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THESIS

**CHARACTERIZATION OF BIO-INSPIRED MEMS
UNDERWATER ACOUSTIC SENSOR USING
A STANDING WAVE TUBE**

by

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June 2022

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ACOUSTIC SENSOR USING A STANDING WAVE TUBE**

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ABSTRACT

NPS has developed MEMS-based underwater sensors based on the auditory structure of the fly *Ormia ochracea*. The sensor produces an output signal based on sound interacting with two mechanically coupled wings attached to a substrate using two torsional legs. The MEMS sensor operates at a resonance frequency determined by the geometrical structure. This thesis discusses the characterization of a water-filled standing wave tube, which is a device that is commonly used to characterize directional acoustic sensors. The standing wave tube generates a plane wave along its axis and provides a convenient way to characterize the directional response of MEMS sensors for underwater applications.

Two MEMS sensors were tested with simulated resonance frequencies of 450 Hz and 640 Hz, respectively. The MEMS sensors operate similarly to pressure-gradient microphone and are expected to exhibit an output signal dependent on the cosine of the incidence angle of sound. Both sensitivity and directionality measurements were taken in the standing wave tube using an underwater omnidirectional loudspeaker as a sound source. This research shows the standing wave tube is a viable testing device for MEMS sensor characterization, and the NPS-designed MEMS sensors for underwater applications clearly demonstrated characteristics of a directional acoustic sensor.

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LIST OF ACRONYMS AND ABBREVIATIONS

CAD	Computer Aided Design
FWHM	Full Width at Half Maximum
PML	Perfectly Matched Layer
MEMS	Microelectromechanical Systems
SWT	Standing Wave Tube
TRANSDEC	Transducer Evaluation Center
UW	Underwater

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I. INTRODUCTION

Undersea exploration has existed for over two centuries. Measurements of systemic activity, sea floor mapping, ocean topography and naval warships like submarines all rely on sonar systems. The principles of sound detection using sonar has not changed but the methodology constantly evolves. The Naval Postgraduate School is developing a microelectromechanical system (MEMS) underwater acoustic sensor based on the hearing organ of the *Ormia orchracea* parasitic fly. This chapter provides a brief description of commonly deployed acoustic sensing techniques for determination of the bearing of sound, followed by MEMS sensors employed in the thesis research.

A. MODERN UNDERWATER SENSORS

Sonar sensors can be designed as omnidirectional or directional hydrophones used to detect sound in the ocean. Modern sonar sensors consist of an array of hydrophones that use time delays between them to create beams or windows to detect sound in a desired direction(s) [1]. These hydrophones are typically made of piezoelectric material and convert acoustic energy or sound to electrical energy via transduction [2]. Sound detection can be done passively by simply listening, or actively by emitting a pulse and receiving the reflected sound wave [2]. A typical sonar detection scheme used in surface warfare is shown in Figure 1 .

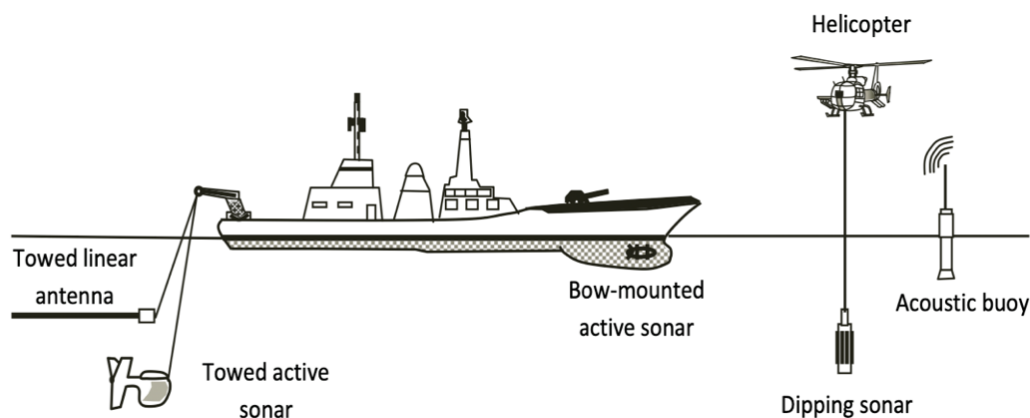


Figure 1. Submarine detection systems. Source: [2].

1. Towed Arrays

Towed arrays are one of the most prominent sonar arrays used for underwater detection by naval warships [1]–[3]. These arrays are symmetric about their acoustic or array axis. In result, if an object is obtained on the left side of the array, there will be an ambiguous angle on the right side of the array and vice versa [4]. This ambiguity makes it difficult to distinguish where the object is, without changing the direction of the array since two identical lobes appear on either side of the array axis. Figure 2 is a visual representation of this problem. In Figure 2, Ψ_s represents the measured bearing of the sensor, and Ψ' represents the direction the beam has been steered. In this scenario the sonar output indicates the object is on the starboard (right) side of the array but in reality, it is on the port (left) side of the array [5].

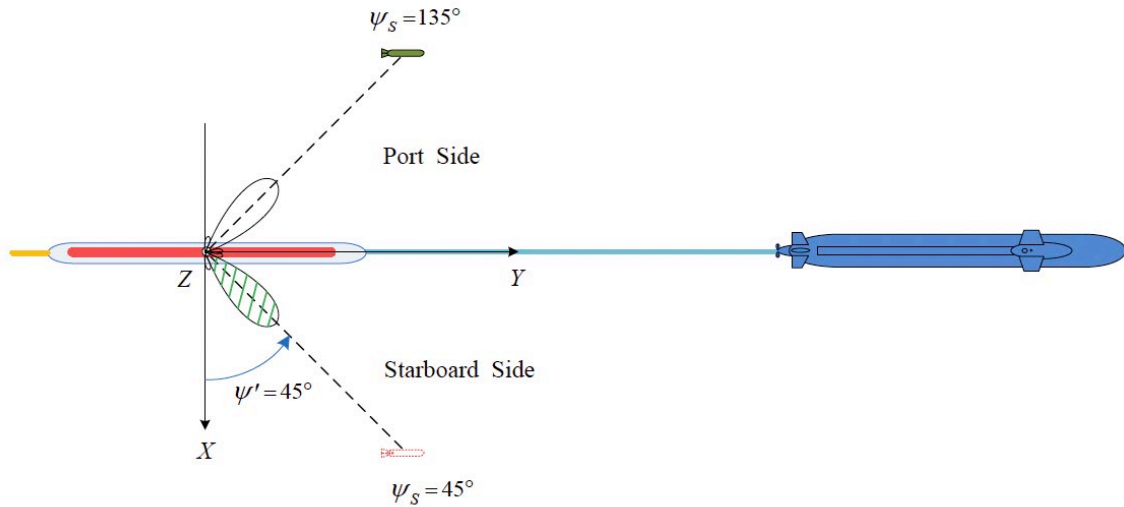


Figure 2. Towed Array Bearing Target Bearing Ambiguity. Source: [5].

Towed array sensors are robust and can detect objects hundreds of miles away. They are tunable with the ability to cover a wide variety of frequencies useful for both civilian and military applications, thus they remain a key instrument for undersea operations [3].

2. Hull Mounted Sensors

Hull mounted sensors detect sound based on the same principles as towed arrays; however, they are commonly designed to be spherically or cylindrically shaped [6]–[7]. Spherical arrays use directional filters which allow beams to be formed along a desired location [6]. Hull mounted sonar array beam widths are smaller than towed arrays, but they are directional in nature eliminating bearing ambiguity [1], [2], [6], [7]. Figure 3 is an image of a U.S. Navy Seawolf class spherical array [1].

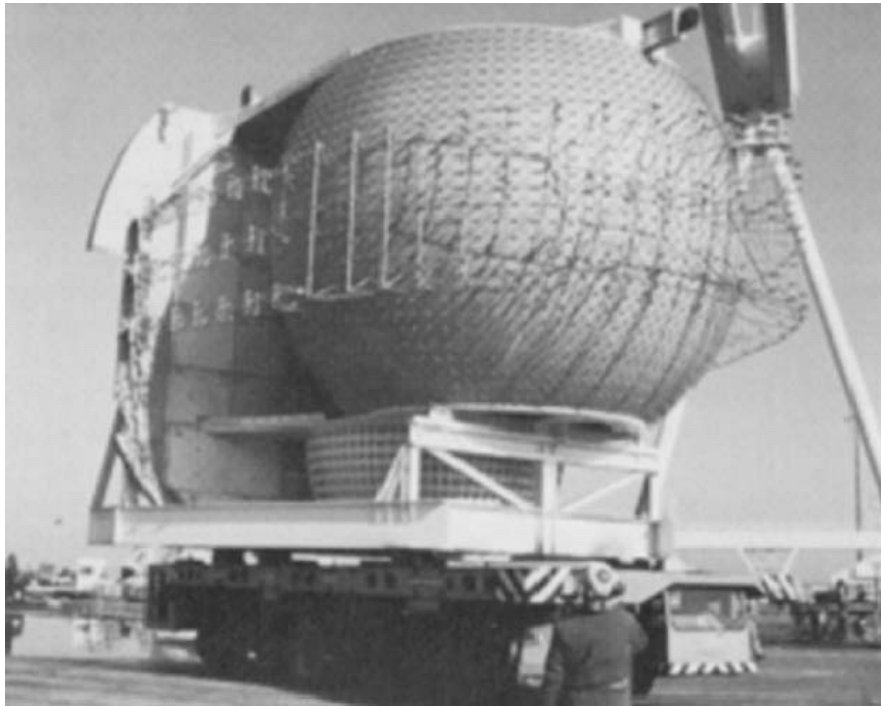


Figure 3. Spherical Array of Seawolf Class Submarine. Source: [1].

B. MEMS SENSOR BASED ON THE *ORMIA OCHRACEA* HEARING ORGAN

The hearing organs of many animals have left and right tympanal membranes (ear drums) that are physically separated causing interaural differences. Interaural differences cause time delays between the two tympanal membranes allowing the brain to discriminate where the sound is coming from [8]. The *Ormia orchracea* parasitic fly, however, has tympanal membranes that are mechanically coupled [8]. When sound is incident on the

eardrums, this coupling produces large interaural differences, and longer interaural delay times resulting in two distinct resonant frequencies [8]–[12].

In the first resonant mode small pressure differences between the eardrums cause them to move out of phase with each other, resulting in an anti-symmetric rocking motion [10], [11],[13]. The second resonant mode is produced from the forces on the eardrums creating a symmetric bending motion [10], [11], [13]. Figure 4 provides a physical representation of the *Ormia*'s hearing organ [13].

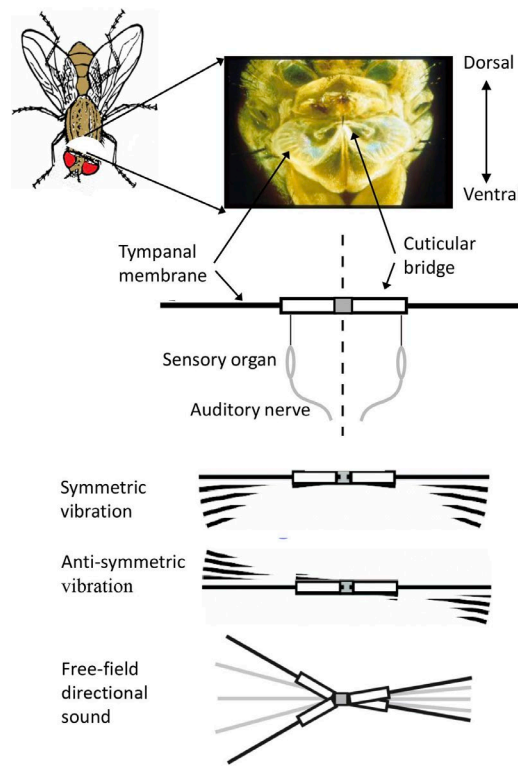


Figure 4. Micrograph of *Ormia*'s Hearing Organ and schematic representation of oscillation modes. Source: [13].

The hearing organ of the *Ormia* fly has motivated the design of MEMS acoustic sensors [8]–[12]. These sensors are desirable because of their size and ability to determine the direction of sound at wavelengths much smaller than the sensor [10]–[12]. The bending mode produces a response that is directionally dependent due to the interaction of sound

from both sides of the sensing element, making it the most common use case for sensor development [10]–[12].

Figure 5 shows the measured directional response in air of an *Ormia* inspired MEMS sensor operating in the bending mode for a set of incident sound pressures [10].

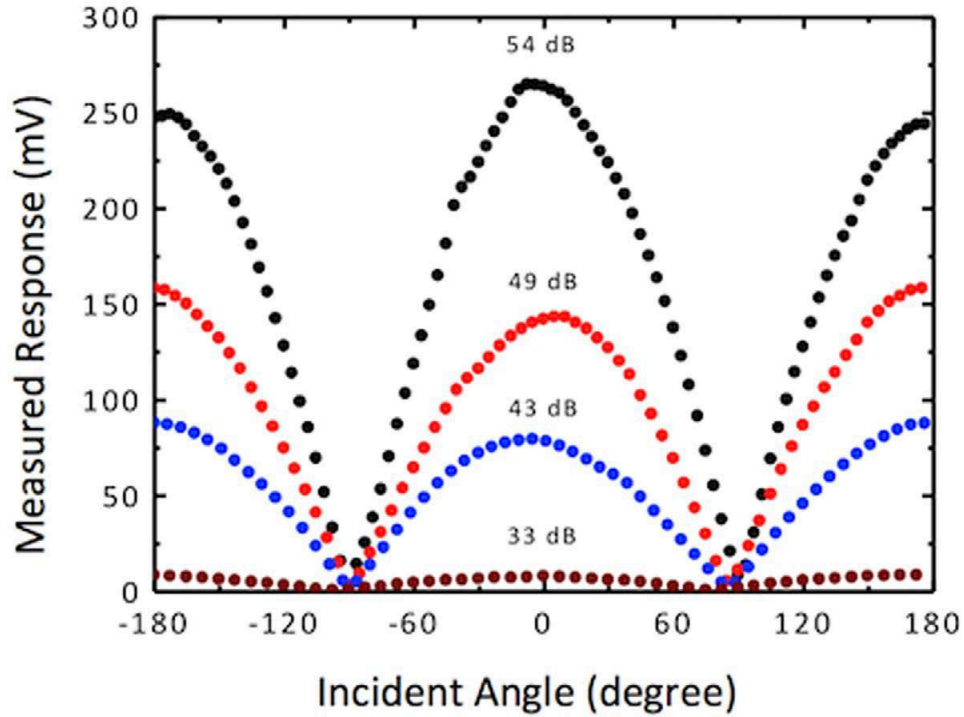


Figure 5. Directional Response of MEMs Sensor. Source: [10].

Other types of MEMS sensors have been developed for directional sound detection. For example, a sensor was developed based on the tube organ of a fish; it uses deformation of piezoelectric resistors that change based on the incidence angle of sound [12]. A bionic sensor that uses a solitary vertical cylinder has also been researched. This sensor uses the piezoresistive properties of resonant tunneling diodes to produce an electrical output from an incident sound wave [12]. In addition, a vector sensor measuring particle velocity using two parallel platinum wire resistances was also developed [11].

