BEAMFORMING AND IMAGING WITH ACOUSTIC LENSES IN SMALL, HIGH-FREQUENCY SONARS

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Abstract - A high-resolution acoustic imaging system is an important aid in turbid water where optical systems fail. Applications include inspecting structures, searching for and identifying mines or contraband on hulls of ships, monitoring work of divers or remotely operated vehicles (ROVs), and monitoring tests in low-visibility water. The three sonars described in this paper use acoustic lenses to form near-video-quality images. The first sonar, Limpet Mine Imaging Sonar (LIMIS), is diver-held, forms 64 beams, each with a beamwidth of 0.35° in the horizontal axis by 7° in the vertical axis. This sonar has a 20° field-of-view, operates at 2 MHz, has a practical range of 10 m, and forms between 5 and 12 images/second. The second sonar, Glendora Lake Acoustic Imaging System, (GLACIS), is used to monitor underwater tests and pans and tilts on a platform that can change depth. This sonar forms 64 beams, each with a beamwidth of 0.55° horizontal and 10° vertical. It has a 32° field of view, operates at 750 kHz, and forms 5 or 9 images/second at an operating range of 60 or 30 m, respectively. The third sonar, Acoustic Barnacle Imaging Sonar (ABIS), mounts on an ROV and forms 128 beams, each with a beamwidth of 0.25° horizontal by 10° vertical. This sonar has a 32° field-of-view, operates at 3 MHz, has a range between 1.8 m and 2.4 m, and forms 6 images/second. All three sonars use a set of thin, acoustic lenses made of polymethylpentene to focus sound on a 1-3 composite linear array. The acoustic lenses form beams at the speed of sound with no circuitry and thus eliminate the complexity and power consumption of conventional beamforming electronics. Two disadvantages are (1) the lenses and the spaces between the lenses add volume in front of the transducer array, and (2) multiple reflections between lens surfaces cause internal reverberation. The reverberation inside these sonars is about 40 dB down from the target echoes and scatters to form a slightly brighter background. No range-shifted “ghosts” of target images are seen.

I. INTRODUCTION

In clear water and with appropriate lighting, optical cameras can image out to 5 m. With increasing frequency, underwater work that would require optical systems is situated in water where optical systems fail. In many rivers, lakes, harbors, bays, and other coastal areas visibility is a fraction of a meter. There, optical systems have white screens, and divers resort to tactile means. The three sonars discussed here use acoustic lenses and bridge the gap between existing sonars and optical systems. Their maximum ranges are relatively small (60 m, 10 m, and 3 m) but their resolutions (0.55°, 0.35°, and 0.25°) allow them to form near-video-quality images. High resolution and a fast frame rate allow them to substitute for optical systems in turbid water. These sonars have a low power consumption (25-30 W), which makes them useful for diver-held operations or on platforms with a power budget.

II. LENS TECHNOLOGY

Acoustic lenses allow both transmission and reception of narrow beams. The lenses operate at the speed of sound, form multiple beams in parallel, and consume no power. Two disadvantages of acoustic lenses are (1) the lenses and the spaces between them add volume in front of the transducer array and (2) multiple reflections between the lens surfaces cause reverberation.

Acoustic lenses are made of plastic, epoxy, rubber, or liquid and refract sound using the same basic laws as optical lenses. The lenses discussed here have a rectangular aperture with curvature only in the horizontal direction. As illustrated in Figure 1, the lenses form a narrow beam of sound in the horizontal plane, and the curved transducer array forms a wide beam in the vertical plane. Each element in the transducer array transmits a short pulse and receives echoes confined within a narrow horizontal direction. The amplitudes and time delays of the echoes are mapped into pixel colors and positions on the sonar display.

