# Taking Sub in School to the next level – Acoustic Testing

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Re-Engineering Australia (REA), Defence Science & Technology (DST), Australian Submarine Corporation (ASC) and industry partners developed the Subs in Schools (SiS) program to engage Australian students in STEM subjects. The program has been running in secondary schools for over five years and requires students to design, manufacture and test submarine hull model forms. The program is aligned with generating interest in the growing Australian shipbuilding industry and preparing young Australians for a career in engineering to contribute to the Royal Australian Navy (RAN) and innovative industries alike. This work aims to expand the current testing criteria through implementing an acoustic testing regime in the SiS competition. The competition seeks to simulate applicable and 'real life' tests, whilst exploring the theory of sound within the context of SiS, thus the inclusion of acoustic testing in the sea trials aspect of SiS would align with the reality of the operational requirements of submarines. The acoustic testing included underwater measurements with hydrophones and a stationary model submarine, tests conducted in an isolated, insulated air medium (acoustic testing box) and resonance analysis and mitigation of the submarine as a structure. For testing and analysis purposes, comparison of the underwater and air data was undertaken to analysis the effect of mass loading and damping of the propeller and structure as a whole (stationary tests).

Outcomes of this research are expected to be, the recorded acoustic data on the model submarine for further benchmarking, extrapolation of underwater acoustic data to in-air data, an educational module on underwater noise and development of an acoustic testing system for the SiS competition.

## INTRODUCTION

The question, 'Can additional trials be included in the Subs in Schools competition to test realism?', has inspired the need for this research. Research and initial testing were conducted to establish the feasibility of underwater acoustic testing. Due to the small scale of the submarine and surface models measured the source noise was not distinguished against the ambient underwater noise level, and thus raw data could not be processed in a meaningful way. Testing was then moved to the air medium, where the effect of damping from mass loading on the propeller and structural vibrations was expected to increase to the source noise, in conjunction with the propagation characteristics of noise in air when compared to water.

This paper is limited to the application of acoustic testing underwater and in air, at a model scale, and primarily within the SiS program. Though it does seek to imitate real engineering design tests. There has been considerable research in the field of underwater acoustics, for communication and military purposes, but not so of acoustic testing of model submarines at this scale, in both the underwater domain and in air, hence this paper explores the phenomena of the existing literature at model scale and its applicability to SiS and actual scale testing.

This paper seeks to determine if stealth can be measured in the Subs in Schools competition. It seeks to do this through conducting acoustic tests in both air and water domains. The output noise of a machine is a key indicator of the quality of build and efficiency of the system. Thus, through acoustic testing, inefficiencies can be found and mitigated. Through testing in two distinct mediums, the difference and similarities of the results in each medium will be analysed and comparisons drawn where applicable.

**METHODOLOGY**

The primary method of transmitting and receiving underwater signal are piezo-electric transducers. Whilst processes such as magnetostriction, hydraulics (mechanics) and electrodynamics, have been used in specific applications successfully, this research will employ piezoelectricity in a passive sonar function to measure signals.

Optics in underwater testing have been used successfully, mainly testing for the presence for turbulence, through the phenomena of refraction, but this approach is too limited for the purpose of this research. In the underwater testing, a Bruel & Kjaer hydrophone was used as the probe in conjunction with PicoScope PC oscilloscope and software. Test were conducted in a stationary tank, with the model submarine prevented from moving forward by foam stops.

In order to test for stealth, there must be a consistent baseline, which different models can be measured relative to, in order to be compared to each other. A portable acoustic testing box was manufactured for this purpose. The tests conducted in air were done with a Bruel & Kjaer Microphone used with supporting apparatus including an internal pre-amplifier and input/output measuring amplifier.

