A highly directional transducer for multipath mitigation in high-frequency underwater acoustic communications

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Abstract: This paper presents a transducer design of the hollow cylinder type designed to minimize transmission multipath and the need for channel equalization over short acoustic communication distances in shallow water. Operating at 750 kHz, the half-maximum envelope of the main lobe is approximately 3°. The transducer was incorporated into a low-complexity modem system in which it acted as both transmitter and receiver. At-sea testing indicated that the system is capable of operating over horizontal distances of 5 m without evidence of multipath distortion. The system was also found to be effective as an omnidirectional transmitter/receiver in the 10–60 kHz band.

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1. Introduction

Most shallow underwater environments act as a waveguide in which indirect acoustic arrivals from a point source arrive at a receiver a short time after the direct signal. In addition, the indirect arrivals suffer relatively little attenuation in comparison to those in deep water. Such an environment poses a challenge to acoustic communications (ACOMMS) as temporal overlap between direct and reflected arrivals quickly reduces the efficacy of the signal.[1] Channel equalization may be employed to reduce this error, but the technique requires an additional pilot signal and imposes additional computational burden at the receiver. Furthermore, as the properties of the waveguide may change rapidly, adaptive equalization may be necessary, requiring constant re-estimation of channel parameters.[2] High-frequency transmissions are especially susceptible to changes in waveguide properties as the degree of associated phase change is inversely proportional to the wavelength. However, due to the short wavelength, high frequencies can be exploited to achieve higher data rates.[3] To circumvent the equalization requirement, multipath clutter may be reduced through the use of a directional transmission in which the main lobe is oriented directly toward the receiver and away from any reflective regions.[4] While the use of a vertical transducer array is one way of producing such a transmission,[5] a simpler and more cost-effective method is to utilize a single, directional transducer.[4]

A hollow-cylinder transducer has been developed with the intention of significantly reducing multipath reflection and thus reducing the need for channel equalization [Fig. 1(A)]. The transducer is composed of a piezo-ceramic tube (manufactured by American Piezo Ceramics International Ltd., PA) encased in polyurethane (Naval Surface Warfare Center, Crane Division, IN) oriented vertically, producing an axisymmetric aperture in elevation. While edge resonance may transmit some acoustic energy in the vertical directions, the associated resonant frequency is well outside the design band of the horizontally propagating component of transmission. Table 1 displays the theoretical resonant frequencies of the ceramic element.

2. Test methods

Testing was conducted in an enclosed 6 m × 6 m tank of fresh water in which the water depth was 4 m. One cylindrical transducer acted as the transmitter and was placed approximately 500 mm from the center of the tank at a depth of 1 m. This transducer was oriented horizontally [Fig. 1(B1)] and was mounted on a Velmex VXM 4800 series

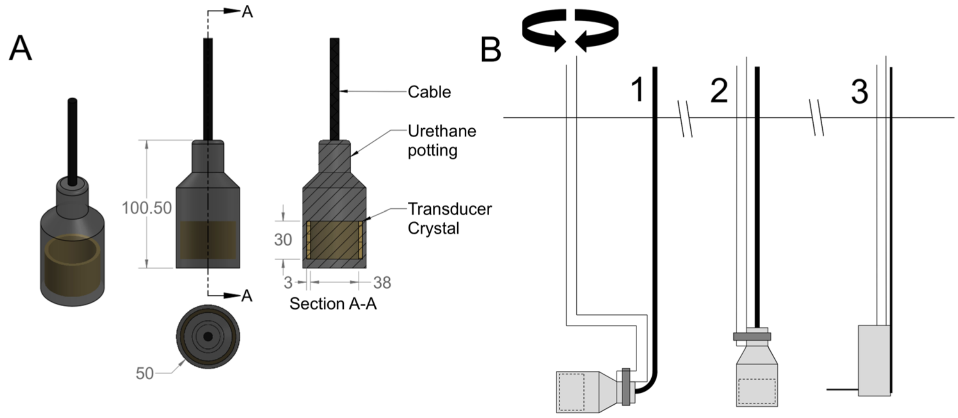

Fig. 1. (Color online) (A) A schematic of the hollow-cylinder transducer showing the dimensions and placement of the ceramic element in urethane potting material. (B) Schematic diagrams showing (B1) the transmission transducer, oriented horizontally, mounted to a rotating axis above the water line, (B2) a second (receive-only) cylindrical transducer mounted vertically, and (B3) the calibrated needle hydrophone.

computer-controlled rotational axis. The axis of rotation was aligned so that it intersected the transmitters' ceramic element at its center. A second cylindrical transducer (receive only) was positioned 1 m horizontally from the first and oriented vertically as shown in Fig. 1(B2). A calibrated, high-frequency needle hydrophone (ONDA HNR-0500 S/N 1681) was also positioned 1 m horizontally from the transmitter [Fig. 1(B3)]. Laser levels were used to ensure the needle hydrophone was oriented directly toward the center of the transmitters' ceramic element. Testing was conducted using the transducer shown in Fig. 1(B1) as the transmitter and either the transducer shown in Fig. 1(B2), broadside to the transmitter (defined as 0°, a bisection perpendicular to the cylinder axis as shown) or the needle hydrophone [Fig. 1(B3)] as the receiver.