The focus of this thesis is analyze the possibility of using MEMS directional sound sensors developed by our group for applications in air, repurposed for underwater sound

detection. The initial characterization of sensors operating in underwater has been done at the NPS tank lab or The Transducer Evaluation Center (TRANSDEC) in San Diego. One of the main issues of using the existing characterization facilities is the interference pattern due to the reflected sound waves from the walls of the tanks, perturbing the directionality of the wave incident on the sensors being tested. The goal of this thesis is to develop a laboratory setup to characterize the MEMS sensors using a standing wave tube (SWT) and characterize two such sensors designed to operate in different frequency bands.

C. STANDING WAVE TUBES

Water filled impedance tubes are sound measurement instruments that can be used to precisely measure acoustic properties of materials such as reflection and transmission coefficients [14], [15]. An impedance tube is often referred to as a standing wave tube (SWT) because when sound propagates through the tube standing waves are generated [15]. In principle, sound produced from a source at one end of the tube will produce a propagating plane wave [14]–[16]. A plane wave is described by the following equation [17]:

$$P = A * e^{i(\omega t - \vec{k}\vec{r})} \quad (1)$$

where P is the acoustic pressure, A is the amplitude of the sound wave which may be complex, ω is the angular frequency, t is time, $\vec{k}$ is the wave number, and $\vec{r}$ is the position vector. Plane waves are advantageous for measuring directional responses of an acoustic sensor, making SWTs good candidates for MEMS sensor characterization in a laboratory environment [2], [14]–[17].

1. Use of Standing Wave Tubes for MEMS Sensor Characterization

Standing wave tubes are suitable for MEMS based sensors characterization due to their compact size [18]–[21]. Often these sensors are designed to have a directionally dependent signal output, which can be used to determine the bearing of the sound stimulus [18]–[21]. The sensors are typically packaged in a protective enclosure made of sound

transparent material filled with non-conducting fluid such as silicone oil [18]–[20]. Figure 6 shows a typical experimental configuration for analyzing a MEMS sensor [20].

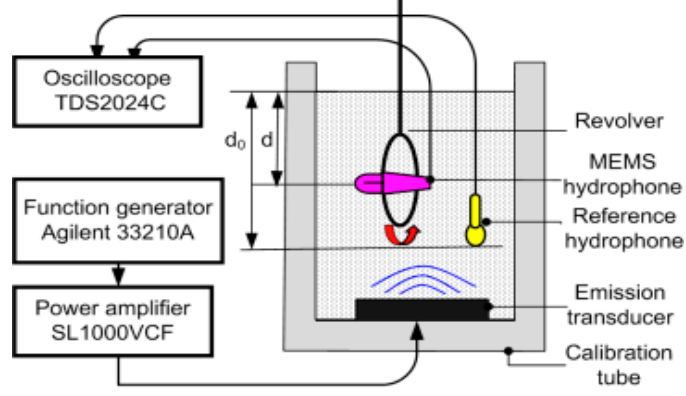


Figure 6. Schematic of MEMS Sensor Experimental Setup. Source: [20].

A reference hydrophone is used to obtain the incident sound pressure inside the testing apparatus in order to determine the sensitivity (V/Pa) of the MEMS sensor [18]–[21]. Sensitivity is an acoustic figure of merit that describes the ability of a sensor to convert acoustic sound to an electrical output; the more sensitive the sensor the larger the signal output [17]. Assuming a plane wave sound is incident on the sensor, the sensitivity can be approximated by Equation 3 [17]:

$$M_s = G * M_h * \frac{V_s}{V_h} \quad (2)$$

where M_s is the unknown sensitivity of the MEMS sensor, and M_h is the known sensitivity of the reference hydrophone. V_s and V_h are the measured voltage outputs of the sensor and reference hydrophone respectively, and G is the gain of the reference hydrophone amplification [17].

D. THESIS ORGANIZATION

In this thesis work, the standing wave tube designed by our research group is characterized and its ability to produce plane waves is verified. Next, two MEMS sensors designed to operate at two different frequencies for underwater applications are

characterized using the standing wave tube. Specifically, the frequency and directional responses are measured and compared with simulation.

This thesis is organized in 5 chapters. Chapter I provides background information of the project regarding current sonar systems, standing wave tubes, and the *Ormia*'s hearing organ working principles applied to MEMS sensors.

Chapter II describes the design and analysis of the standing wave tube. Specifically, a description of measurements validating that a plane is generated in the tube, in the desired range of frequencies, is provided.

Chapter III provides a description of the assembly containing the two MEMS sensors to be tested, named Generation 7–3 and Generation 7.4.

Chapter IV describes the experimental setup for testing the sensors, as well as the experimental results of the tests and a comparison to COMSOL simulated data.

Chapter V provides the conclusions from the research and recommendations for future work.

II. STANDING WAVE TUBE ANALYSIS

A. STANDING WAVE TUBE DESIGN

The standing wave tube (SWT) was constructed using a 9-inch inner diameter, 2 foot long aluminum tube with 0.5 inch-thick walls attached to a 1-inch thick aluminum base plate. The bottom of the tube has six mounting holes with the purpose of attaching an underwater loudspeaker [22]. Figure 7 is a computer aided design (CAD) drawing of the standing wave tube assembly.

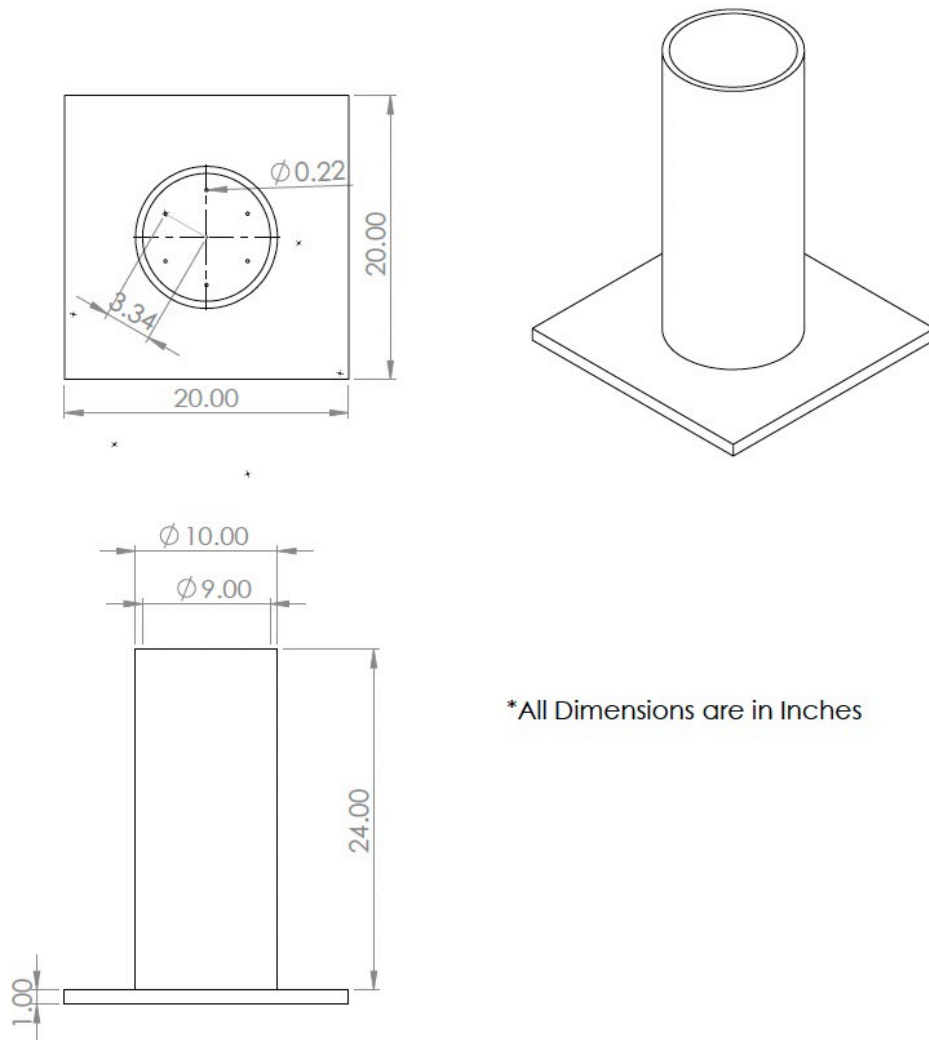


Figure 7. CAD Drawing of Standing Wave Tube Assembly

The top left portion of Figure 8 is a top view of the mounting assembly for the loudspeaker. The bottom left is a front view of the tube, and the top right is a side view of the tube. Additionally, the tube was placed on top of a wooden block to provide extra stability, and to minimize vibrations. Figure 8 shows a picture of the constructed SWT assembly used for MEMS sensor research at NPS.

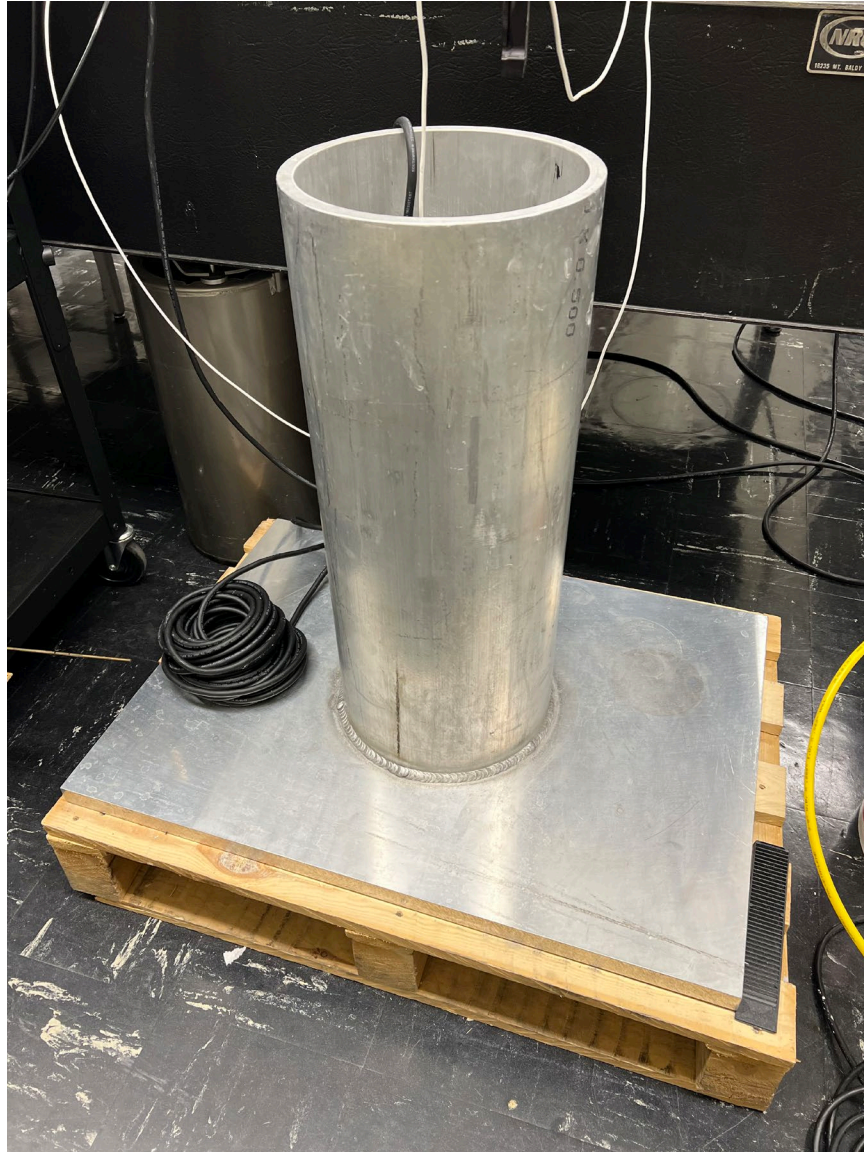


Figure 8. SWT Assembly for MEMS Research

B. STANDING WAVE TUBE EXPERIMENTS

1. Experimental Setup

To generate sound a UW 30 underwater loudspeaker was placed at the bottom of the tube with a layer of foam between the base and speaker [22]. The speaker was excited by a frequency generator connected via a Hewlett Packard 467A (HP467A) power amplifier [23],[24]. A calibrated B&K 8103 hydrophone was used to measure the sound field inside the tube. A Stanford Research 560 low noise pre-amplifier (SR560) was used to amplify the signal of the hydrophone [23],[25],[26]. Both the loudspeaker and hydrophone were connected to a Zurich mid-frequency lock-in (MFLI) amplifier to provide the excitation signal to the speaker and measure the output signal of the hydrophone. The MFLI is necessary for small amplitude sound detection and is controlled using a computer [27]. Figure 9 is a schematic diagram that represents the experimental setup and Figure 10 is an image of the assembled experimental setup.