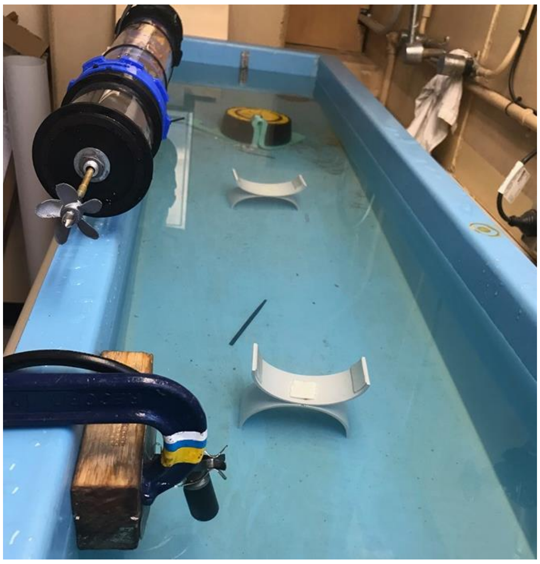

**Figure 1:** Initial Underwater Test Setup

## EXPERIMENTAL SETUP

### Measuring Acoustics

The basic premise of measuring sound waves in both mediums discussed thus far, is similar. Using a hydrophone/microphone, an transducer employed in a passive mode, to detect fluctuations in pressure, through the piezo-electric effect, thus giving a voltage signal through an oscilloscope, which can be read through appropriate software on a PC, and interpreted by applying known scaling factors of the respective probe.

Water as a propagation medium has many distinct differences from air as a propagation medium, some beneficial and others detrimental to wave propagation. Electromagnetic radiation suffers little attenuation in the air and can travel great distances, whilst sound lacks penetration and suffers high levels of attenuation. Underwater the roles are reversed. Acoustic waves travel at 1482 m/s in water at 20°C (4.32 times the speed of sound in air at 20°C), thus they can travel large distances with less attenuation. The dB scale will be used to measure pressure level of the sound wave. The log scale is used because such a vast range in sound intensities are encountered, in air and water.

$$SPL = 20 \times log_{10}\left(\frac{P}{P_o}\right)$$

Where SPL = level of sound pressure
P = measured sound pressure
Po = reference sound pressure (taken to be 1 μPa underwater and 20 μPa in air)

The differences in reference pressure and impedance of the medium and the defining factors in analysing the differences in the measured signals, but for the purpose of this report an arbitrary power level will be used to easily compare signals.

$$Voltage\ Signal\ in\ dB\ scale = V_{dB} = 10 \times log_{10}(V)$$

Impedance describes a measure of opposition to alternating current (Butler & Sherman, 2016). The impedance of water is 3500 times greater than air thus, a sound in water with a given pressure, is 3500 less intense in air (Lurton, 2002). Reciprocally, if a sound in water and another in air have the same intensity, then the pressure is much smaller in air.

$$c = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{1}{\chi\rho}}$$

Where
$c = bulk\ speed\ of\ sound\ in\ medium\ (\frac{m}{s})$
$E = Elastic\ Modulus\ (Pa)$
$\rho = density\ of\ medium\ \left(\frac{kg}{m^3}\right)$
$\chi = compressibility\ coefficient\ (\frac{m^2}{N})$

Through use of the wave equation,

$$\lambda \times f = c$$

Where
$\lambda = wavelength\ (m)$
$f = frequency\ (Hz)$
$c = bulk\ speed\ of\ sound\ in\ medium\ \left(\frac{m}{s}\right)$

Comparisons can be drawn between tests underwater and in air, within the frequency domain.

**Instrumentation**

The below tables detail the equipment used in testing and some key characteristics of the respective equipment.

Table 1: Amplifier 2610 Specifications

| **Model** | 2610 |
|---|---|
| **Gain** | 0.003 - 50 |
| **Frequency Range** | 2 Hz – 200 kHz |
| **FSD** | 10 µV – 30 V |
| **Mass** | 5.2 kg |

Table 2: Microphone Specifications

| **Model** | 4147 (4193 new) |
|---|---|
| **Voltage sensitivity** | 12.5 mV/Pa |
| **Frequency Range** | 70 mHz to 20 kHz |
| **Polarization** | 200 V |
| **Preamplifier** | Type 2639 |

Table 3: Oscilloscope Specifications

| **Model** | 2205A |
|---|---|
| **Bandwidth** | 25 MHz |
| **Memory** | 16 kS |
| **Sample Rate** | 200 MS/s |
| **Input Sensitivity** | 4 mV/div to 4 V/div |
| **Voltage Resolution** | 12 bit |

Table 4: Transducer Specifications

| **Model** | 8104 |
|---|---|
| **Voltage sensitivity** | 56 uV/Pa ± 15 uV |
| **Frequency Range** | 0.1 Hz to 10 kHz |
| **Length** | 120 mm |
| **Mass (inc. cable)** | 1.6 kg |