In tests using both receivers, the transmitter was rotated through the desired angular positions using the computer-controlled axis at each of which a series of waveforms were sent. The waveforms were single-tone pulses that were modified by a raised-cosine filter ($\beta = 0.2$), ranging in frequency from 550 to 950 kHz in the case of testing using the needle hydrophone or 8 kHz to 1.1 MHz in testing using the cylindrical receiver. To accommodate the longer period of the low-frequency waveforms used, pulse durations of 0.8 ms were used when recordings using the cylindrical receiver were taken. Otherwise, pulses were of 0.5 ms duration to eliminate contamination of the direct arrival from the surface reflection. A high-frequency amplifier (Krohn-Hite DCA-10) with a flat 26 dB gain over the bands in question was used to amplify the waveforms before they excited the transducer.

Data were recorded using a LeCroy Wavesurfer 424 oscilloscope operating at a sampling frequency of 250 or 500 MS/s for the cylindrical receiver and needle hydrophone, respectively. Signal processing was conducted using MATLAB® R2014a. While the voltage output from the cylindrical receiver was recorded directly, signals from the needle hydrophone were pre-amplified by a 20 dB ONDA preamp. Signal pulses were created using a Hewlett Packard® 3220OA function generator connected to a personal computer running LABVIEW® 2013 SP1. A LABVIEW script controlled the rotational axis and function generator, stepping through the desired angles and frequencies and triggering the recording function on the oscilloscope. An appropriate time delay was added to the trigger signal sent by the function generator so as to place the direct arrival at the center of a recording of 0.5 or 1 ms length (for the needle hydrophone and cylindrical receiver cases, respectively).

At each angular position, for each frequency, eight pulses were recorded for the purposes of averaging to reduce electrical noise (an ~18 dB gain in voltage SNR). The spectral content of each pulse was used to check the consistency of the eight pulses before averaging. Spectral information from the averaged pulse was obtained by taking

Table 1. Theoretical resonant frequencies for the un-potted transducer shown in Fig. 1.

Estimated resonant frequencies (un-potted)		
Length (30 mm)	Diameter (34 mm ID)	Thickness (3 mm)
55 kHz	22 kHz	670 kHz

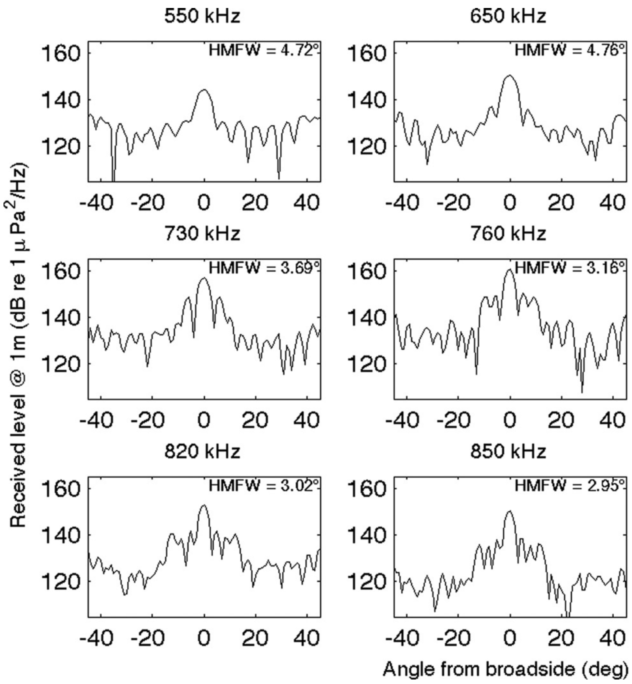

Fig. 2. Calibrated directivity plots of transmissions from the cylindrical transducer over a ±45° deviation from broadside over the 550–950 kHz band. The half-maximum full width (HMFW) value of the main lobe in each case is shown on the upper right of each sub-plot.

a single fast Fourier transform (FFT) of the 250 000-point data file, zero padded to the next power of two (262 144) and windowed with a Kaiser-Bessel window (alpha = 2.5). The pressure spectral density of the bin-center closest to the frequency of interest was retained.

3. Frequency response and directivity

Figure 2 Shows the calibrated directivity of the cylindrical transducer between ±45° for nine frequencies between 550 and 950 kHz. The half-maximum full width (HMFW) of the main lobe is indicated in the upper right corner of each plot. The main lobe became increasingly directional as the frequency increased up to and beyond maximum transducer resonance. In the 750–760 kHz band, HMFW of the main lobe was 3.16°, indicating that the main lobe width was approximately 55 mm at 1 m. The first side lobes at 760 kHz are 10 dB down from the main lobe, and this value remains consistent throughout the results although the side lobes are reduced to below the noise floor at the extremities of the investigated band. Peak received level at broadside occurred between 750 and 760 kHz in comparison to the theoretically calculated (un-potted) resonance at 670 kHz. Off-axis at 760 kHz, the received level drops by

