Effects of Diffraction on the Sensitivity of Needle-type Ultrasonic Receivers

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Abstract: The low-frequency sensitivity of piezoelectric receivers usually is assumed to be limited by the combination of loading (e.g., amplifier) resistance and total capacitance of the receiver, cable, and amplifier. For typical needle-type hydrophones such as are used in medical ultrasound exposuremetry, this limit is less than 50 kHz. However, theoretical models have shown that diffraction effects at the needle tip can cause a low-frequency roll-off in sensitivity at frequencies much higher than that predicted by this simple electrical analysis. To examine this effect, broadband frequency response measurements of several needle-type hydrophones were made in the frequency range 0.2-2 MHz. The active sensor material was polyvinylidene fluoride, and needle tip diameters ranged from approximately 0.5 mm to 1.5 mm. In all cases the sensitivity ultimately decreased with decreasing frequency, with the -3 dB points at the response at 1.5 MHz all lying above 300 kHz.

INTRODUCTION

The objective of this investigation was to measure the low-frequency response of piezopolymer needle-type hydrophones currently used in biomedical ultrasound exposuremetry. This work was motivated by studies showing that a flat low-frequency response (below approximately 1 MHz) is important for accurate measurement of diagnostic ultrasound pulses, particularly the peak rarefactional pressure (1,2). Factors affecting the frequency response of needle-type hydrophones include the resonance characteristics of the sensitive element, diffraction effects at the needle tip, surface waves in the backing material, and the resistive and capacitive electrical loading (3-6). Of these, tip diffraction seems to be most significant at low frequencies for the hydrophones used to measure diagnostic ultrasound fields (4,6). Based on a result from Jones (7), the response of a hydrophone modeled as a rigid, semi-infinite cylindrical rod can be expected to decrease monotonically below a frequency in megahertz of approximately 1/d, where d is the needle tip diameter in millimeters.

METHOD

Six hydrophones from four commercial sources were studied, all having the piezoelectric polymer polyvinylidene fluoride (PVDF) as the sensitive element. Geometrical diameters of the sensitive elements ranged from 0.2 mm to 1.0 mm, and needle tip diameters ranged from 0.5 mm to 1.5 mm.

The frequency response was measured using a technique for generating broadband acoustic pulses in water via impulse excitation of a thick piezoelectric transducer (8). A unipolar voltage pulse having a pulse width of approximately 0.5 µs was applied to a 6.35 cm diameter by 2.54 cm thick lead zirconate titanate transducer (Navy Type I). In (8) it was shown that the spectra of the radiated front-face pressure pulse and the electrical excitation pulse are proportional for frequencies above approximately 0.2 MHz, so a broadband hydrophone response can be computed from measurements of this excitation pulse and the hydrophone's output voltage in response to the radiated pressure pulse. Spectra were measured in this way from 0.2 MHz to 2 MHz for the six hydrophones.

RESULTS AND DISCUSSION

Figure 1 shows the hydrophone sensitivity plots, all normalized to unity at 1.5 MHz. Table 1 lists the geometrical and needle tip diameters of the hydrophones, as well as the -3 dB frequencies relative to the value at 1.5 MHz. The frequency of 1.5 MHz was chosen as a convenient reference value to illustrate the general trend of broader low-frequency response with increasing needle tip diameter.

With respect to comparisons with the diffraction-based derivation of Jones (7), all hydrophones are hollow cylinders (rather than rigid rods) filled with the center conductor and backing materials of unknown acoustic impedances. For H4 the needle
diameter increases about 2 mm from the tip, and for both H3 and H5 the needle body near the tip is tapered. Thus, while direct comparison with (7) is hampered by these deviations from the rigid rod model, it does appear that an enhanced low-frequency response can be achieved by mounting the sensitive element on a larger diameter needle. This could be an important design consideration, because the diffraction based roll-off in response calls the use of these devices into question when accurate knowledge of the pressure waveform is required, particularly with regard to measuring the peak rarefactual pressure in pulsed waveforms displaying significant finite amplitude distortion (1,2).

![Diagram](image)

**FIGURE 1.** Plots of normalized hydrophone sensitivity vs frequency.

<table>
<thead>
<tr>
<th>Hydrophone Designation</th>
<th>Geometrical Diameter (mm)</th>
<th>Tip Diameter (mm)</th>
<th>$f_{3 \text{ re Response at } 1.5 \text{ MHz}}$ (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>1.0</td>
<td>1.5</td>
<td>0.32</td>
</tr>
<tr>
<td>H2</td>
<td>1.0</td>
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<td>0.7</td>
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<tr>
<td>H5</td>
<td>0.5</td>
<td>0.7</td>
<td>0.44</td>
</tr>
<tr>
<td>H6</td>
<td>0.2</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
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**REFERENCES**