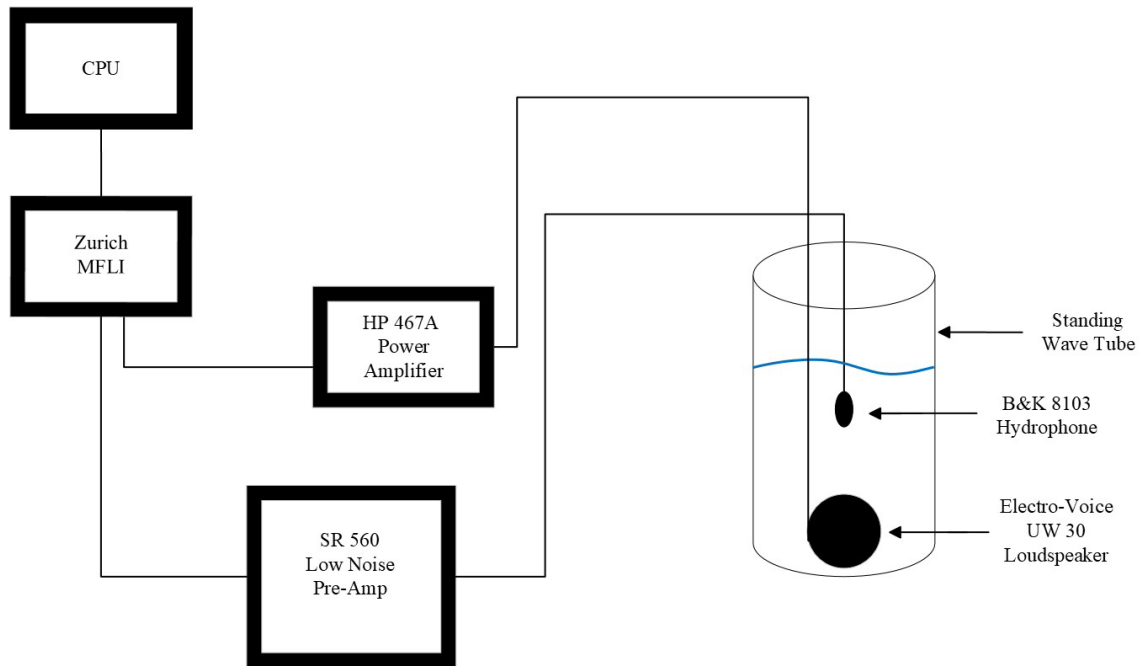


Figure 9. Diagram of Experimental Setup for SWT Analysis

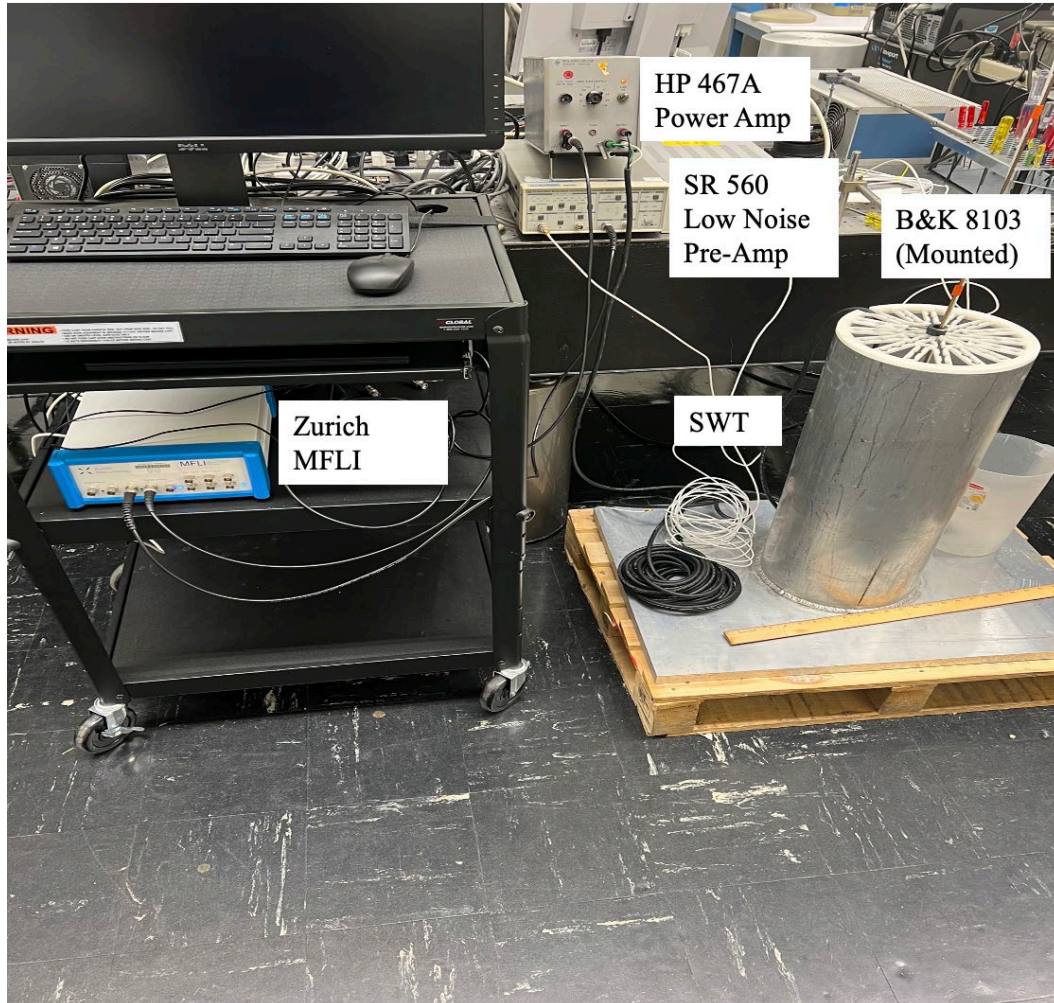


Figure 10. Assembled SWT Experimental Setup

2. Hydrophone Response at a Fixed Depth

The B&K hydrophone is omnidirectional and can be used to measure pressure at various depths of the tube [25]. The first set of measurements were carried out to determine the linearity of the acoustic field as the excitation voltage is varied. To perform this experiment, the hydrophone was placed at the center of the tube at several depths below the waterline. At each depth an excitation voltage of 10 mV and 100 mV was applied to the UW30 loudspeaker. Using the SR560, the hydrophone was amplified with a gain of 100; the output signal of the hydrophone was measured over a frequency band of 200–1000 Hz, which correlates to the expected operating band of the MEMS sensors.

Figures 11–14 show the measured frequency responses at various depths for two different excitation voltages applied to the speaker amplifier. The spectral features seen are primarily due to output characteristics of the speaker and tube resonances since the hydrophone has a flat sensitivity of $22.6 \mu\text{V}/\text{Pa}$ ($-211.5 \text{ dB re } 1\text{V}/\mu\text{Pa}$) in this range of frequencies [25].

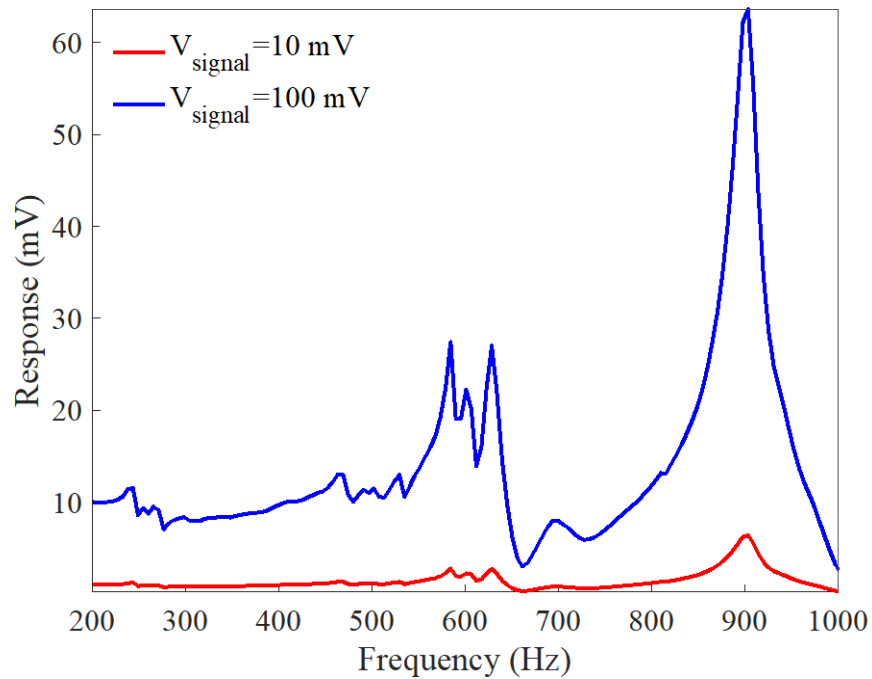


Figure 11. B&K 8103 Response at 3 Inches below the Waterline

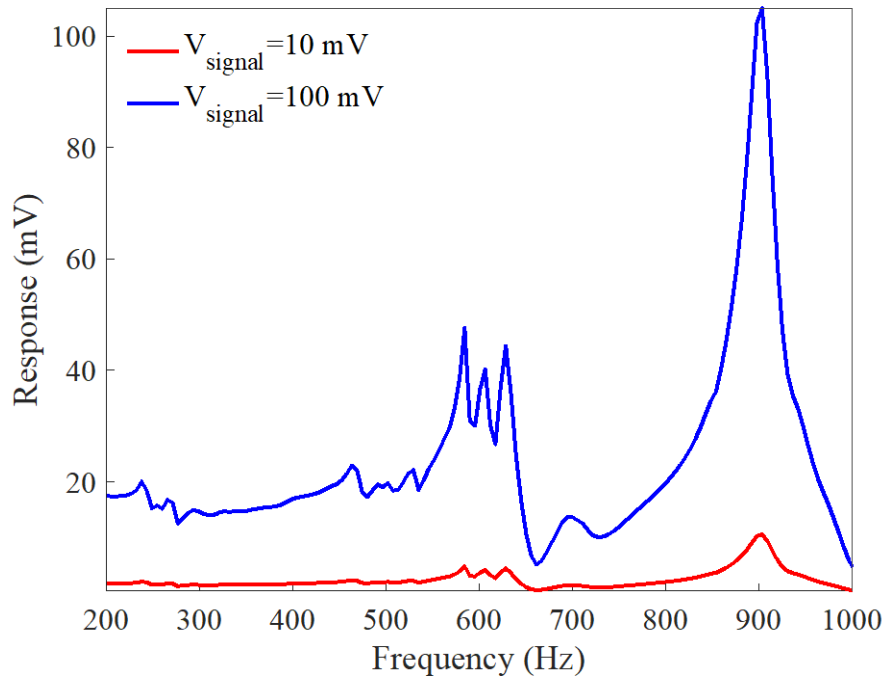


Figure 12. B&K 8103 Response at 5 Inches below the Waterline

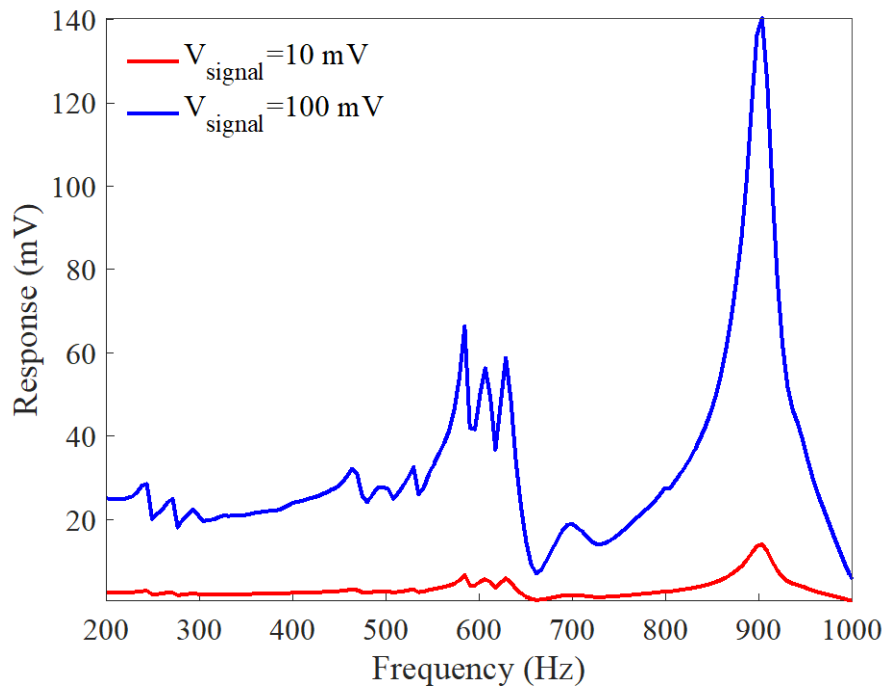


Figure 13. B&K 8103 Response at 7 Inches below Waterline

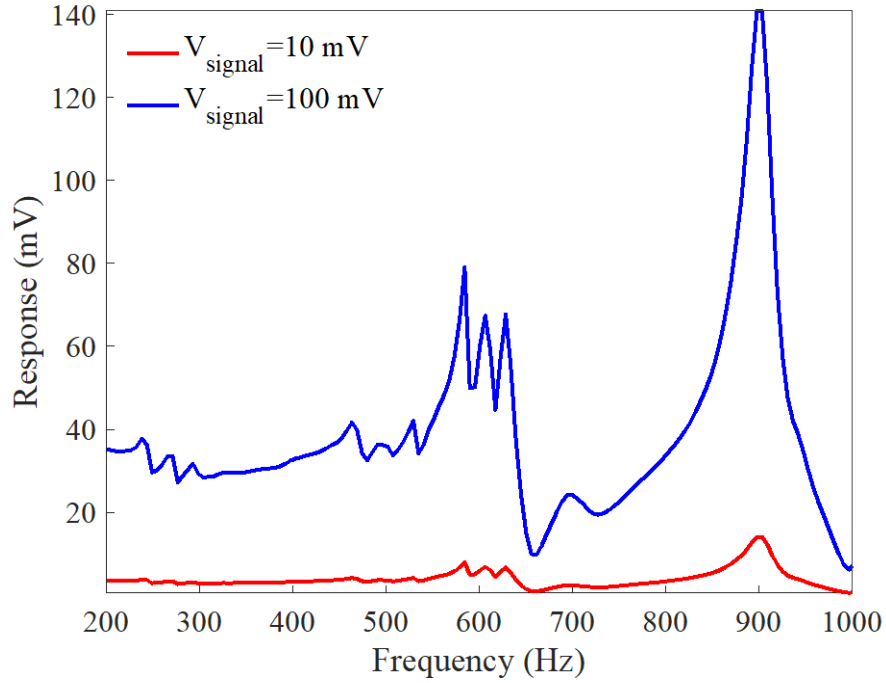


Figure 14. B&K 8103 Response at 9 Inches below Waterline

The resonance observed at 900 Hz likely arises from one of the resonances of the SWT. Treating the SWT as a waveguide, it is possible to estimate the observed resonance frequency using Equation 2 [17].

$$f = \frac{c}{4 \cdot L} \quad (2)$$

In Equation 2, f is the resonance frequency, c is the sound speed in water and L is the length of the waterfilled portion of the tube. The water column during the experiments was 15.5 inches deep. Using a sound speed of 1480 m/s [17], the resonance frequency equates to 940 Hz, which is within five percent of the measured value of 900 Hz.

The results show for a fixed depth the shape of the response curve is primarily dependent only on the UW30 signal amplitude. It also shows that as the hydrophone moves closer to the speaker the response increases, which is expected for a sound field in a SWT [15]. To confirm the linearity of the sound pressure with the signal of the speaker across the frequency spectrum the output voltage for the 100 mV stimulus was divided by the

output voltage for the 10 mV stimulus at all depths. If the sound field is linear the ratio should produce a horizontal line with a value of 10. Figures 15–18 show the results of dividing the 100 mV signal by the 10 mV signal at a set of depths.