A. Lens Design

A lens design must consider beamwidth, sidelobe amplitudes, field of view, and lens efficiency. Designing an acoustic lens begins with optical lens design techniques. There are many optical lens design computer

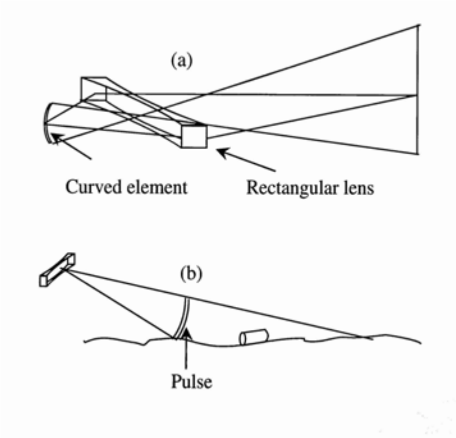

Fig. 1(a). The lens systems use a rectangular lens and curved element to form a focused narrow beam of sound. (b). When a sound pulse exits from the lens, and is directed toward a slanted object plane, it interrogates a narrow line on the object plane as a function of time. The echo response is mapped on the display.

programs. Two such programs[1,2] that run on PCs were used as part of the design of the acoustic lenses described here. A candidate design is found with these programs, which primarily use ray models. Next, a wave analysis model[3,4] predicts the beamwidth, sidelobes, and lens loss for each of the beams formed by the candidate design, and how these beams would change with changes in the salinity and temperature of the ambient water. The wave analysis often indicates that the beam patterns need improvement. If so, new candidates with different lens prescriptions and sometimes different lens materials are designed and analyzed. After several iterations between candidate designs and wave analysis, a successful design prescription is found, and the lenses are fabricated.

B. Lens Transducer Array

The three sonars discussed in this paper all use linear transducer arrays with one element designated for each beam formed in the sonar. The horizontal width of the element is small compared to its height. For example the array on the diver-held sonar consists of 64 elements with a pitch of 1.37 mm and a height of 46 mm. The elements in all three arrays are made with PZT 1-3 composite constructed by the dice-and-fill method. The 1-3 composite allows us to have a wide bandwidth, shape the transducers without much concern about unwanted resonances, and curve the element surfaces to control the vertical beamwidth in each beam. A quarter-wave layer on the array face further increases the array's efficiency and bandwidth.

C. Internal Reflections

We chose a plastic, polymethylpentene (TPX RT-18), for the major component of lens materials in part because its acoustic impedance is close to that of water. Less than 1% of acoustic energy is reflected as sound passes through each water/plastic interface. This is important from the viewpoint of efficiency but even more important from the viewpoint of reverberation within the lens. To measure internal reflections, we transmitted 10-μs acoustic pulses into the sonars. The transducer arrays first received the focused pulse, and then they received a series of pulses that were delayed because of multiple reflections in the lens set. The amplitudes of the first set of reflected pulses were down 40 dB or more from those of the focused pulses. Reflected pulses with exponentially decaying amplitudes continued to arrive for 0.3 ms after the first pulse arrived. Ghosting is a potential problem but has not been seen in the displayed images. The lens reverberation scatters and blurs any potential ghosts, so they manifest as a slightly brighter noise floor, not as a range-shifted image of the object.

III. THREE ACOUSTIC LENS SONARS

A. Limpet Mine Imaging Sonar (LIMIS)

The Limpet Mine Imaging Sonar[5] (Figure 2) was developed, as the name implies, to detect mines attached to hulls of ships. It allows a diver or the operator of a remotely operated vehicle (ROV) to identify mines at distances up to 5 m and to detect mines up to 10 m from the sonar. The sonar display[6] mounts on the diver's mask and, with the help of optical lenses, a virtual image

Fig. 2. A diver views images from the LIMIS diver-held sonar through a mask-mounted color video display.

appears a comfortable distance in front of the diver even in zero visibility water. The high resolution and rapid update rate of LIMIS make it a viable replacement for a video system on underwater vehicles in turbid water.