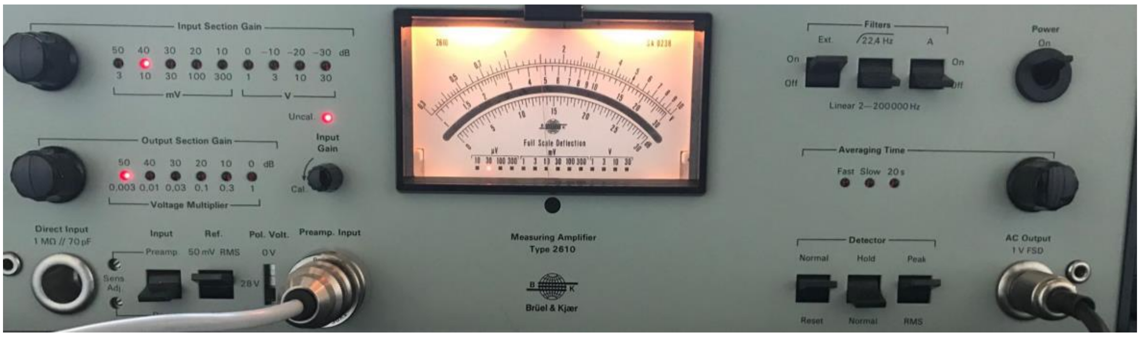


**Figure 2:** Measuring Amplifier used in Air Tests

**TEST CONDITIONS**

Although both the microphone and hydrophone have designated sensitivities, these are more nominal values than absolute values. The microphone was able to be calibrated using a designated calibrator as a known sound source, but the hydrophone was unable to be calibrated, thus the nominal sensitivity was used.

**Fundamental Frequency (RPM)**

For comparisons to be drawn between the two mediums, the source of sound must be operating under the same parameters in both mediums. Rudimentary methods can estimate the RPM using the max RPM of the brushless DC motor and the power setting of the controller, but to accurately determine the RPM of the shaft, hence fundamental frequency, a digital tachometer was used in later tests.

**Underwater**

The underwater testing was conducted in a $1520\ mm\ \times 350\ mm$ test tank with water at a depth of 180mm. The model submarine running at minimum RPM (approximately 15% of full power at 3000 RPM). The model was prevented from moving forward by foam stops held down by a 10kg weight. The probe was then placed 100mm adjacent to the propeller at the same depth level, xx mm underwater. The probe support was clamped to the side of the test tank.

**Air**

An acoustic testing box was purpose designed for gathering air data for the model submarine operating under the same conditions as the water tests. The dimensions of the acoustic testing box are 1200 mm x 400 mm x 300 mm (less the sound absorbent material thickness for internal space). Ambient conditions in the anechoic chamber were compared to the acoustic testing box to validate the use of the box as an isolated and insulated testing medium and illustrate its limitations.

Three calibration tests using a Bruel & Kjaer ½ inch microphone calibrator yielded the following average microphone sensitivity, known sound source of 94dB read 241.2 mV on PicoScope with input gain set to 1 and output gain set to 0.3. Thus 94 dB correlates to 72.40 mV, therefore for testing purposes a microphone sensitivity of 1298.34 dB/V will be used for air measurements.

**Processing**

Acoustic analysis was processed using PC Picoscope 6 as the interface. MatLab R2018a was then employed to further analyse the raw data through domain transformations and relevant scaling.

**Gain**

The gain of the pre-amplifiers using in underwater testing were both set to 20 dB, which correlates to a factor of 10 in voltage gain, through use of the logarithmic relationship between power and dB. Therefore, the output voltage of the underwater signal was divided by 100 ($\frac{1}{10\times 10}$) to determine the actual voltage signal. Due to the differing signal intensities measured when testing different propellers, a non-constant voltage multiplier had to be used to obtain the most suitable signal. An input gain of 1 was used across all air tests and the output voltage multiplier was 0.3 for the three bladed propeller and 0.1 for the four and five bladed propellers.

## Results and Discussion

### The Influence of the Testing Environment and Propeller Configuration

For the underwater tests above, the noisy signal depicts no significant change in spectral tones with a change in number of propeller blades. The tones seen are relatively consistent among the three different tests and would seem independent of the number of blades. This suggests the fundamental frequency of the propeller, shaft and model is driven by something other the Blade Passing Frequency (BPF).