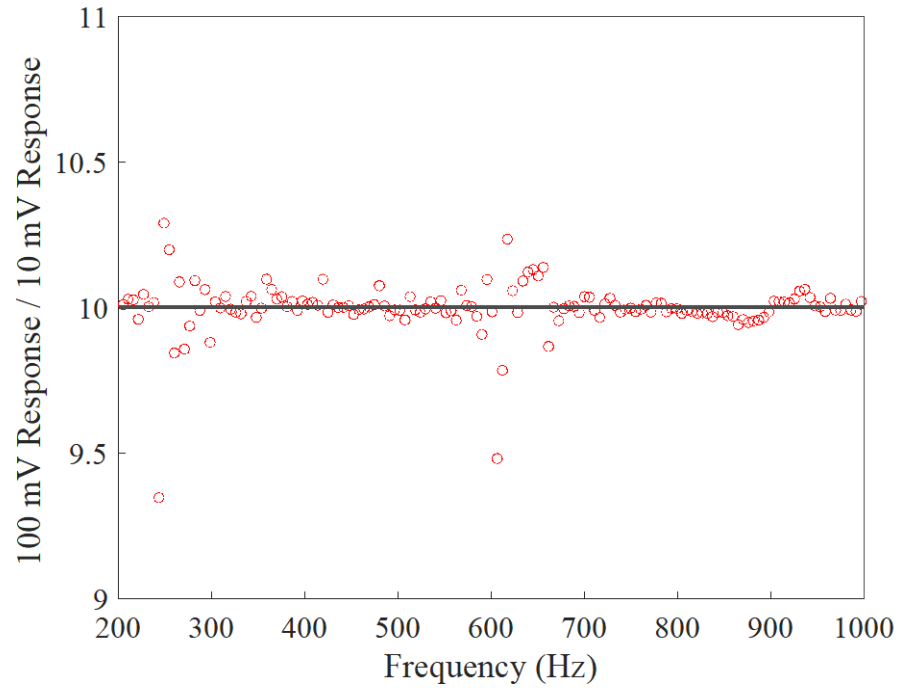


Figure 15. Ratio of Response Curves at 3 Inches below Waterline

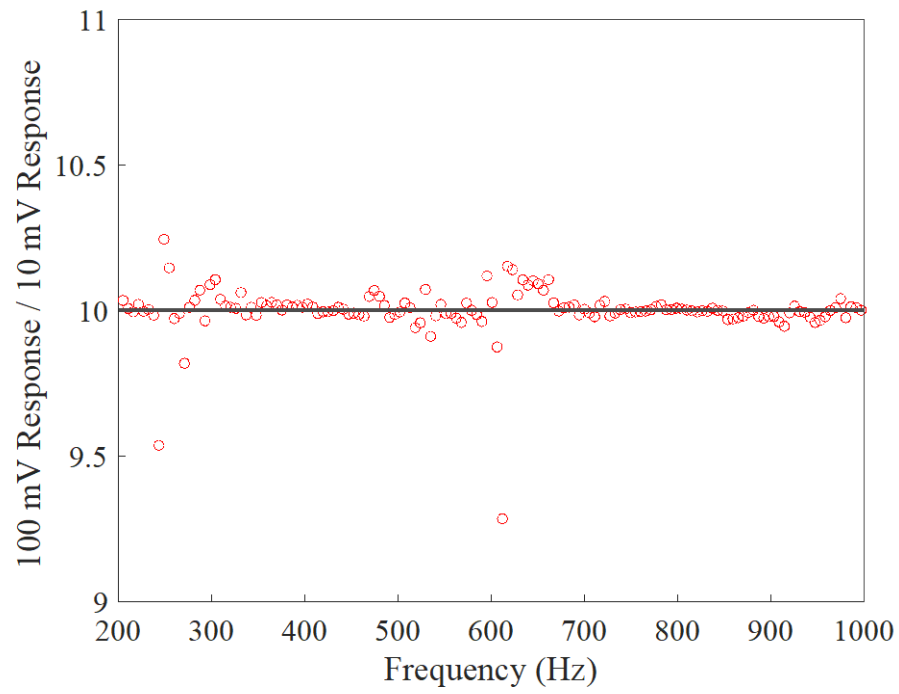


Figure 16. Ratio of Response Curves at 5 Inches below Waterline

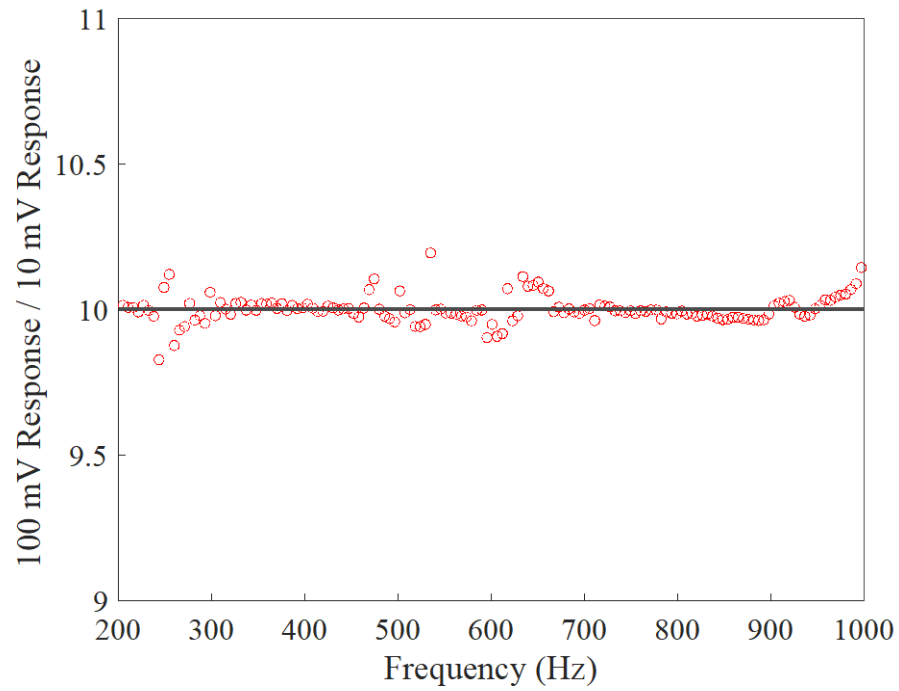


Figure 17. Ratio of Response Curves at 7 Inches below Waterline

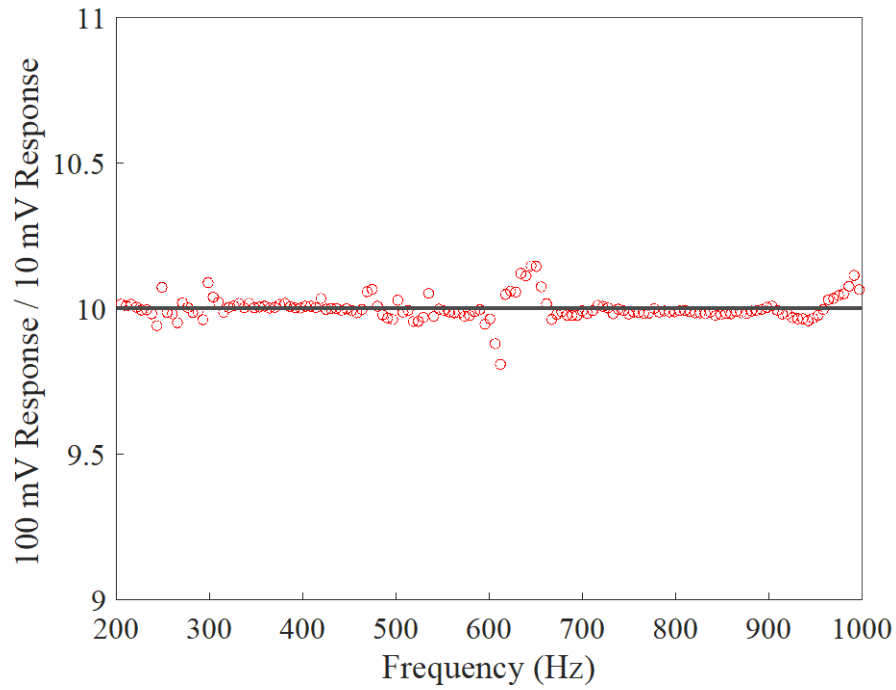


Figure 18. Ratio of Response Curves at 9 Inches below Waterline

The largest percentage difference across the frequency and depth spectrum was 6%. This indicates there is linear change of the sound pressure due to changes in the excitation voltage of the loudspeaker.

3. Profile of the SWT

The radiating surface of the UW30 loudspeaker is omnidirectional, which means at a fixed depth the acoustic field in the circular cross-section of the tube should be the same [15], [17]. This is possible because the wavelengths in the frequency range of interest are much larger than the cross-section of the tube. At a fixed depth, if a plane wave is produced, as described in Equation 1, the response of the hydrophone should depend only on the signal amplitude of the loudspeaker as it moves across a cross section of the tube [15]. Both simulations and measurements were carried out to characterize the sound field inside the SWT.

a. Simulated characteristics of the SWT

The acoustic field inside of the standing wave tube was simulated using COMSOL multiphysics software. The underwater speaker was modeled by modifying an existing speaker model in the COMSOL library to match the configuration of the UW30 underwater speaker. The simulation was performed assuming an 18 inch water column and a 6 inch air column above the water. The top of the air column was terminated with a perfectly matched layer (PML) to mimic the infinite space above it. Figure 19 shows the simulated sound pressure levels in dB along the tube at 450 Hz and 640 Hz. It can be seen in Figure 19 that in the middle region of the tube, pressure across each cross section (contour plots) is uniform indicating the propagation of a plane wave along the axis of the tube. However, closer to the speaker and the water-air interface the wave front is not flat.

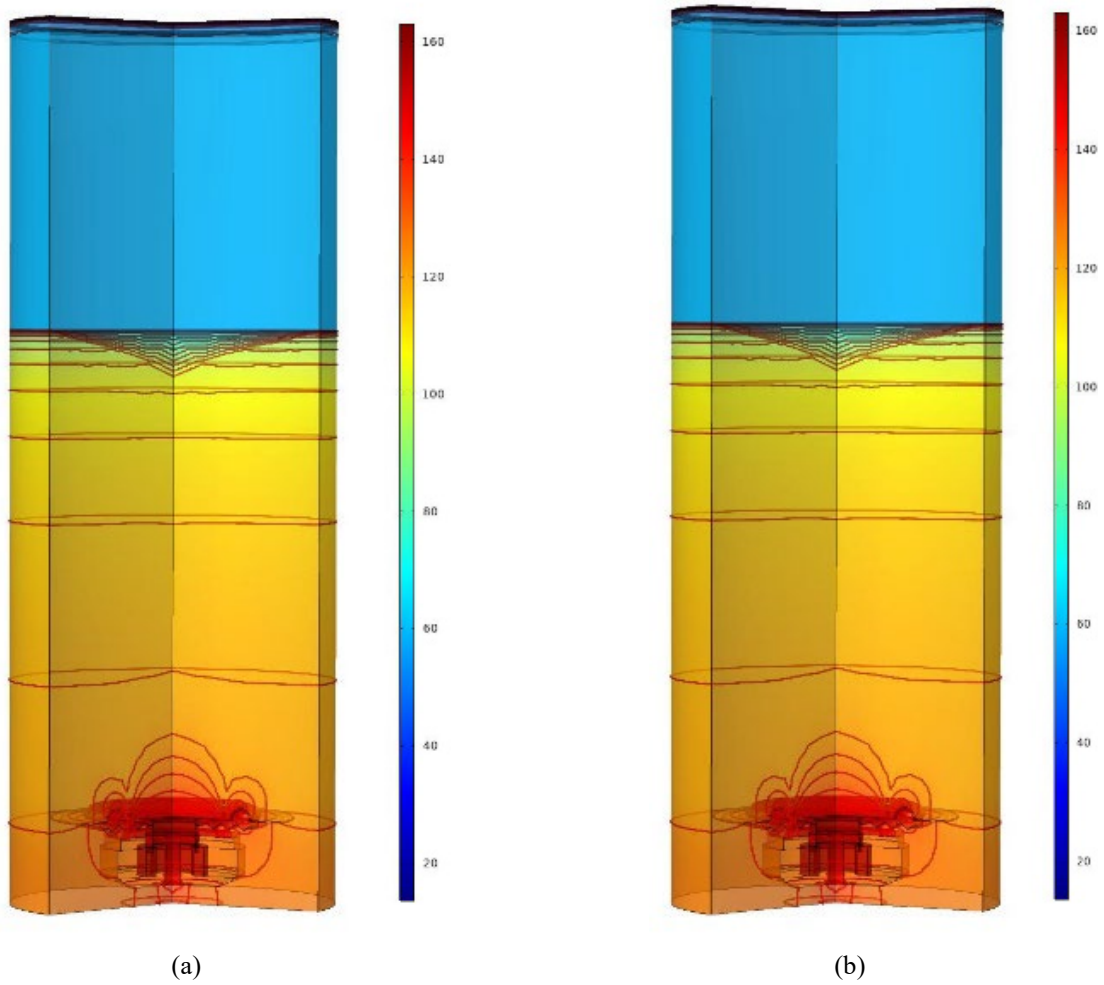


Figure 19. Simulated sound field in the SWT, (a) 450 Hz and (b) 640 Hz

b. Measured SWT Characteristics

To take accurate measurements across the tube a 3D printed cutout mimicking the circular cross section of the tube was made. Figure 20 is an image of the 3D-printed cutout.

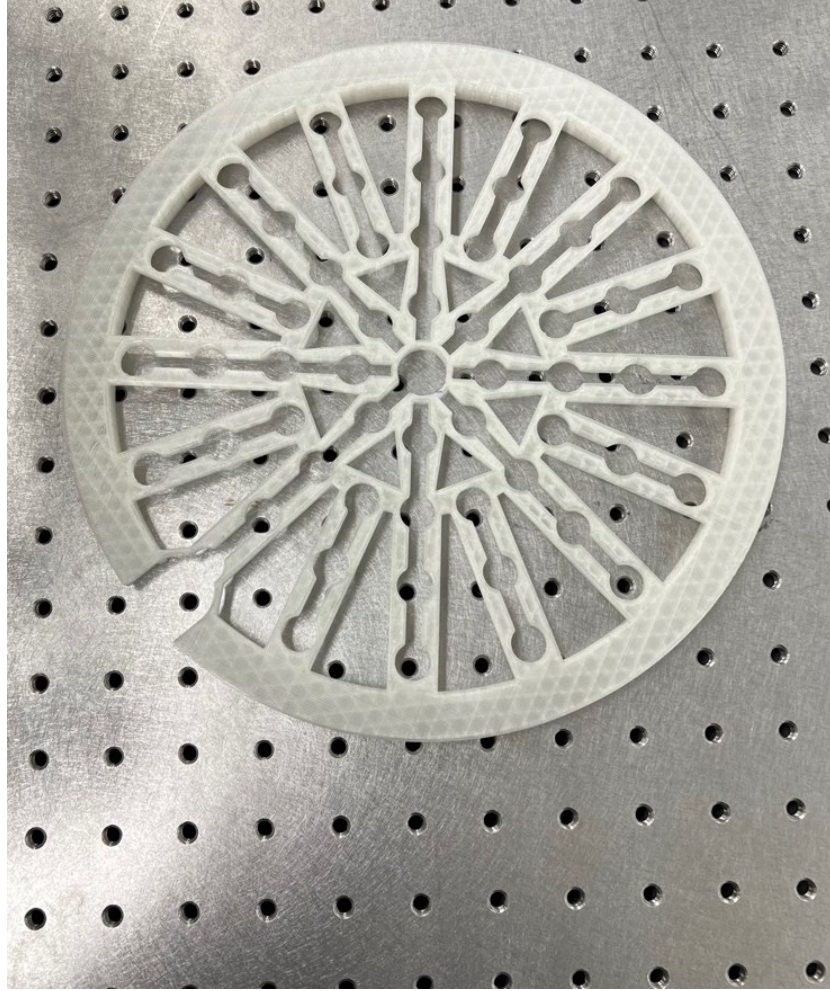


Figure 20. 3D-Printed Circular Cross-Section of the SWT

The 3D-printed cutout is divided into sections 22.5° apart, with one-inch spaced holes (nodes) and fits at the top of the tube. Figure 21 shows the measured output voltage of the hydrophone throughout the circular cross section of the SWT (all nodes) at various depths at a frequency of 700 Hz. The results indicate a constant pressure level at given cross section, with amplitudes that vary with depth only.