LIMIS measures 17.8 cm wide, 20 cm high, and 36 cm long, including a 10-cm handle. It weighs 7.7 kg in air and is 100 g buoyant in seawater. A set of acoustic lenses (Figure 3) occupies the upper, rectangular region of the sonar, and electronics occupy the lower region. LIMIS operates at 2 MHz, forms 64 beams with beamwidths of 0.35° in the horizontal axis by 7° in the vertical axis, and consumes 25 W. Figure 4 shows three LIMIS images. Their near-video quality is very important because divers and ROV operators want to positively identify the objects they are imaging. LIMIS provides a smooth display of dynamic scenes with updates of at

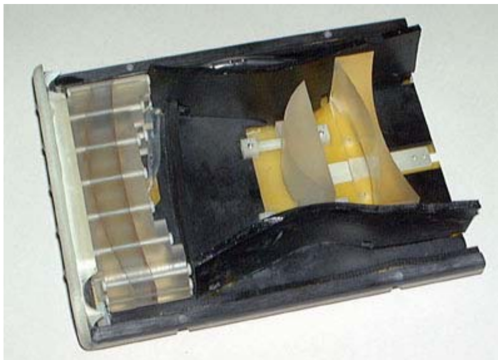

Fig.3. The lens set begins with a triplet plastic-liquid-plastic lens (left side of the photo) followed by two plastic lenses. The transducer array (not shown) fits in the rectangular opening on the right side of the housing. When the sonar is submerged, ambient water fills the spaces between the lenses and the transducer array.

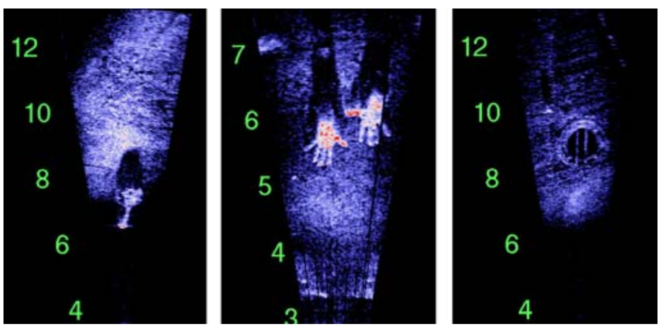

Fig. 4. Three sample images taken with LIMIS. The left image shows a limpet mine on the hull of a ship 7 feet from the sonar. The center image shows two hands. The right image shows an intake on the hull of a ship. The intake is approximately 46 cm in diameter and is 9 feet from the sonar. The left and right images were taken in Chesapeake Bay in water with 15-cm visibility.

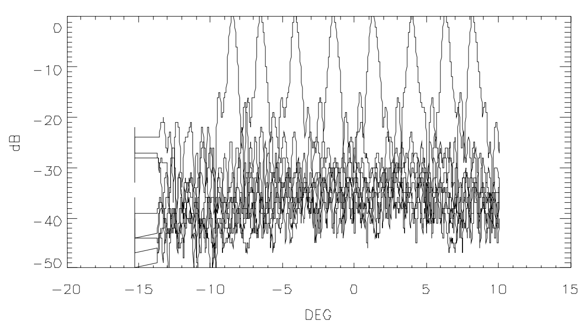

Fig.5. Eight of 64 beam patterns of LIMIS collected at APL's Acoustic Measurements Facility. Beamwidths are 0.35° and sidelobes are down between 16 dB and 18 dB.

least 11 images/second for targets 8 m or less from the sonar. Figure 5 shows one set of eight of the 64 beam patterns.