**Varied Propeller Data Underwater**

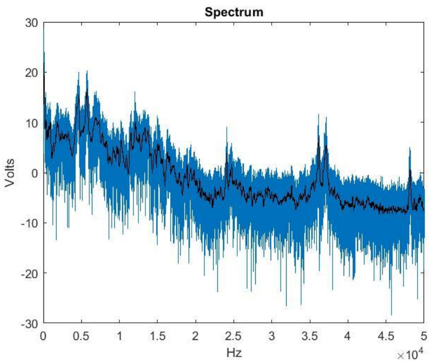


Figure 3:Three Blade Propeller

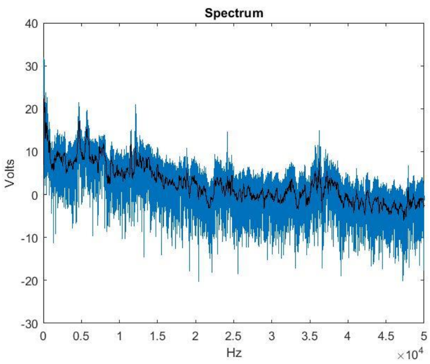


Figure 5:Four Blade Propeller

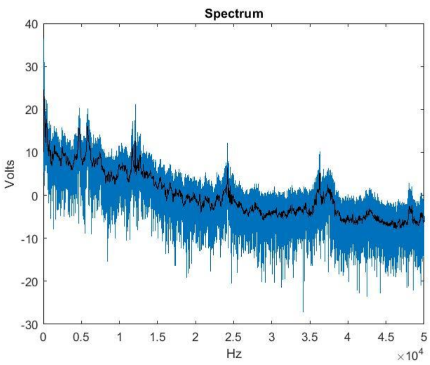


Figure 7: Five Blade Propeller

**Varied Propeller Data in Air**

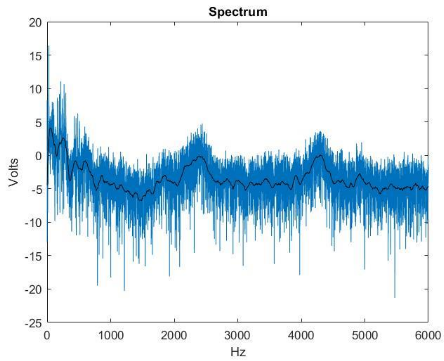


Figure 4: Three Blade Propeller

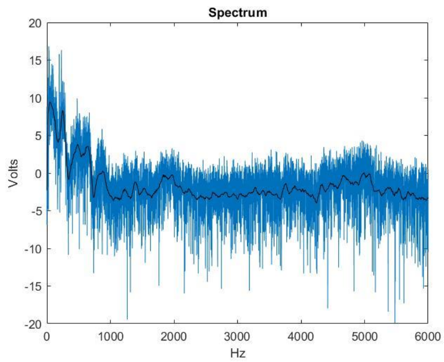


Figure 6: Four Blade Propeller

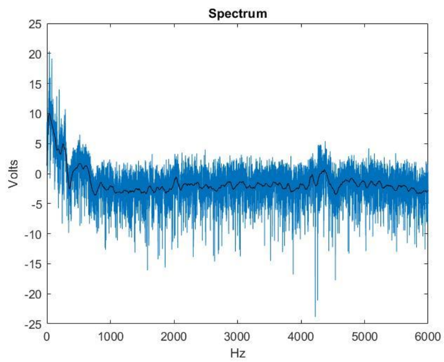


Figure 8: Five Blade Propeller

**The influence of Propeller velocity**

The below data was measured in the acoustic testing box with the five bladed propeller attached and shaft RPM was recorded at the time of testing with use the digital tachometer. The lack of variance in tones between 600 RPM and 2000 RPM suggests that the shaft speed is not the cause of the fundamental frequency and again the BPF is not the cause either. The spectrum of the 3500 RPM tests shows higher frequency tones, likely caused by structural vibrations of the whole model.

