Investigation and Design of a Towable Hydrophone Array for General Ocean Sensing

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***Abstract*— An eight-element oil-filled hydrophone array is used to measure the acoustic field in littoral waters. This prototype array was deployed during an experiment between Jeffrey's Ledge and the Stellwagen Bank region off the coast of Rockport, Massachusetts USA. During the experiment, several humpback whale vocalizations, distant ship tonals and high frequency conventional echosounder pings were recorded. Visual confirmation of humpback moving in bearing relative to the array verifies the directional sensing from array beamforming. During deployment, the array is towed at speeds varying from 4-7 kts in water depths of roughly 100 m with conditions at sea state 2 to 3. This array system consists of a portable winch with array, tow cable and 3 water-resistant boxes housing electronics. This system is deployed and operated by 2 crew members onboard a 13 m commercial fishing vessel during the experiment.**

Non-acoustic sensor (NAS) information is obtained to provide depth, temperature, and heading data using commercial off the shelf (COTS) components utilizing RS485/232 data communications. Acoustic data sampling was performed at 8 kHz, 30 kHz and 100 kHz with near real-time processing of data and enhanced Signal to Noise Ratio (SNR) from beamforming. The electrical system components are deployed with 3 stacked electronics boxes housing power, data acquisition and data processing components in water resistant compartments. A laptop computer with 8 TB of external storage and an independent Global Positioning System (GPS) antenna is used to run Passive Ocean Acoustic Waveguide Remote Sensing (POAWRS) software providing beamformed spectrogram data and live NAS data with capability of capturing several days of data. The acquisition system consists of Surface Mount Device (SMD) pre-amplifiers with filter to an analog differential pair shipboard COTS acquisition system. Pre-amplifiers are constructed using SMD technology where components are pressure tolerant and potting is not necessary. Potting of connectors, electronics and hydrophones via 3D printed molding techniques will be discussed.

Array internal components are manufactured with Thermoplastic Polyurethane (TPU) 3D printed material to dampen array vibrations with forward and aft vibration isolation modules (VIM). Polyurethane foam (PUF) used to scatter breathing waves and dampen contact from wires inside the array without attenuating high frequencies and allowing for significant noise reduction. A single Tygon array section with a length of 7.5 m and diameter of 38 mm contains 8 transducer elements with a spacing of 75 cm (1 kHz design frequency). Pre-amplifiers and NAS modules are affixed using Vectran and steel wire rope positioned by swaged stops along the strength member. The tow cable length is 100 m with a diameter of 22 mm that is potted to a hose adapter to break out 12 braided copper wire twisted pair conductors and terminates the tow cable Vectran braid.

This array in its current state of development is a low-cost alternative to obtain quality acoustic data from a towed array system. Used here for observation of whale vocalizations, this type of array also has many applications in military sonar and seismic surveying. Maintenance on the array can be performed without the use of special facilities or equipment for dehosing and conveniently uses castor oil as an environmentally safe pressure compensating and coupling fluid. Array development including selection of transducers, NAS modules, acoustic acquisition system, array materials and method of construction with results from several deployments will be discussed. We also present beamformed spectrograms containing humpback whale downsweep moans and underwater blowing (bubbles) sounds associated with feeding on sand lance (Ammodytes dubius).

Keywords: Acoustics, Array, Signal Processing

I. Introduction

Hydrophone array technologies have seen vast improvements over the past several years with high resolution Analog to Digital Converters (ADC), lightweight fiber-optic tow cables and real-time hardware to process data [1], [2], [3]. With rapid-prototyping technology, 3D printing Thermoplastic Polyurethane (TPU), low-cost multilayer printed circuit board manufacturing and sensor components being readily available, low cost high-quality acoustic arrays are realizable. Single element hydrophones with simple recorder systems are abundant in the field but do not provide the directional sensing, Signal to Noise Ratio (SNR) enhancement and the ability to survey and monitor wide areas. The robust expansion of ocean acoustic sensing has primarily been held back by the lack of affordable multi-sensor systems as the ability to analyze this data becomes more widespread.

Here we investigate the hardware development cycle with testing in theatre a prototype hydrophone array in the waters off the coast of Rockport, Massachusetts USA. On the morning of 23OCT18 FV Karen Lynn departed Gloucester, Massachusetts with science crew of 5. The survey area consisted of a 18.5 km radius offshore of Rockport with sea state and winds increasing toward the end of the experiment. This window of opportunity led us to several recordings of multiple humpback whales feeding on sand lance.