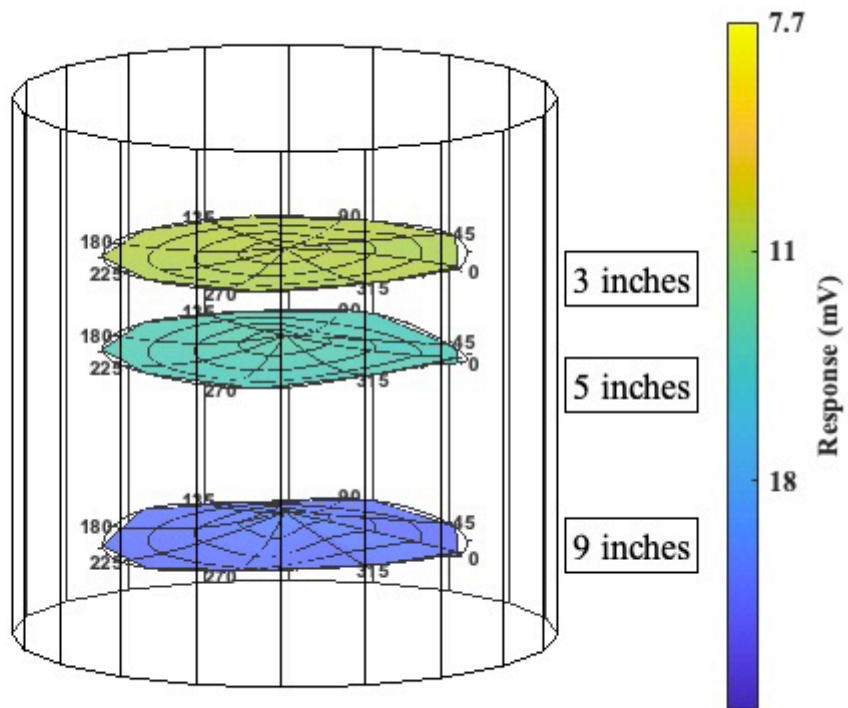


Figure 21. Polar Profile of Sound Field in SWT at 700 Hz

For characterization of the MEMS sensors, the sensors are positioned along the horizontal axis of the SWT. Three radial profiles of the tube measured at 450 Hz (blue) and 640 Hz (red), respectively, are shown in Figure 22. These frequencies were chosen because they are in the expected resonance region of the MEMS sensors.

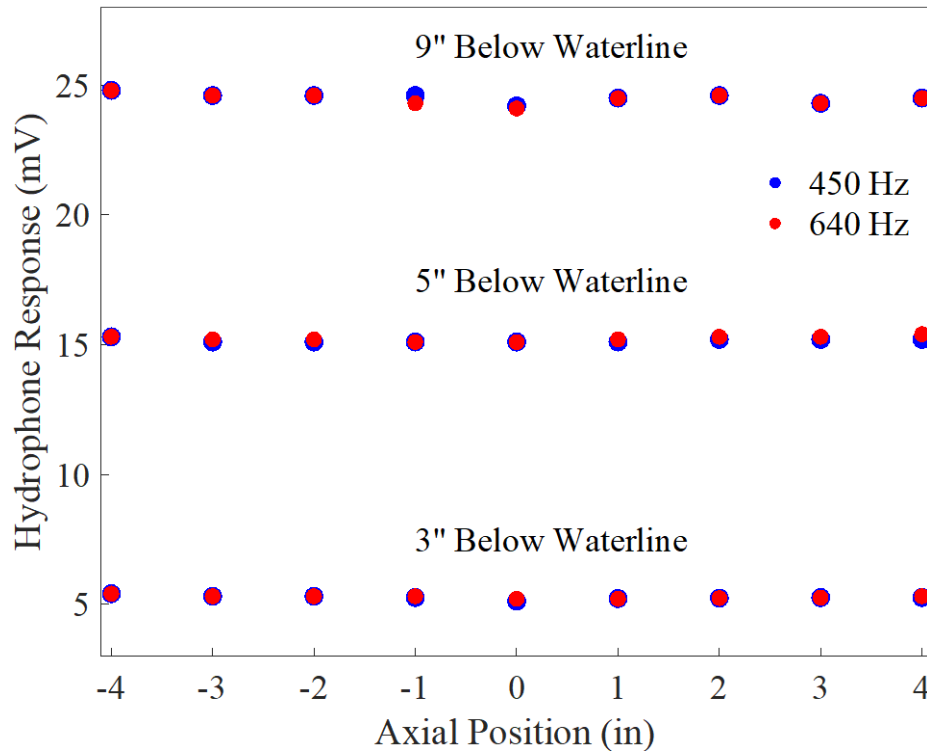


Figure 22. Sound Field Profiles at 450 and 640 Hz

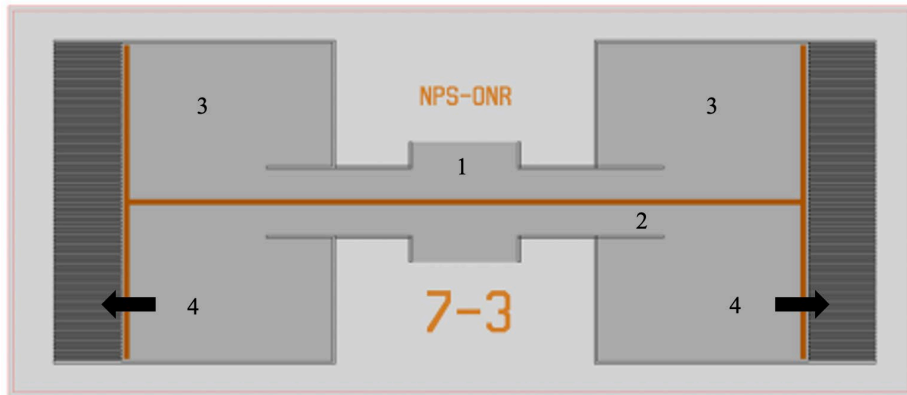
The results show for a given depth the sound field is nearly constant across the SWT. The values of the amplitudes only change with depth and are consistent between both measured frequencies. The data also shows good agreement with the simulated COMSOL data, and the cross-sectional data presented earlier, indicating that the sound wave can be approximated plane. For the characterization of the MEMS sensors this assumption will be used to find directionality and sensitivity.

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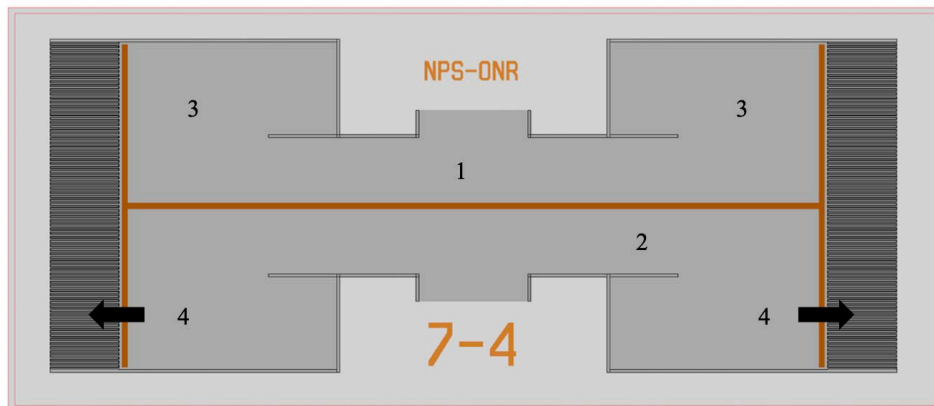
III. MEMS SENSOR ASSEMBLY

1. MEMS Sensor Design

The MEMS sensors employed for this research consist of two wings connected by a bridge fabricated using 25 μm thick silicon layer, mimicking the hearing organ of the *Ormia ochracea* fly. The wing-bridge assembly is attached to a 400 μm thick silicon-on-insulator (SOI) substrate using two legs. Two sensors with identical dimensions except the width of the bridges were designed and fabricated. Figure 23 shows the schematics of the two sensors Gen 7-3 and Gen 7-4 with bridge width of 0.5 mm and 1 mm, respectively.



(a) Sensor components: (1) leg, (2) bridge, (3) wing, (4) capacitive comb fingers.

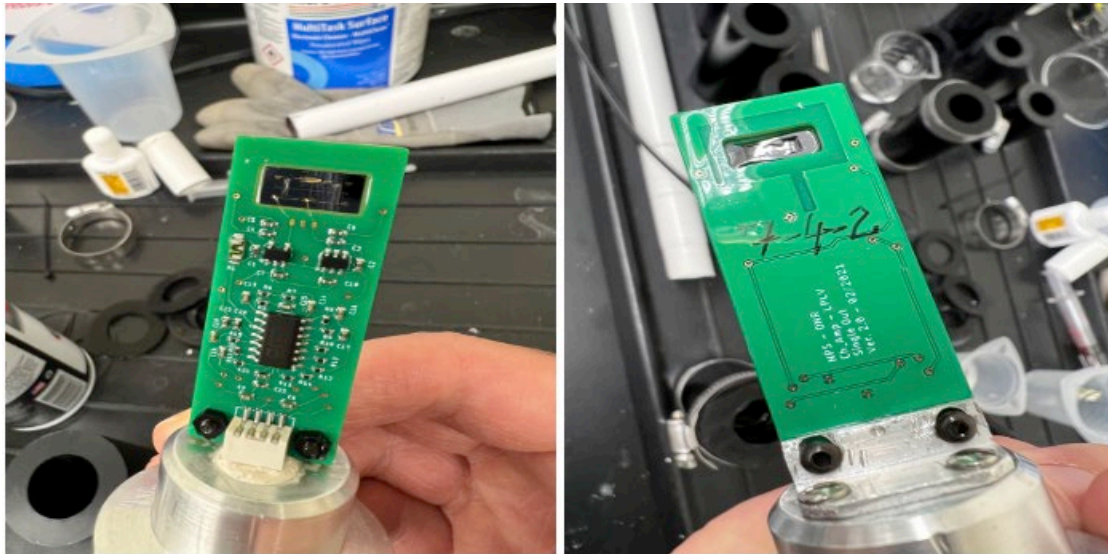


(b) Sensor components: (1) leg, (2) bridge, (3) wing, (4) capacitive comb fingers.

Figure 23. Schematics of (a) Gen 7-3 and (b) Gen 7-4 MEMS Sensors

Capacitive comb fingers are attached to the wings and substrate to produce an electrical output based on wing deflection [10]–[12]. The mechanical structure of the sensor exhibits two resonances (rocking and bending) depending on the stiffness of the legs and bridge, respectively. Two sensors were designed with bending resonance frequencies at 450 Hz and 640 Hz using COMSOL finite element modeling. The rocking resonance which depends on the pressure difference between the two wings is not usually excited when the sensor is operated in underwater due to relatively long wavelengths involved.

The sensor is cemented, and wire bonded onto a printed circuit board containing readout electronics. The circuit board has an opening (see Figure 24) for sound to interact with both front and back sides of the sensor. There are two additional holes in the circuit board closer to one of the edges for attaching the sensor to an enclosure for underwater testing. Figure 24 is an image of a MEMS sensor attached to the circuit board assembly for underwater applications.



(a) Frontside

(b) Backside

Figure 24. MEMS Sensor Circuit Board Assembly

2. Enclosing the MEMS Sensors

Two cylindrical rubber enclosures distinguished by their hardness's of 80A and 60A were used for this thesis. The hardness's are rated on the durometer scale, which is commonly used to measure the hardness of elastomers [28]. Rubber enclosures are routine practice for underwater acoustic sensor assemblies because they provide protection and have a high enough sound transmission [29]. For the NPS MEMS sensors, the enclosure is filled with silicone oil which has similar acoustic properties to water and does not damage or inhibit the operation of electrical components [12]. Figure 25 is an image of a rubber enclosure used for housing the MEMS sensors.

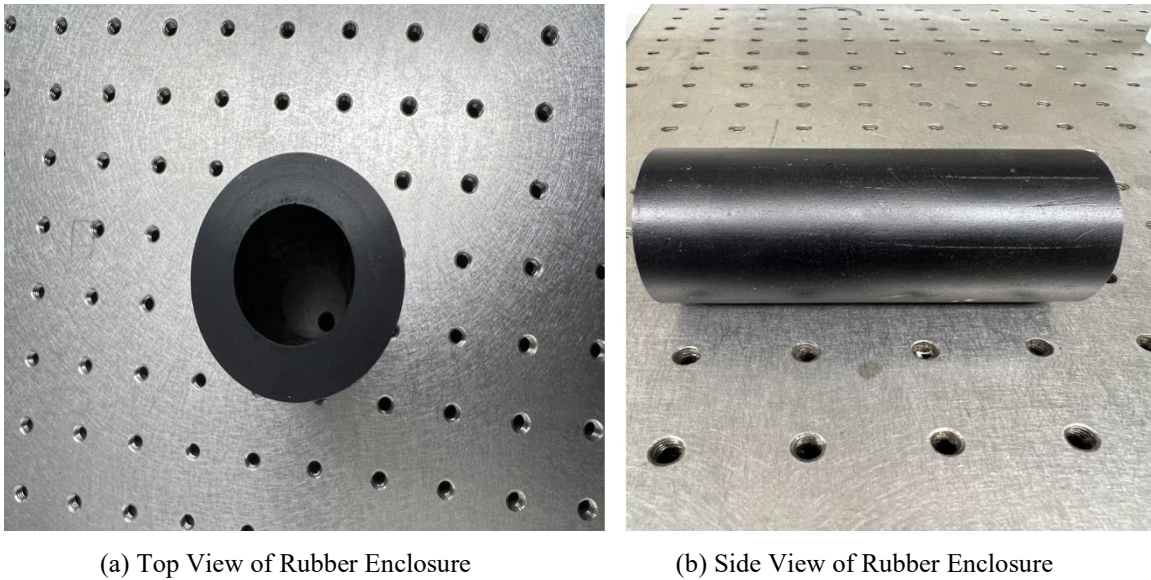


Figure 25. Rubber Enclosure Used for MEMS Characterization

Prior to filling the enclosure with silicone oil, a blank aluminum flange is inserted at one end of the tube. Once the enclosure is filled with oil the second flange, with the circuit board (see Figure 25 (a)), is inserted from the other side of the enclosure to seal the sensor inside. Hose clamps are used to fix the two flanges in place at both ends of the rubber enclosure. The hose clamps are tightened enough to secure the flanges without causing excess stress on the rubber enclosure which could deform and affect the directional characteristics of the sensor.

An underwater electrical cable is routed through a machined hole atop the flange where the circuit board was employed for providing power and extracting the signal. To prevent oil from escaping the enclosure or water from entering, marine sealant is coated around the hole and wire creating a pressure-tight seal. Figure 26 is the top and side views of a MEMS sensor enclosed in a rubber enclosure.