B. Glendora Lake Acoustic Imaging System (GLACIS)

The Naval Surface Warfare Center's Glendora Lake Facility (GLF) in Sullivan, Indiana, monitors and measures the motions and configurations of objects under test with GLACIS (pronounced "glasses"). GLACIS consists of a sonar mounted on an underwater platform (Figure 6) and a control and display station separated from the platform by 500 ft of cable. The operator in the control room can pan and tilt the sonar on its platform and raise and lower the platform in the 100-ft water column. The sonar operates at 750 kHz and forms 64 beams, each 0.55° horizontal by 10° vertical. GLACIS updates images with ranges out to 60 m five times per second and images with ranges out to 30 m nine times per second. The field-of-view is 32°. Figure 7 shows the horizontal beam patterns of the 32 even-numbered beams. Note that the sidelobes are down almost 30 dB. The GLACIS lens set (Figure 8) uses an epoxy lens (L1) to reduce the sidelobes. The other lenses are made from polymethylpentene. Figure 9 shows the GLACIS shore display that gives the platform and sonar parameters (such as depth, heading, pitch and roll) as well as an acoustic image. The resolution of GLACIS is demonstrated in Figure 10, which shows the image of an Air Deployed Active Receiver (ADAR) sonobuoy. The image indicates that the five arms have deployed and the bright spots on the arms indicate the locations and separations of the articulated joints.

C. Acoustic, Barnacle Imaging Sonar (ABIS II)

At the time of this writing, ABIS II is beginning in-water tests. ABIS II will image fouling, damage, and foreign objects on hulls of ships. The sonar will mount on an ROV and will be used to determine what sections of the hull need to be cleaned, initially with an operator in the loop and ultimately only with pattern classification methods. The system will work in zero visibility water. The sonar operates at 3 MHz and has 128 beams, each measuring 0.25° horizontal by 10° vertical. The sonar has a 32° field-of-view and updates at the rate of 6 images/second. Figure 11 shows the soundhead and electronics module. The division into two modules gives more flexibility in placement on a submersible. Figure 12 shows the ray diagram of the lens set for beams spaced between 0° and 16° off-axis. The predecessor[7] of ABIS II has four mechanically scanning elements and updates images at the rate of 2 images/second. ABIS II has no moving parts and three times the update rate. The quicker updates will improve feedback needed for navigation and pattern recognition.

Fig. 6. Glendora Lake Acoustic Imaging System. The sonar mounts on a platform that is 27-kg positive. It moves up and down the water column by reeling out and in three weights resting on the lake bottom.

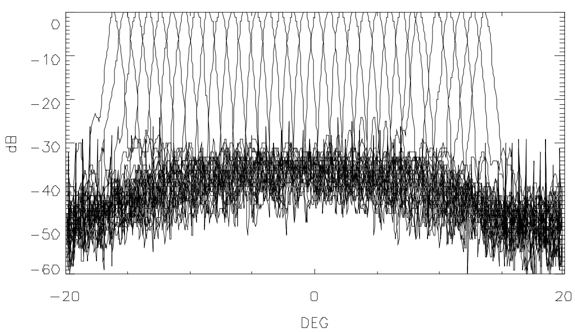

Fig. 7. Beam patterns of 32 even-numbered beams from the 64-beam GLACIS sonar. The beamwidths are 0.55° and the sidelobes are down 30 dB.

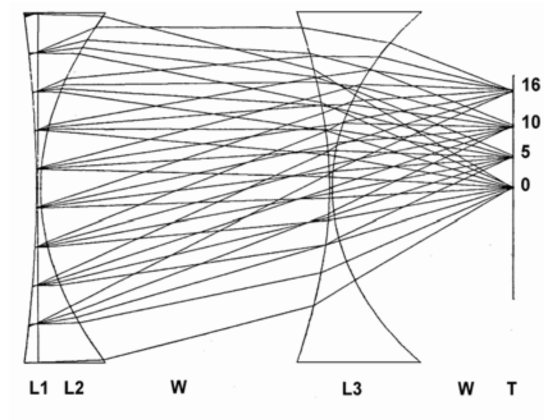

Fig. 8. A diagram of the GLACIS lens system. L1 is an epoxy lens used primarily for reducing the sidelobes. L2 and L3 are lenses made from polymethylpentene. Four wavefronts, arriving 0°, 5°, 10°, and 16° off-axis are traced to the transducer array, T, where they focus in four unique locations. Water, W, fills the spaces between the lenses and the transducer.