II. Array Design Criteria

In this design our target of interest is Baleen whales that typically vocalize below 1 kHz and low frequency ship tonals. While general ocean sounds are of interest, the design frequency must be considered to avoid spatial aliasing and to set the criteria for sampling to avoid temporal aliasing. The ability to determine the bearing of a target and increase SNR is directly related to the design frequency. To eliminate spatial aliasing, we set the array inter-element spacing to twice the wavelength of interest. With this target design spacing, the beam pattern will be free of grating lobes up to the 1 kHz design frequency for narrow-band signals with a gain of 9 dB at the design frequency with 8 elements [4]. The sampling rate is adjustable from 8 kHz, 30 kHz and 100 kHz to exceed Nyquist rate for the design frequency.

For evaluating and testing components, ideally all of the components can easily be reproduced, transported with minimal personnel and deployed on small vessels of opportunity. This limits the array length to be shorter so it may be handled without use of cranes or special equipment. A tow cable length of 100 m is typically a minimum cable length to achieve sufficient distance between the array and the tow vessel even for a small twin outboard tow vessel. Tonals and broadband sounds from the tow ship are typically dominant in forward endfire for this length although the self-noise does not limit targets of interest from this region as they will not be completely overwhelmed.

At the design frequency the far-field zone for this array is 24 m which is acceptable for the targets of interest. With directional sensing in a linear uniformly spaced array, there exists a left-right ambiguity that can be resolved with maneuvering. This can prove difficult in some cases on a small vessel depending on sea state. The technique requires a sharp turn or several sharp turns to break the ambiguity. Depending on the activity of the target, it may be necessary to repeat this several times. Tracking a target directly broadside is ideal for the finest resolution and gain but is often difficult as a beam-sea or unfavorable following sea will dictate maneuvering on small craft.

III. ARRAY CONSTRUCTION

Passive hydrophones require a resonant frequency that is much higher than the desired frequency of interest to provide linear gain over this frequency. Navy Type II Lead Zirconate Titanate (PZT) are ideally suited for passive applications. Hydrophone sensitivity is a function of size and frequency which in this case for an array system the hydrophone size should be kept to a minimum. Using series-stacked air backed PZT allows for minimal size and high sensitivity [5]. The region of interest is below 50 kHz making the overall specifications for the hydrophone to be based on this figure. Here we test hydrophones with sensitivity ranging from -185 to -210 dB re 1μPa.

The hydrophones are potted with a clear liquid polyurethane 95 Shore A hardness with a specific gravity of 1.04 g/cm^3. Disposable Polylactic Acid (PLA) material is used as a mold shell with 4 small standoffs in the bottom of the mold to give a thickness offset on the base. These standoffs are then drilled out and refilled with polyurethane. The polyurethane is degassed before pouring to ensure a uniform acoustic window and allows for visual inspection of any defects after the potting process [6].

Flexible TPU mounts are 3D printed using low density infill to reduce vibrations induced by strength member attachment. Each hydrophone has a low density TPU mount that holds the hydrophone in place with zinc-plated copper swage locks to prevent movement. All wires passing by and attaching wires are secured away from the transducer to prevent contact while underway. Careful cable management is critical to prevent noise from objects inside the array colliding with the hydrophone face. The orientation and routing of the wires are of little consequence in attenuating or otherwise distorting the incoming pressure waves. Additionally, 10 PPI Polyurethane Foam (PUF) is used to scatter breathing waves and dampen contact from wires inside the array. The PUF is placed fore and aft of the hydrophone with a thin layer wrapped around the hydrophone element area. This method does not attenuate high frequencies and allows for a significant noise reduction.

The array tow cable has a double jacketed polyurethane coating that is reinforced with Vectran fiber, twelve 0.75 mm^2 twisted pairs wrapped with Mylar and Polyvinyl Chloride (PVC) filler. Two cable to tube adapters were tested using 316 stainless machined parts. A cable/tube adapter with a direct potting method, this design is similar to [7] with added features for filling and strength member termination. The second design is a Cable Connector Plug (CCP) molded to the tow cable using 2-part 80 Shore D hardness epoxy and a Bulkhead Connector Receptacle (BCR) threaded to an adapter. Connector potting is carried out using 3D printed molds that can be cut away after use.

