Defense University Center
Spanish Naval Academy

FINAL YEAR PROJECT

Implementation and testing of a SONAR echo cancellation system.

MECHANICAL ENGINEERING BACHELOR DEGREE

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Universidade Vigo

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Mechanical Engineering Bachelor Degree
Naval Technology Specialization
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Abstract

Giving the higher tactical superiority of a submarine over a surface vessel and the lack of defence capabilities of this one against submarine threats, this thesis intends to increase acoustic stealth for a better protection.

In this project we aim to implement and test a system capable of cancelling an active SONAR echo to reduce our own target strength and so, the enemy's detection range. In order to implement this system, we implemented a basic experimental setup that allowed us to verify if a SONAR echo could be cancelled using un underwater acoustic source. Experiments were carried out in air, in a swimming pool and in the sea to study the feasibility of our system. The results were obtained by computing the reduction in the transmission loss from the original echo to the cancelled one, and these results indicated that echo cancelation was indeed feasible, given rise to a reduction in our target strength of up to 20 dB. That reduction results in a decrease in the enemy detection range of almost 68.4%.

KEY WORDS

SONAR perturbation, echo cancellation, stealth technology.

Resumen

El objetivo de este trabajo de fin de grado es el diseño, implementación y estudio de viabilidad de un sistema de cancelación de pulsos SONAR basándose en la interferencia destructiva de las ondas.

A lo largo de la historia, y más recientemente, se han desarrollado multitud de sistemas y procedimientos para confundir o destruir una amenaza submarina. Generalmente los medios para evitar ser detectados por un SONAR activo son muy pobres, salvo aquellos dirigidos a los SONAR activos de los torpedos, para los cuales encontramos diferentes contramedidas pensadas para seducir, confundir o destruir dicha amenaza.

Sin embargo, el submarino y el torpedo siguen siendo el mayor de las preocupaciones para cualquier barco de superficie. Con el fin de minimizar esta amenaza nace este proyecto, que basándose en la teoría de la interferencia destructiva de las ondas podría reducir muy notablemente la probabilidad de ser detectado. A día de hoy existen algunos artículos sobre esta idea, pero que se sepa hasta la fecha, no existe ninguna unidad militar que tenga un sistema similar en funcionamiento.

Antes de comenzar el diseño tenemos que estudiar las ecuaciones matemáticas de las ondas y de la propagación acústica (ecuación SONAR) para comprender previamente el comportamiento del sonido en el agua y obtener unas expectativas previas además de tener una forma práctica de analizar los resultados de los experimentos.

Una vez realizado el estudio teórico comenzamos con la planificación de los experimentos, los cuales empezaron teniendo lugar en el aire, con dos altavoces y un micrófono (transmisores y receptor). Debido a la falta de medios y tiempo no hemos podido realizar los experimentos de forma similar a la realidad, es decir, un transmisor muy potente actuando como un SONAR activo cuyo eco se refleja en el blanco donde se encontraría nuestro sistema de cancelación de sonido. Por ello hemos realizado los experimentos utilizando un altavoz que simula la reflexión del pulso y otro que simula la transmisión del sistema a estudiar.

Una vez realizados los experimentos en el aire con resultados que cumplían con las expectativas, llevamos nuestro proyecto al agua utilizando dos transductores en sustitución de los altavoces y un hidrófono en sustitución del micrófono. Estos experimentos se llevaron a cabo en la piscina y en la dársena de la Escuela Naval Militar, y por último desde la isla de Tambo hasta el muelle de Torpedos, desde dónde experimentamos tanto con pulsos de onda continua como modulados en frecuencia (que es, a fin de cuentas, como funcionan los SONAR activos).

Los resultados en el agua fueron también satisfactorios a pesar de las dificultades que presentaba cada emplazamiento: la reverberación en la piscina; el ruido de las embarcaciones que dificultan las mediciones y nos obligan a utilizar frecuencias más altas (y más difíciles de cancelar) tanto en la dársena como en la ría de Pontevedra; y por último la gran distancia entre Torpedos y la isla de Tambo que es difícil de salvar por la reducida potencia de nuestro equipo transmisor.

Analizando los resultados de las diferentes pruebas llegamos a la conclusión de que el sistema no sólo es viable, sino que también reduciría notablemente el alcance de un SONAR activo, el cual es, al fin y al cabo, la finalidad del sistema. Por otro lado, creemos que la idea de aprovechar la interferencia destructiva de las ondas se puede aplicar también para reducir la firma acústica de un barco, lo cual significaría un avance de gran calibre dado que los submarinos generalmente funcionan con el SONAR pasivo para evitar ser detectados.