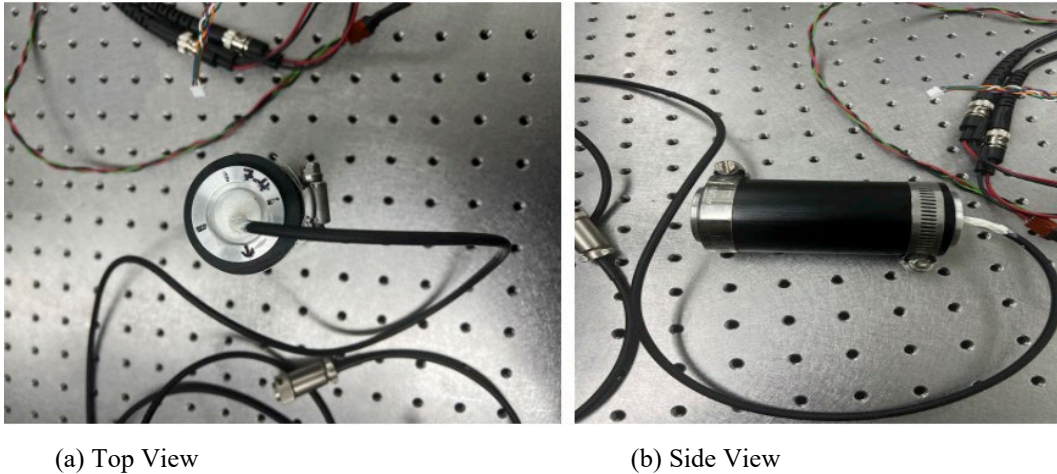


Figure 26. MEMS Sensor Enclosure Assembly

3. Sound Pressure Inside Rubber Enclosure

The effect the enclosures has on the sound pressure can be determined by placing a calibrated reference hydrophone inside the enclosure, then measuring the sound field and comparing it to a measurement taken outside the enclosure in the same location. The sound pressure inside the enclosure as a function of frequency was measured by placing it at the center of the SWT using the B&K 8103 hydrophone. In the measurement, a 20 mV excitation voltage was applied to the amplifier connected to the UW30 loudspeaker while setting the gain of SR560 to 1000. The measured responses for the two different rubber enclosures along with the response without the enclosures are shown in Figure 27.

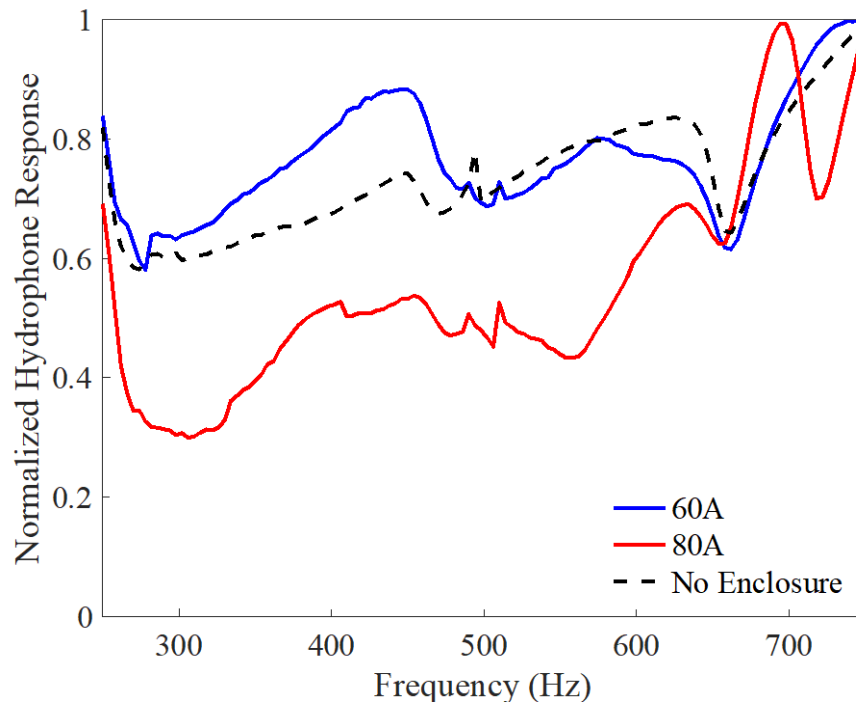


Figure 27. Normalized B&K 8103 Responses Inside and Outside Enclosures

It can be seen in Figure 27 that depending on the hardness of the rubber enclosure the sound pressure inside can be larger or smaller compared to the field without the enclosure (dashed line) at some frequencies. The sound pressure inside the hard enclosure (red line) remained below the sound pressure without the enclosure for frequencies between 300–600 Hz. The observed higher sound pressure (for both enclosures) is most likely due to resonant responses of the rubber enclosure to incident sound. The resonant effects can interfere with the directional response of the MEMS sensor due to the cylindrical symmetry of the enclosure.

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IV. MEMS SENSORS TESTING AND RESULTS

A. EXPERIMENTAL SETUP

The measurement instrumentation used for the MEMS directional sensors is similar to that used to characterize the SWT as illustrated schematically in Figure 28. The MEMS sensor assembly is connected to an external power supply and to a Zurich MFLI lock-in amplifier to extract the output signal of the sensor. An additional MFLI lock-in amplifier is connected to a calibrated B&K 8103 hydrophone placed near the MEMS sensor housing to measure incident sound pressure. The two MFLI's are synchronized with each other such that data collection of the B&K 8103 hydrophone and the sensor can be taken at the same time. Synchronization of the two signals is critical for determining the sensitivity of the MEMS sensor. Figure 28 shows a schematic diagram of the experimental setup used to characterize the MEMS sensors.

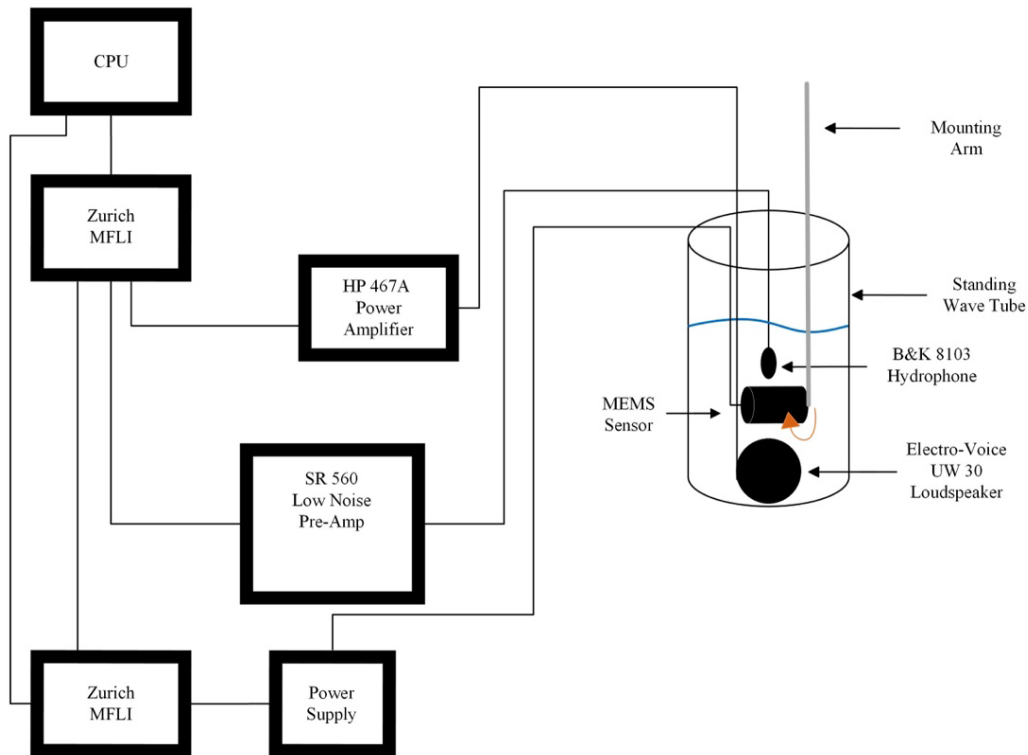


Figure 28. Diagram of Experimental Setup for MEMS Sensor Characterization

The MEMS sensor is attached to a rotating stage at the bottom of a mounting arm. The stage can be rotated 360° and is marked in 2° increments. Rotation of the sensor provides the directional characteristics of the MEMS sensor, which is expected to exhibit a cosine dependence with respect to the angle of incidence [10]–[12]. Figure 29 is a top view of the inside of the SWT during MEMS sensor characterization.

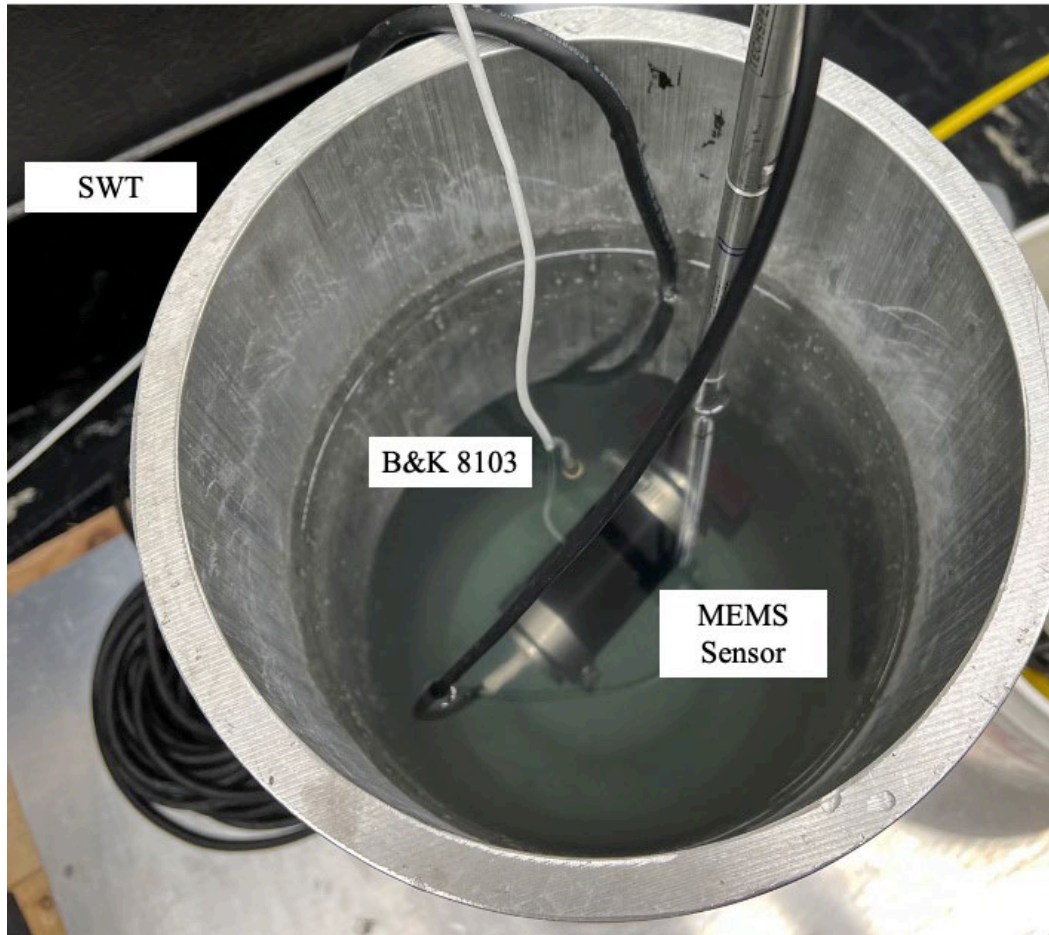


Figure 29. Top View of SWT Experimental Setup for MEMS Sensor Characterization

1. Placement of MEMS Sensor in SWT

The results shown in the SWT experiments indicate the plane waves are in the midsection of the tube. However, as the receiver (hydrophone or sensor) moves closer to the source, the plane wave assumptions breaks down due to near-field sound propagation

(see Figure 19). At sufficiently large amplitudes, near-field acoustic sound propagation can also produce non-linear effects that cannot easily be accounted for [17]. To avoid these concerns, the receivers must be placed sufficiently far enough from the source where the wave front can be approximated to a plane wave. Additionally, the wavelength of sound should be longer than the size of the source; under these conditions the source will radiate sound isotopically throughout the water column. Based on the simulations and measurement of the sound field inside the SWT, it was found that the sound field is consistently planar at each depth, throughout the middle section of the 18 inch water column. For all testing, the MEMS sensors were placed in the middle of the SWT, 14 inches away from the UW30 loudspeaker.

B. SENSOR CHARACTERIZATION

1. MEMS Sensors Operating Principles

As previously discussed, the MEMS sensors are expected to show the directional characteristics similar to a pressure gradient hydrophone. A typical pressure gradient hydrophone is designed to sense pressure at two points (front and back) [17], [30], [31]. The pressure difference is maximum at normal incidence (perpendicular to the sensing membrane) and minimum at 90 degrees (parallel to the sensing membrane), proportional to the cosine of the incidence angle [17], [30], [31].

The underwater acoustic MEMS sensors designed at NPS operate using similar fundamental concepts. In the case of these sensors, the sound wave interacts with top and bottom sides of the wings of the sensor causing them to deflect based on the pressure gradient. These deflections create a difference in capacitance between the comb fingers attached to the wings and static fingers attached to the substrate which is sensed by the readout electronics and converted to an output voltage. Therefore, the amount of deflection directly relates to the signal output of the sensor, which is analogous to the pressure difference of a pressure gradient hydrophone.

2. Equipment Configuration

For characterization, the MEMS sensors were placed at the axial center of the SWT, at a depth of 5 inches, with a B&K 8103 hydrophone adjacent to it as shown in Figure 29. A 20 mV excitation sinusoidal voltage generated by the internal function generator of a MFLI lock-in amplifier was applied to the UW30 loudspeaker via a HP467A power amplifier. The B&K 8103 hydrophone signal was amplified using a gain of 1000 via the SR560 amplifier and the output signals of the hydrophone and sensor were acquired using the synchronized MFLI lock-in amplifiers.

a. Rubber Encloser Considerations

The 60A durometer (medium hard) rubber tube with the two ends capped was used as housing for the Gen 7–3 sensor and the 80A durometer (hard) rubber tube was used for housing the Gen 7–4 sensor. Hose clamps were used to seal the rubber tubes which slightly deforms them and could affect the cylindrical symmetry and can interfere with the directional response of the MEMS sensor.

The relatively small size of the SWT made it difficult to collocate multiple hydrophones and the sensor being tested simultaneously. Instead, the measurements of the hydrophone inside and outside the enclosure were taken immediately following the testing of the MEMS sensors. To reflect this sequence of measurements in the estimation of sensitivity, Equation 2 [17] was modified into Equation 5,

$$M_s = G * M_h * \frac{V_s}{V_h * \frac{V_{h_{enclosed}}}{V_{h_{outside}}}} \quad (5)$$

where M_s is the unknown sensitivity (V/Pa) of the MEMS sensor, and M_h is the known sensitivity (V/Pa) of the reference hydrophone (22.6 μ V/Pa). V_s and V_h are the measured voltage outputs of the sensor and reference hydrophone respectively, and G is the amplification gain used for the hydrophone [17]. The additional term ($V_{h_{enclosed}}/V_{h_{outside}}$) is the ratio of the reference hydrophone signal when placed inside the enclosure ($V_{h_{enclosed}}$) over the measurements of the hydrophone signal outside the enclosure ($V_{h_{outside}}$). For these measurements the frequency response of the hydrophone was measured by placing it inside

the enclosure, and once complete the measurement was taken again with the hydrophone removed from the enclosure. For both measurements the hydrophone was placed at the same location that was used to characterize the MEMS sensors.