Tygon B-44-4X tubing is used for the array section as it has a high resistance to chemicals, Ultra Violet (UV) rays and is resistant to abrasion. A forward void section and a 50 m aft tail rope provide vibration isolation. Rigid bodies of TPU are placed between the elements to keep the transducer section linear. Two Vectran braids are used for strength member attachment and tensioning. The forward end has two Vectran strands directly potted or mechanically terminated by two M6x1 screws in the adapter and the aft end uses a slotted cross to have tension applied and the Vectran terminated. The tubing is secured to the barbed end of the adapter by heat-shrink clamps to maintain a seal as seen in Fig.1.

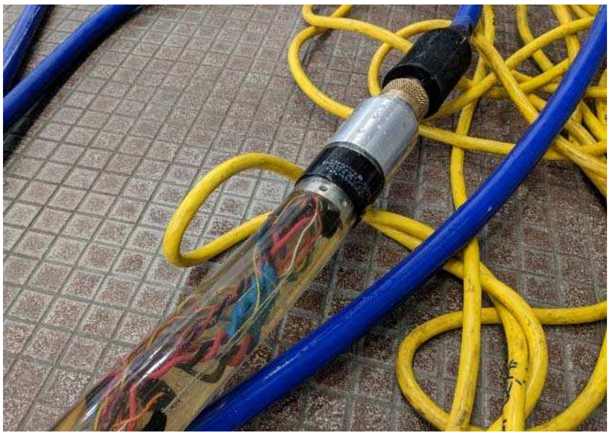

Fig. 1. Array Connector and Adapter Body

Using 3D printed material allowed for molds of any shape to be quickly tested. The best filament for molding that was tested is T-Glase printed at 0.1 mm layer height and prepared with a light coating of mold release. This provides a clear mold to see any potential trapped air and comes off easily. For components that are potted, and the 3D print is not cut away, Acrylonitrile butadiene styrene (ABS) plastic that is UV and chemical resistant is used. Sulfur free modeling clay or electrical tape is used to seal off edges around cables or removable parts. A 3D printed box is used to pot the connector with a silicone rubber mold cast. The mold box has alignment dowels keep the box halves centered and clamps are placed on the outside to create a seal. Adequate venting is used for the mold box and the excess areas are trimmed off after curing.

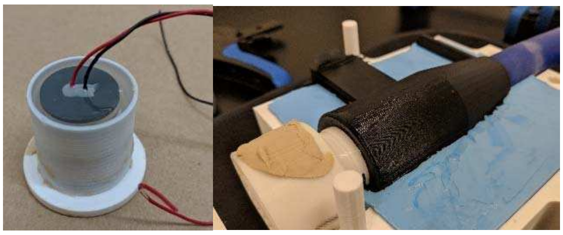

Fig. 2. Potting Hydrophone and Test Cable

Pre-amplifiers are placed in the array using TPU mounts with the pre-amplifier leads soldered directly to the hydrophone. Each pre-amplifier has a second order Sallen-Key architecture high-pass filter implemented to filter out low frequency noise (<10 Hz). The gain of the preamplifier (40 dB) and filter corner frequency is fixed for this experiment. Selection of an instrumentation amplifier is ideal for this case with ultra-low noise FET input, high input impedance and low input bias current (10 pA). Differential pair output provides noise cancelling for transmission in the tow cable. The signals are received on a 24-bit ADC with adjustable sample rates up to 105 kHz. Signals are directly captured in MATLAB and are immediately processed for viewing.

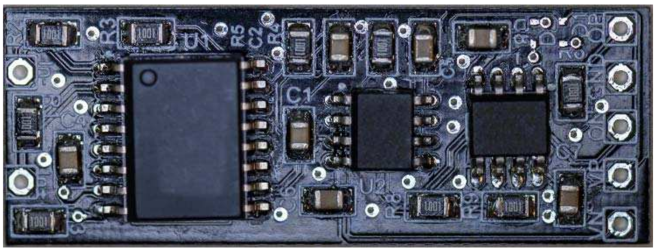

Fig. 3. SMD Preamplifier

Selection of Surface Mount Devices (SMD) for pre-amplifier and other components subject to pressure is critical. Internal voids in components such as electrolytic capacitors or crystal oscillators will fail under pressure. Here we use ceramic capacitors, metal film resistors and SOIC-8/16 packages. For integrated circuits FET op-amps are used and all components perform well over time with pressure cycling. For ease of installation and to ensure fewer variable changes in revisions, later models included pre-amplifiers potted in tubes or mounted directly to the hydrophone. When potted the pre-amplifiers are connected by solid 0.644 mm tinned solid copper wire to connect the input/output of the amplifier. These solid copper wires are pressed into modeling clay and and potting is carried out using 3D printed tubes filled with clear 83 Shore D 2-part epoxy.