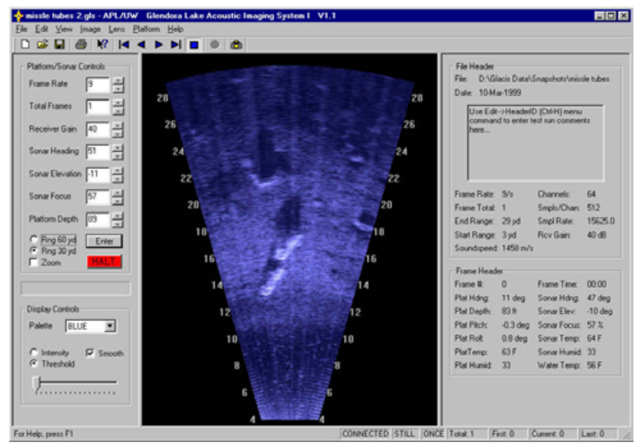

Fig. 9. The shore display for GLACIS allows the operator to control the platform and sonar, read their status, and observe and store sonar images. In this case, the image is of two missile tubes on the bottom of the lake.

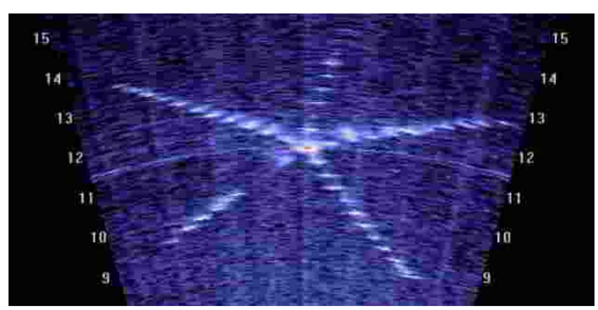

Fig. 10. GLACIS image of an ADAR sonobuoy showing five arms that hold an array of transducers. The bright returns reflect off joints in the articulated arms and allow detailed analysis of proper extension.

Fig. 11. The ABIS soundhead and electronics module form a forward-looking sonar that mounts on an ROV. The ROV will inspect hulls for fouling and clean selected sections. The images will update 6 times/second and provide 1-cm resolution at 3-m range.

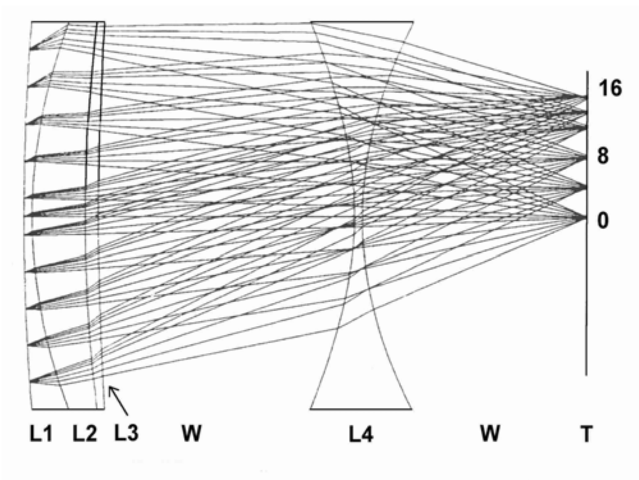

Fig. 12. A diagram of the ABIS lens system. L1, L2, and L3 form a lens triplet. L1, L3, and L4 are made from polymethylpentene. L2 is a fluid, FS-5. Six wavefronts 0° to 16° off-axis are traced to the transducer array, T, and focus at unique locations. Water, W, fills the spaces between the lenses and the transducer array. ABIS forms 128 beams over a 32° field-of-view.

IV. CONCLUSIONS

Acoustic lenses make very good beamformers. They require no power and can transmit or receive many beams simultaneously. They simplify the electronics because they eliminate the high-speed sampling and signal processing required in digital beamformers. The lenses described here have all been machined. If lens sonars were mass-produced, lenses could be injection molded for additional savings in fabrication costs.

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