Simulation of MEMS Sensors

For this research, Gen 7-3 and Gen 7-4 MEMS underwater acoustics sensor characteristics were designed and analyzed using COMSOL multiphysics software. The sensors were modeled in a spherically symmetric volume filled with silicone oil with a sound absorbing layer around the sphere (PML) to mimic the infinite space. Three modules of COMSOL (structural, acoustic and thermoviscous acoustic) were employed in the simulation, to consider the interaction of sound with the mechanical structure of the sensor. The frequency responses of the two sensors correspond to 1 Pa plane wave at normal incidence acting on the sensors are shown in Figure 30.

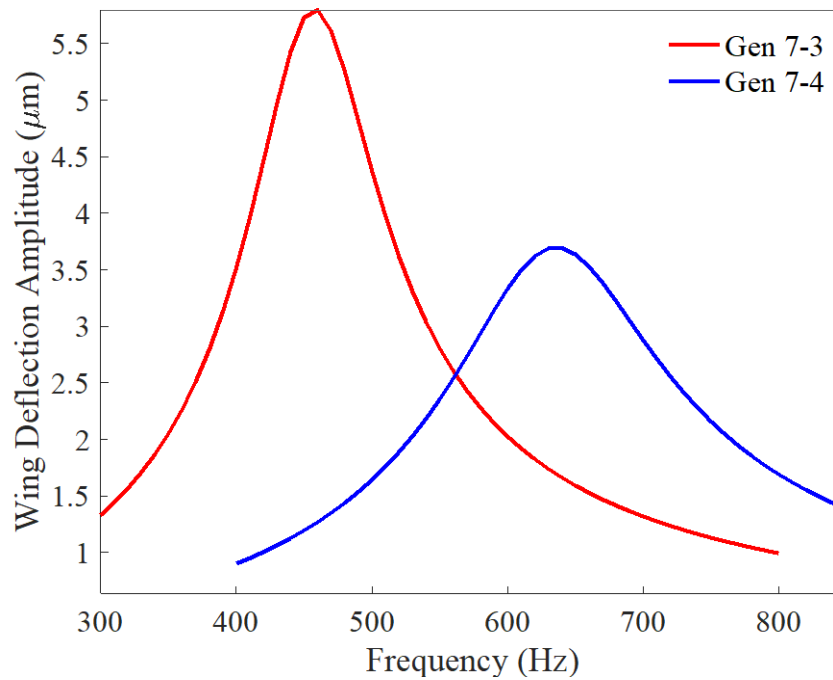


Figure 30. COMSOL Simulated Frequency Responses for Gen 7-3 and Gen 7-4 Sensors

The simulation results in Figure 30 show that the resonance frequencies are at 450 Hz and 640 Hz for the Gen 7–3 and Gen 7–4 sensors, respectively. The bridge of the Gen 7–4 sensor is twice the width of the Gen 7–3 which makes the bridge stiffer, increasing the resonance frequency of the sensor and reducing the oscillation amplitude. In addition to the increased resonant frequency, it was found that full width at half maximum (FWHM) increased from 100 Hz (Gen 7–3) to a 160 Hz (Gen 7–4). This is most likely due to higher drag dampening associated with larger surfaces from the increase of the bridge width.

3. Gen 7–3 Sensor Characterization

The Gen 7–3 sensor characteristics were measured using the SWT, where initially the backside of the sensor was oriented at normal incidence (0°) to the sound waves. The frequency response of the sensor was measured in the 250–650 Hz range and rotated in 15° increments for a full 360° . Using Equation 5 the measured sensitivity (V/Pa) of the MEMS sensor was calculated and plotted at various incidence angles. The results are shown in Figures 31 and 32.

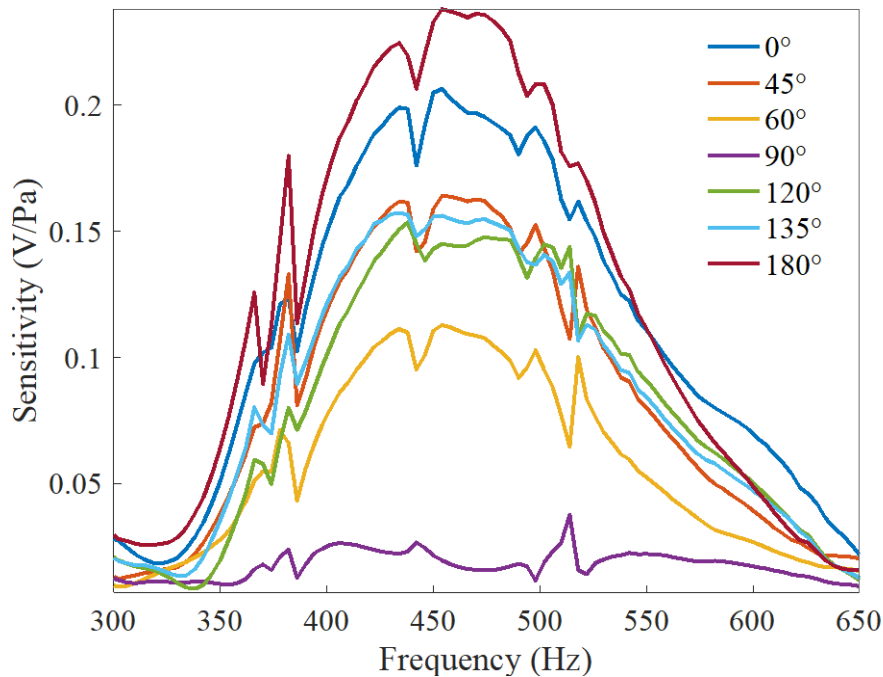


Figure 31. Gen 7–3 Sensitivity from 0° to 180°

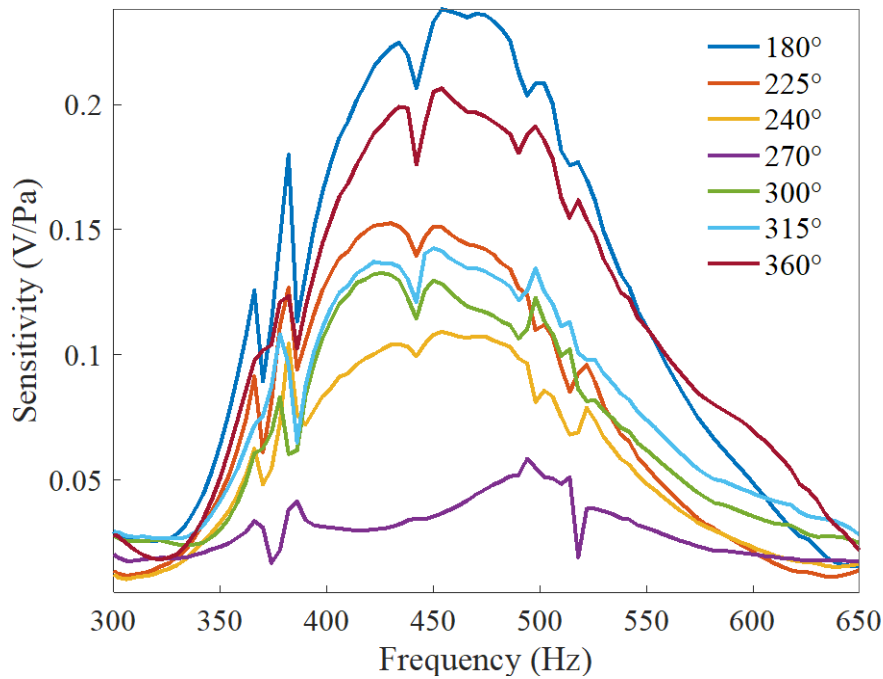


Figure 32. Gen 7–3 Sensitivity from 180° to 360°

The largest sensitivity corresponded to a pressure wave at normal incidence on the front of the sensor (180°), producing a resonance frequency of 454 Hz, and a sensitivity value of 0.24 V/Pa. The highest responses at 90° and 270° were 90 % less than the maximum resonance response measured and did not exhibit the same spectral characteristics as the measurements at other angles. Ideally, the MEMS sensor should not respond at these angles since the pressure gradient vanishes. This means any signal output at 90° and 270° from the sensor is likely influenced by the cylindrical rubber tube which was found to vibrate in response to incident sound. The resonance frequencies for each angle were all within 1% of 454 Hz indicating consistency through all orientations of the sensor.

As stated above, the magnitude of the response at normal incidence on the frontside of the sensor was slightly less than the backside of the sensor. The most likely cause of this is from the stress of the hose clamps placed on the encloser. However, the response pattern for both the backside and frontside of the sensor were nearly the same, indicating consistent performance through the full rotation of the sensor.

As the incident direction of the sound is varied, a distinct angular dependence can be seen from the results shown in Figures 31 and 32. Figure 33 shows the polar plot of sensor output amplitude at the resonant frequency of 454 Hz, where the frontside of the sensor corresponds to 0–180° and the backside corresponds to 180–360° respectively. The magnitude of the response on the backside of the sensor was 13% less than the frontside of the sensor, with significantly diminished outputs at 90° and 270°. The measured responses were normalized using the maximum value obtained, corresponding to sound at normal incidence on the front of the sensor.

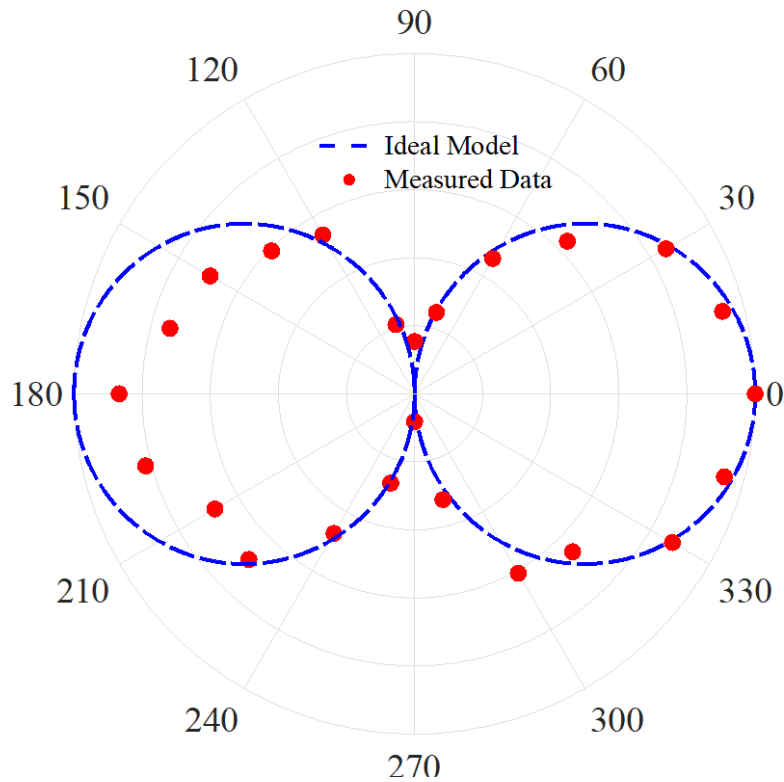


Figure 33. Polar Plot of Directional Response of Gen 7–3 Sensor at 454 Hz

The results indicate that the Gen 7–3 sensor does exhibit a directional pattern that is proportional to the cosine of the incidence angle. The most notable divergence is the magnitude difference between the back and front lobes, but these differences can be minimized with improvements to the enclosure assembly. The responses at 90° and 270° are not zero, which may require further refinement of housing material. However, the

sensor still produced a very significant reduction of sensitivity which can be easily distinguished.

For comparison, a plot of normalized COMSOL simulated and measured frequency responses are shown in Figure 34. The measured resonance frequency (454 Hz) was within 1% of the simulated while the measured FWHM (120 Hz) was 20% larger. Discrepancies between the measured data and simulated data are not unexpected because characteristics of the SWT, loudspeaker, and the rubber enclosure influence the response of the sensor. Regardless, the measured data shows good correlation to the simulated data.

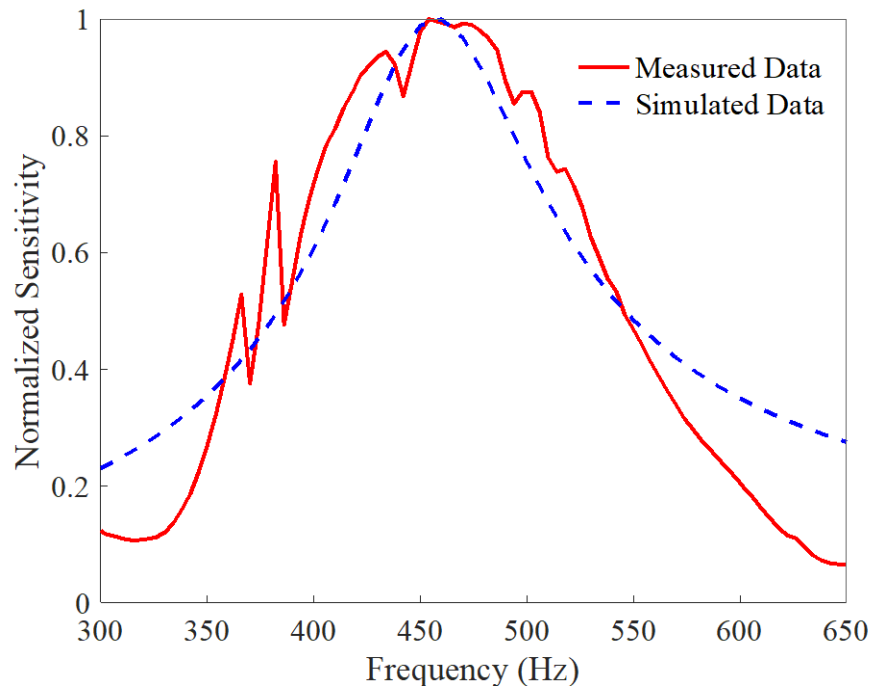


Figure 34. Gen 7-3 Simulated Versus Measured Frequency Responses

4. Gen 7-4 Sensor Characterization

The Gen 7-4 sensor was placed in the same starting orientation as the Gen 7-3 sensor: normal incidence on the backside of the sensor corresponding to 0° . The sensor response was measured over a frequency range of 450–850 Hz and rotated in 15° increments for a full 360° . Using Equation 5 the measured sensitivity (V/Pa) of the MEMS

sensor was calculated and plotted at different incidence angles. The results are shown in Figures 35 and 36.