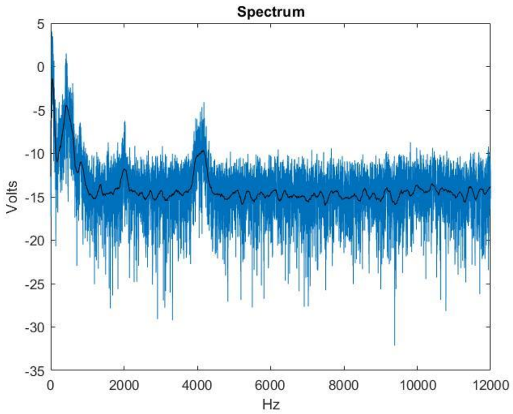


Figure 9: 600 RPM

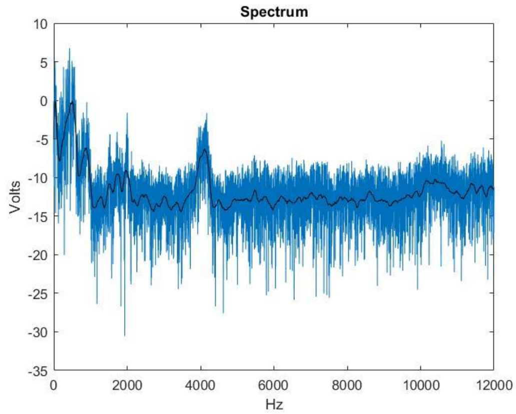


Figure 10: 2000 RPM

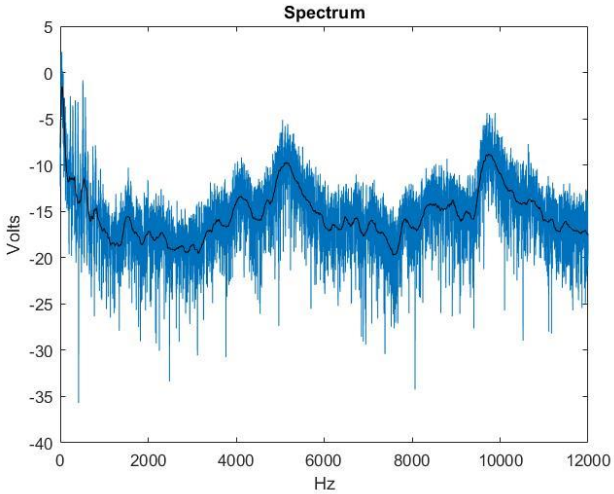


Figure 11: 3500 RPM

**Discussion**

The power axis in the above spectrums are given as $10 \times log_{10}(V)$ on the Y axis so the volts can only be interpreted qualitatively as of yet, as the dB scale has not been applied with respect to a reference pressure. The signals are relatively noisy, but this is a side effect of having to use pre-amplifiers. This will be mitigated in future testing and processing through use of appropriate filtering.

Following on from the above discussion of the spectrums, data thus far has not led to conclusive evidence of the source the fundamental frequency. The spectrums present a relatively noisy signal, but demonstrate the repeatability of the data.

Repeatability of data is crucial to obtaining unique signatures of each hull/propeller. Collection of unique data for individual models will provide confidence in the certainty of the measured data.

## Future Works

Further testing will be conducted to reach conclusive evidence of the cause of the fundamental frequency. Data comparisons such as Figure 13 shown below, will be used to process and analyse future tests.

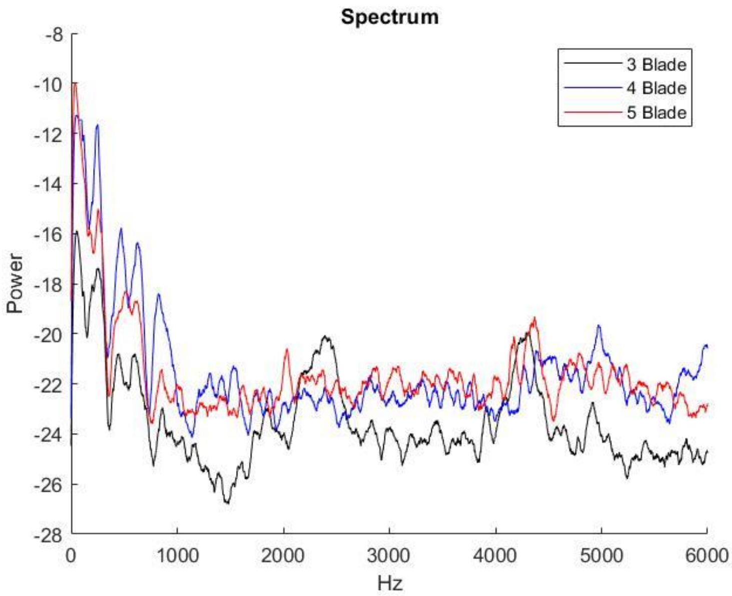


Figure 12: An overlay of the filtered spectrum of the varied propellers

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