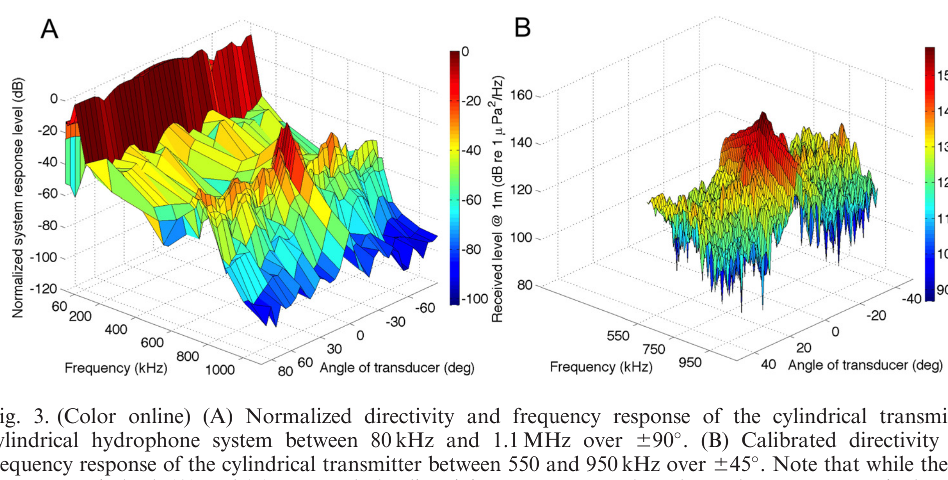

Fig. 3. (Color online) (A) Normalized directivity and frequency response of the cylindrical transmitter-cylindrical hydrophone system between 80 kHz and 1.1 MHz over ±90°. (B) Calibrated directivity and frequency response of the cylindrical transmitter between 550 and 950 kHz over ±45°. Note that while the frequency axes in both (A) and (B) are equal, the directivity axes are not. The color scale represents equivalent values to the vertical axes associated with each respective subfigure.

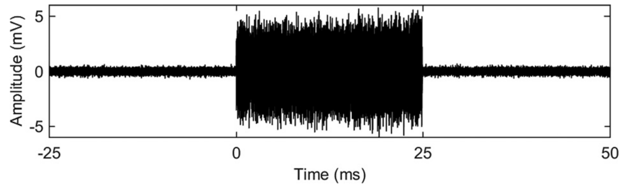

Fig. 4. High-pass filtered (fc = 25 kHz) time-series recording displaying a 25 ms communication packet and no discernible multipath from initial at-sea testing of the cylindrical transducer-cylindrical transducer system.

0.6–1.4 dB, 1° from broadside. Received level continues to drop by 3.4–5.5 dB and 9.9–14.9 dB 2° and 3° from broadside, respectively.

4. System performance

In addition to transmission, the cylindrical transducer was employed as a receiver in a transducer-transducer system to evaluate the feasibility of using a single transducer as both a transmitter and a receiver. While sensitivity tests using a calibrated high-frequency source were not performed, system tests using two cylindrical transducers—one transmitting and one receiving—provide a relative frequency and azimuthal estimate of system performance. Figure 3(A) shows the normalized frequency response of the system over 180° (directly below to directly above the transducer) between 8 kHz and 1.1 MHz. A clear peak at broadside between 750 and 760 kHz exists, narrower in frequency than that created by the transmitting cylindrical transducer by itself [Fig. 3(B)]. At 750 kHz, a ±5° displacement of either the transducer or receiver results in a 10–18 dB reduction of pressure spectral density. Figure 3(A) also shows that the system operates as an omnidirectional transmit-receive system between 10 and 60 kHz, a band in which the system is 5–8 dB more efficient, albeit in an omnidirectional manner.

Preliminary at-sea testing of an ACOMMS system using the cylindrical transducer as both transmitter and receiver demonstrated that the system is capable of sending and receiving high-frequency acoustic transmissions over 5 m of horizontal distance. Two transducers were positioned with their cylindrical axis oriented vertically, approximately 2 m from a sea floor comprised of silt and fine sand in an area of approximately 12 m depth during calm conditions in a protected bay. Figure 4 shows a typical communications recording of 25 ms duration at a center frequency of 750 kHz. If present, a surface reflection of the signal should have arrived approximately 14 ms after the direct arrival. No evidence of surface or sub-bottom reflection is visible above the electrical noise floor observed between transmissions.

5. Future work

These preliminary results show that the cylindrical type of transducer tested here is capable of producing and receiving highly directional high-frequency transmissions that are free of multipath in shallow-water ocean environments. They also show that this type of transducer can act as a low-frequency omnidirectional transmitter and receiver. A dual-band system in which low-frequency signals are re-transmitted in an encoded manner using high-frequency directional communications is possible with this transducer design. Similar testing using a calibrated sound source is required for the true sensitivity of the transducer as a receiver to be established. Further at-sea communications testing will establish the veracity of this design as a high-data-rate and/or dual-band underwater communications transducer.

Acknowledgments

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