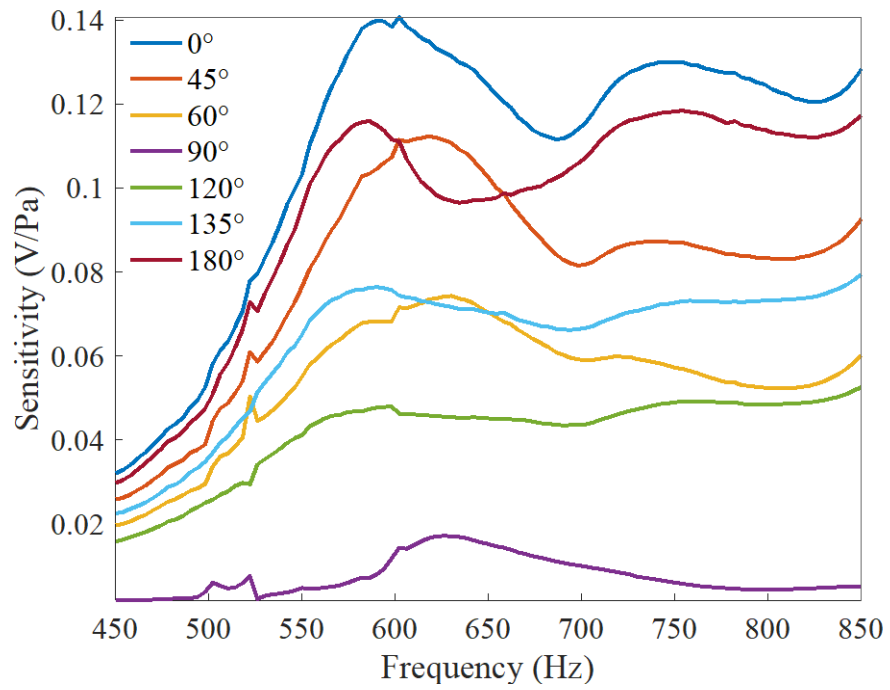


Figure 35. Gen 7-4 Sensitivity from 0° to 180°

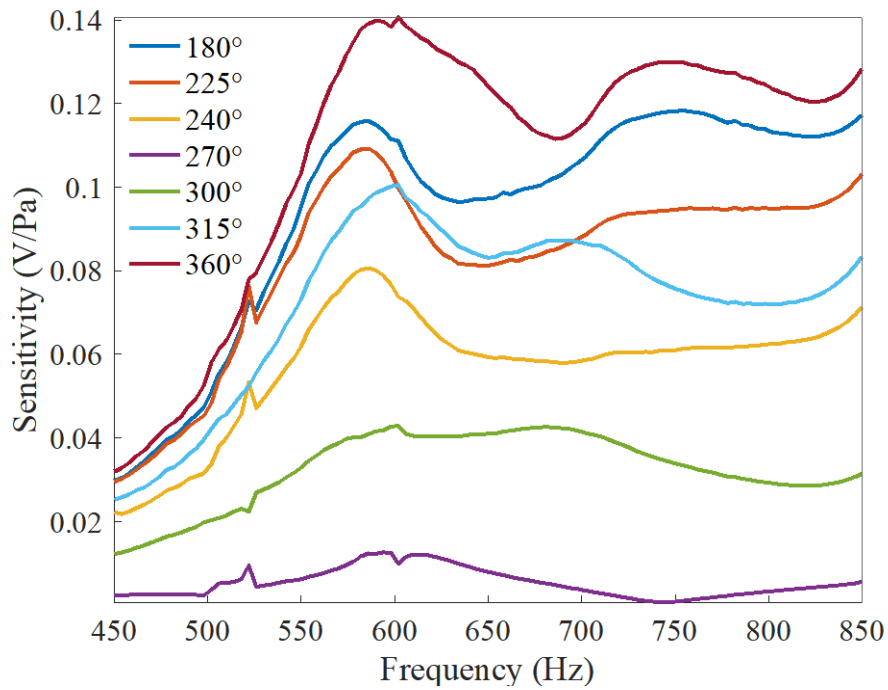


Figure 36. Gen 7-4 Sensitivity from 180° to 360°

In contrast to the Gen 7-3 sensor, the peak sensitivity occurred with sound at normal incidence on the back side of the sensor, at a frequency of 602 Hz with a value of 0.14 V/Pa. Peak responses decreased by about 90% at 90° and 270°, however the frequency response at 90° is not as flat as what was seen with the Gen 7-3 sensor, which can be associated to differences in the rubber enclosures used for each sensor. A variation of 8 Hz between the resonance peaks of each angular measurement was observed, corresponding to a 1% difference. Note that the precise determination of the peak position is difficult to find due to additional spectral features that are likely attributed to resonances of the rubber enclosure and standing wave tube, which requires further analysis to properly quantify.

The response of the Gen 7-4 sensor did exhibit an angular dependence as shown in Figure 37, where the frontside of the sensor corresponds to 0–180° and the backside corresponds to 180–360°, respectively. The peak response of the backside of the sensor was 16% larger than the frontside. The difference is likely caused by excess pressure on the rubber enclosure due to the hose clamp, which was also observed with the Gen 7-3 sensor measurements.

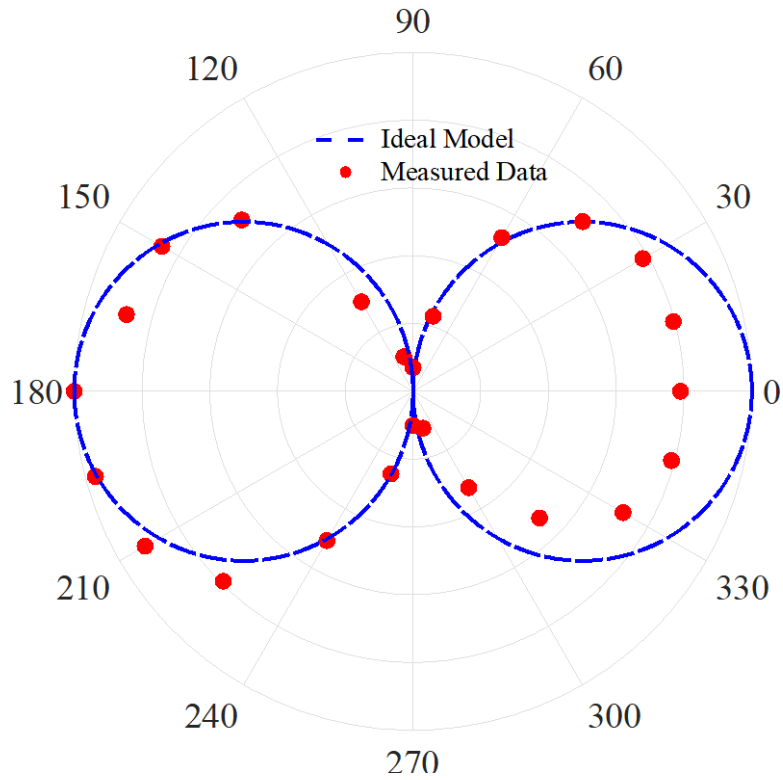


Figure 37. Polar Plot of Directional Response of Gen 7-4 Sensor at 602 Hz

A plot of normalized COMSOL simulated and measured frequency responses are shown in Figure 39. The measured resonance frequency (602 Hz) and FWHM (144 Hz) were 6% and 9% less than their simulated values, respectively. The harder enclosure material employed was found to attenuate (see Figure 27) the sound pressure inside the tube which in turns lower the signal of the MEMS sensor.

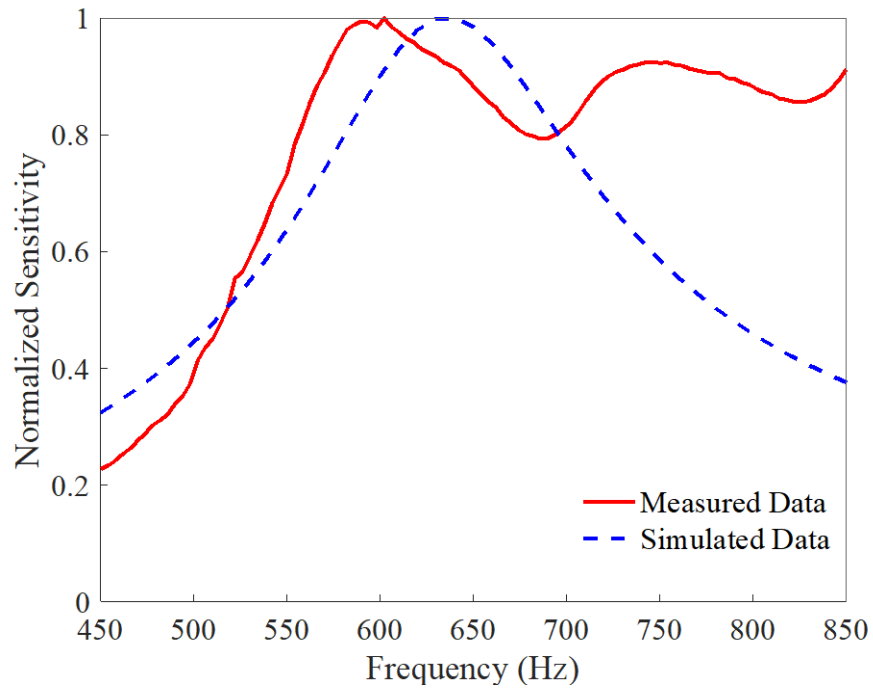


Figure 38. Gen 7-4 Simulated Versus Measured Frequency Responses

5. Gen 7-3 and Gen 7-4 Comparison

The COMSOL simulations suggest a 37% percent decrease in the output response of the Gen 7-4 sensor compared to the Gen 7-3 sensor due the different bridge sizes. The FWHM is also expected to increase by 60 Hz, due to the structural design differences of the bridge. Figure 39 shows measured sensitivities of the Gen 7-3 and Gen 7-4 sensors as a function of frequency.

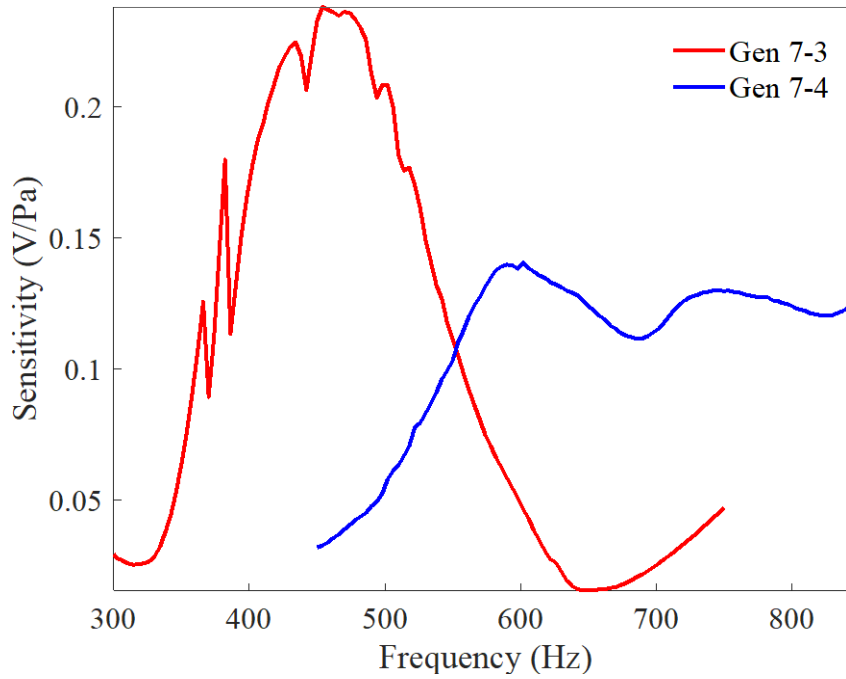


Figure 39. Gen 7-3 and Gen 7-4 Comparison

The results show a clear shift in the resonance frequency between the two sensors, as well as different bandwidths. A 42% reduction in the magnitude of the peak sensitivities can be seen, indicating the structural changes to the wing-bridge assembly produce measurable differences. The bandwidth change is difficult to estimate due to the broadening of the spectral response. Both the Gen 7-3 and Gen 7-4 sensors demonstrated expected cosine directional characteristics when placed in an underwater environment. The experimental data shows that MEMS based underwater directional acoustic sensors can be fabricated with detection frequency tuned to a narrow band based on the geometrical parameters of the mechanical structure of the sensor.

V. CONCLUSION

A. IMPLICATIONS OF RESULTS

The focus of the research conducted in this thesis was to characterize MEMS based directional acoustic sensors developed at NPS for operation in an underwater environment. For measuring the directional characteristics, it is necessary to have a plane acoustic wave incident on the sensor. Previous attempts to characterize these sensors using the existing water tanks at NPS and TRANSDEC found that reflection of sound waves from the surface and walls interfered with the measurements. These issues led to the development of a new sensor characterization setup using a standing wave tube. The standing wave tube can generate a plane-wave sound field which is suitable for characterization of acoustic sensors. It was found in this work that the SWT did generate a plane wave which significantly increased the accuracy of the characterization of MEMS directional acoustic sensors.

In this research, two MEMS directional acoustics sensors (Gen 7–3 and Gen 7–4) with different resonant frequencies were characterized using the SWT. Measurements of frequency responses showed a distinguishable shift in the resonance frequency between the Gen 7–3 and Gen 7–4 sensors, as expected. Both Gen 7–3 and Gen 7–4 sensors sensitivity responses showed a good correlation to that of the simulated measurement; both were less than 10% different than that of the simulated responses. Adverse effects such as imperfections of the enclosure assembly cannot be considered in the simulation environment, which is a contributing factor to the differences seen.

The directional pattern of both sensors showed similar characteristics to that of a pressure-gradient sensor, exhibiting a cosine dependence. The magnitudes and shapes of the front and back lobes were different in both cases, but when accounting for the effects the enclosure has on the sensor's characteristics, these discrepancies are expected.

The obtained results represent a significant advancement on underwater sensors characterization capabilities at NPS. Furthermore, it validates the finite element models used to design MEMS acoustic sensors for underwater operation.

B. RECOMMENDED FUTURE WORK

Ideally, the response of the B&K 8103 hydrophone inside the housing would be flat because the sensitivity of the hydrophone in the frequency regime analyzed for this thesis is constant. Resonances of the tube and operating characteristics of the loudspeaker introduces unwanted spectral features. The most distinguishable feature measured is the resonance around 900 Hz which can be attributed to the SWT. In theory, this resonance can be shifted by adjusting the water column height, which would likely shift the resonance seen at 900 Hz and provide a flatter response throughout the operating frequency spectrum of the MEMS sensors.

The rubber cylindrical enclosure assembly impacts the response of the sensor in various ways. Specifically, it can attenuate the incoming sound wave and alter the directional characteristics. An alternative enclosure structure and materials should be investigated to reduce these undesirable characteristics of the rubber encloser. Additionally, sealing the enclosure with a gasket or an o-ring on the inside, would remove the excess pressure and defamations that are caused by clamping the enclosure on the outside.

In previous research, directionality of the MEMS sensors has been tested in a neutrally buoyant configuration where the sensor is housed in an air cavity. This eliminates the need for the use of a rubber based housing which can reduce some of the reported issues. It would be worthy to explore the possibility of adapting the SWT to characterize the sensors operating in a neutrally buoyant configuration.

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