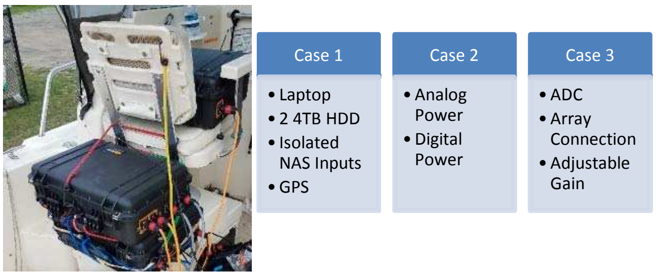

Fig. 4. Array electronics deployed on RV Kraken

Three water-resistant cases are used to house electronics with interconnect between boxes for AC/DC power and data. Connectors are all IP68 rated commercial off the shelf (COTS) connectors. A laptop with an i7-8550U processor and 16 GB of RAM and a 512 GB SSD is mounted to the workstation box that houses two 4 TB HDD with shock-proof mounting. Interfacing to ADC and Non-Acoustic Sensors (NAS) is over USB with isolators on the serial lines to prevent noise in the analog portion of the system. Electronics boxes are typically stacked as seen in Fig.4.

The tow cable is wound on a spool that does not use a slip-ring, therefore the tow cable must be disconnected from the electronics to be pulled in/out of the water in situations with limited deck space. During towing, lace-up grips are typically used when a block is not available. In a scenario where the array is deployed vertically, chafing gear is used and the tow cable is tied off to a cleat. This system uses a portable hand winch to deploy and retreive the array, the connector end is simply attached to the drum during this process.

Fig. 5. Array being deployed on RV Kraken and FV Karen Lynn

A heading sensor is potted and affixed in the forward section of the array to provide magnetometer and accelerometer data used to calculate array heading. In the aft section a pressure sensor and thermistor is affixed to provide depth and temperature data. Each sensor is secured in similar fashion using 3D printed high-infill TPU mounts that are swaged to the strength member.

The array components are spaced accordingly along the strength member and swage locks are crimped in place. Wiring is then dressed leaving periodic service loops. Between each hydrophone element a rigid TPU spacer is placed to provide wire organization and to keep the array section linear. The crimped string of components is then pulled through the tube using a cross woven poly strapping cord that is sent through the tube using compressed air. This leader cord is tied to a hand winch and force gauge to monitor the pull. All of the components are lubricated with castor oil prior to entering the tube. The array is then filled by vertically hanging the tube section with the aft end toward the top. The castor oil is viscous and will need time to fill the entire tube as it passes by the PUF and components. There will still be a considerable amount of air trapped within the array, during deployment this is expelled from the pressure at maximum depth. This is done by deploying the array vertically at the beginning of an experiment and extending the tow cable out to maximum.

A Global Positioning System (GPS) antenna is mounted to the workstation electronics case. All of the sensor data is handled in Python which is then saved in MATLAB format for processing. A readout of depth is printed in a terminal to ensure the array does not run aground in shallow operation. Additionally, the GPS data, heading and depth data can be viewed using Open Chart Plotter Navigation (OpenCPN) in real time.

Fig. 6. OpenCPN Track during experiment (Black) 18.5 km range ring from vessel (Red)

IV. Results

Data is processed using MATLAB to produce beamformed spectrograms. Beamformed spectrograms are produced in 8 bearings $\pm\ (90°, 45°, 25°, 8°)$ where 90° corresponds to forward endfire and -90° to aft endfire with data recordings of 60 second segments sampled at 8 kHz. A linear discrete array beamformer is used with a Hann window as described in [8].

Upon arriving to the site no whales were present in the area and moving further offshore from ANZ251 to ANZ250 proved to be difficult with rising wave height and wind speed, making visual observation difficult to see spouts. Without any visual observation of our target we picked up a down-sweep moan in Fig.7 that is characteristic of a humpback whale.

