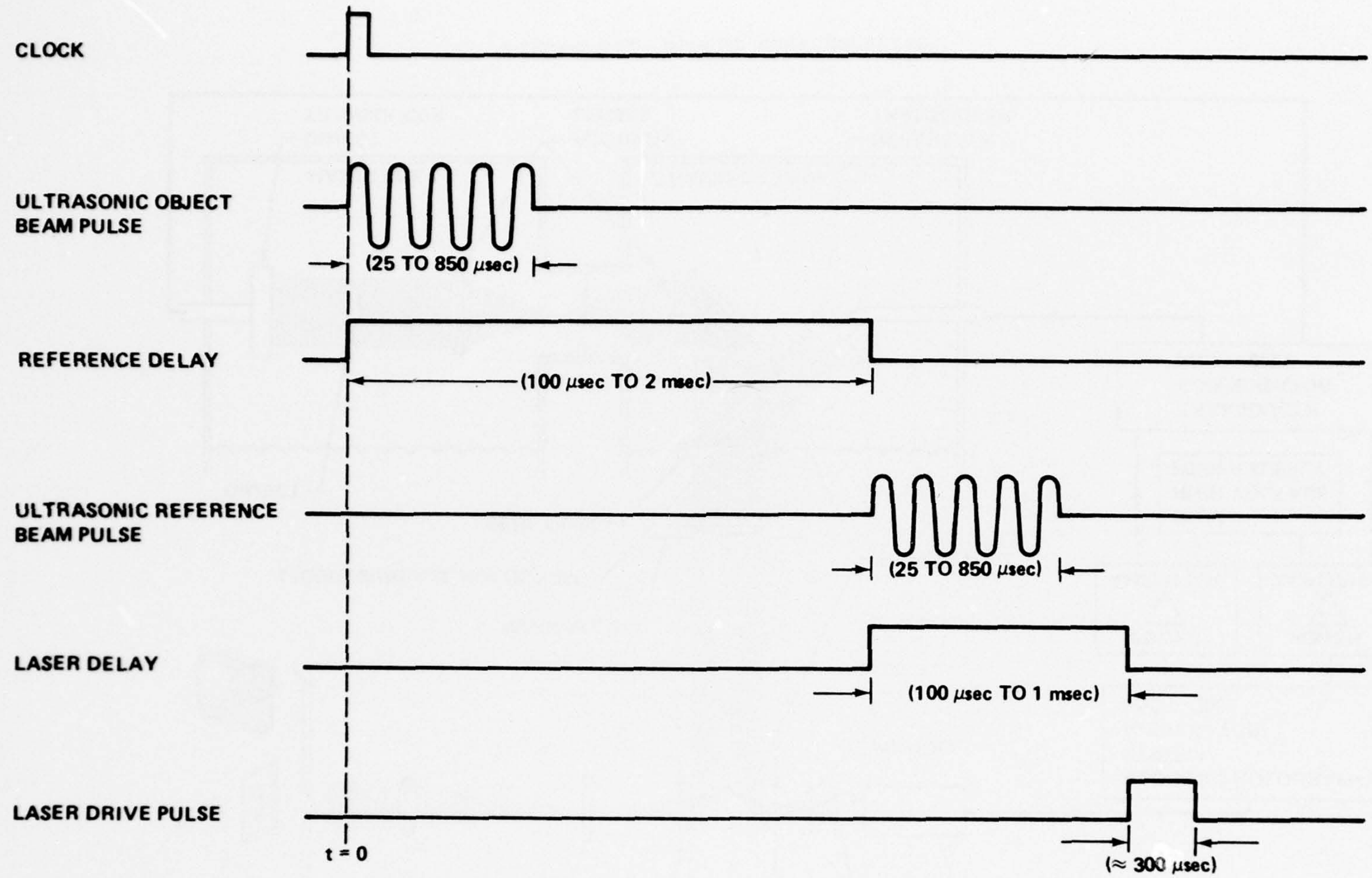


Figure 18. Pulse timing relationships.

Transducer excitation levels are insufficient to drive the 5-in. diameter transducer crystals, which require up to 5000 V peak-to-peak at a resonant impedance of 6000 to 10,000 ohms.

A dual high-voltage power supply was built to operate the two power amplifiers. Each section of the supply is controlled independently by the amplifier to which it is connected. Variable transformers on the supply are used to adjust the high voltage to each amplifier from 0 to 300 V thus providing a level control of the RF pulses supplied to each transducer.

To cover seven octaves (1 to 7 MHz) of tuning range, the output circuit of the RF power amplifiers require approximately 200 pF of additional capacity at 1.0 MHz to match the transducer load. Variable capacity of this amount is provided by the transducer compensator unit when it is connected to the RF power amplifier output circuits. At frequencies other than 1 MHz, the variable capacitors in the compensator are adjusted to their minimum values. At all frequencies, the compensator may be used to fine-tune the power amplifier output circuits.

VII. SUMMARY AND CONCLUSIONS

A complete real-time acoustical holography system was designed, fabricated, assembled, and tested. The size and power output of the transducers and amplifiers exceeds that of other known similar systems. The system produces good results but further small refinements and tune-up of the system should improve it considerably. It has the high power and light capabilities to advance the state-of-the-art in this technological field significantly. The present optics and acoustics are a reasonable match for the transmission pattern of the 4-in. wide region of the test object being insonified.

The acoustics system in the ARTHIR is operating at or very near the best possible resolution. Theoretical diffraction limit is at an acoustic magnification as large as four. For example, at an acoustic magnification near unity, the 3-MHz beam resolves a 1.5-mm bar very clearly. Internal voids in slip cast fused silica approximately 2 mm in size were detected and imaged very clearly.

The highest contrast output was attained by single pulse transmission. The test object was then recorded by a camera whose lens directly accepts the optically filtered laser beam.

It was observed that further improvements in the contrast and penetration can be obtained by use of the following:

a) Quarter wave antireflection coatings on each side of the test objects.

b) A double pass through the object tank at 1 MHz to get into the far field before insonifying the test object.

c) Dust covers to keep out dust in the air currents.

d) Light shields to minimize stray room light.

e) Telescopic lens with antireflection coatings optimized at the argon laser wavelengths.

f) Vibration damping on the power to the reference transducer.

Image enhancement using the computer controlled fringe reader could produce useful mapping procedures for detecting flaws in opaque missile components such as silica radomes.

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