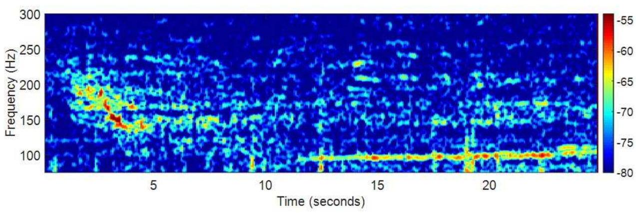

Fig. 7. Down-sweep moan

Moving the array into broadside from the bearing estimated from the direction with the highest SNR, we then observe in Fig.8 a humpback moving in bearing making a mid-frequency tonal wail [9], [10]. The whale surfaced several times and we were able to track the whale relative to the array heading. During the segment the range of the whale is approximately 2 km from the array with the whale surfacing periodically so we can assume most of the vocalizations are made very close to the surface (within 30 m depth). The intensity of segment A suggests that the heading of the whale was directly at broadside to the array during that time period. For section B the whales heading based on surface observation was in the direction of aft endfire, with the 120 second mark being the closest point of arrival. In section C and D, the whale was close to the surface and was not diving. With the whale being close to the surface we observe a Lloyd Mirror Effect (LME) with the received signals causing the distinct LME interference pattern in Fig.8 [4], [12].

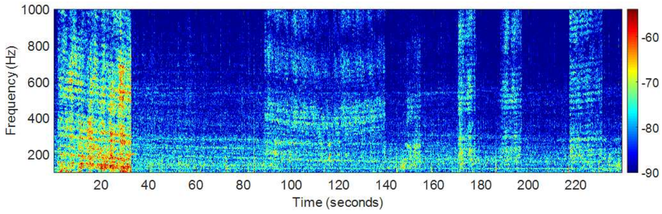

Fig. 8. Humpback Whale Vocalizations A(0-60 sec 25°) B(60-120 sec 8°) C(120-180 sec -8°) D(180-240 sec -25°)

While underway to determine bearing and heading to place the array broadside quickly, we observe the beamformed spectrograms to determine the direction of maximum energy for our signal of interest. In Fig.9 there is a clear SNR enhancement in the 25° bearing. Using this information, we guide the array into the broadside position providing optimal SNR enhancement.

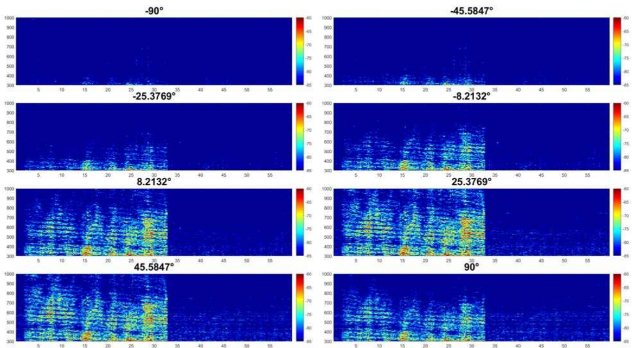

Fig. 9. Beamformed Bearings

During this time period multiple humpbacks were sighted and another whale watching vessel approached the area roughly 3 km from the array. Strong frequency wavering narrowband tonal signals, characteristic of propeller noise [5] were detected in the bearing of the incoming ship with center frequency of 565 Hz in Fig.10.

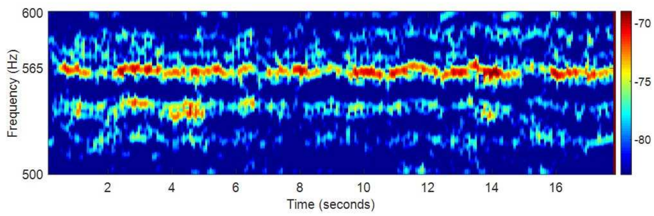

Fig. 10. Ship Tonal

V. Conclusion

This array in its current state of development is a low-cost alternative to obtain quality acoustic data from a towed array system. We demonstrate here that this array can be used for observation of whales and ship tonals at ranges up to 5km. Receiving acoustic signals from target of interest with enhanced SNR and directional sensing capabilities. Marine mammal vocalizations have been captured by this prototype array and the whale species has been identified by visual observation.

Current array technologies are typically cost prohibitive for many institutions. Array systems such as the Five Octave Research Array (FORA) [3] have been a valuable tool to the ocean acoustics community but require costly ship time and a large maintenance period. Using rapid prototyping methods and procedures that do not require specialized tooling can produce a high-quality array for test and evaluation of devices. Using methods and design work presented here, the future of array hardware can be realized at a significant cost reduction.

Acknowledgments

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