PALABRAS CLAVE

SONAR activo, Perturbación acústica, Cancelación de ondas acústicas.

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1 INTRODUCTION AND OBJECTIVES

1.1 Background.

Nowadays, the biggest threat in war is submarines. The submarine can be the most dangerous weapon at sea because she can sail underwater, remain undetected while it comes very close to a target and attack with a torpedo, which is a device capable of breaking a warship in two. The submarine can be even more dangerous when it is equipped with nuclear weapons. Anti-Submarine Warfare (ASW) is the collection of techniques, disciplines and devices that try to keep us safe from this threat.

Even though a frigate mounts hull and towed sonars to detect and track submarines, it has been demonstrated that up to three modern frigates are needed to successfully detect and track a single submarine.

With this thesis, I will study the possibility of increasing underwater stealth capabilities, or in other words, to minimize the target strength of a vessel and hence the ability of a torpedo to home in a submerged or surface vessel. To achieve this, I will explore the use of acoustic cancellation techniques to apply in an anti-active-SONAR system. The main idea can be explained as follows: when a torpedo's sonar's pulse arrives to the vessel it will be detected by the system, the received pulse will be inverted and emitted in the torpedo direction, so that the coherent sum of both pulses cancels each other due to destructive interference.

1.2 Objectives.

The main objective of this project is to study the feasibility of a device capable of reducing the target strength of a vessel against an active sonar using sound cancellation. We also aim to build a prototype, within time and budgetary limitations, to gather some knowledge about the performance of such a system.

1.3 Project Structure.

The thesis is organized as follows:

- In chapter 2 we will introduce the underwater warfare elements such as the submarines, the torpedoes and their sensors. In addition, current systems and results in connection to the objectives of this thesis will be studied.
- In chapter 3 we will study SONAR equations and how they affect to our thesis.
- In chapter 4 we will present the software and hardware used in the experiments, how these experiments were carried out and which were their objectives.
- In chapter 5 we will show the computed results of the experiments.

- In chapter 6 we will analyse and discuss those results and provide the final conclusions and ideas for further work.

2 STATE OF THE ART

2.1 History of submarines.

A submarine is a vessel capable of sailing under the surface of the water, which gives it a great tactical and strategical advantage as it cannot be detected by neither the naked eye nor with any conventional instrument.

It is said it all begun back in 1578 when the British man William Bourne publicized “Inventions or Devices” where he explained how it would be possible to build a ship that could contract itself to go deeper and expand to go back to the surface, however, it was not possible to get it done with the technology of his time.

Even though we have the main principle of a submarine, the capability of immersion, we also need a propulsion system, which it is firstly achieved in 1620 by the Dutchman Cornelius van Drebbel [1]. He designed the “Drebbel I” (Figure 2-1). It was a 12-oarsman crew rowboat that would sink thanks to its sloping foredeck which would force the boat down as it gained forward speed. Later, in 1636, a French priest, Marin Mersenne suggested a cylindric shape and copper as main material for underwater vessels for a better resistance in deeper (and high pressure) waters.

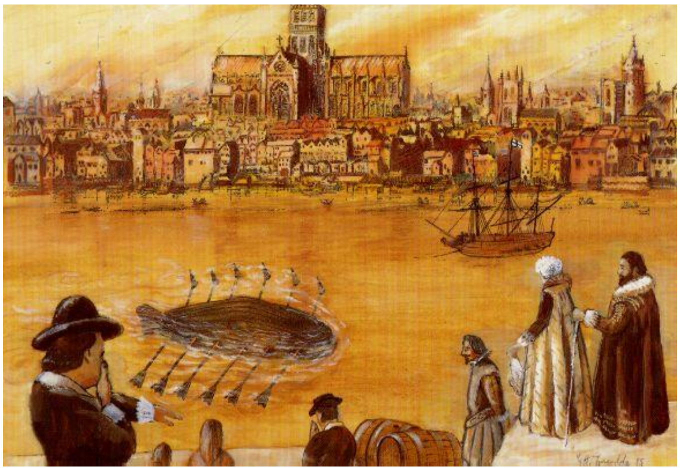


Figure 2-1. "Drebbel I" picture. [1]

Later, During the First Anglo-Dutch war, between 1652 and 1654, the Dutch Navy built the “Rotterdam Boat”. It was the first military semi-submerged ship, with a clockwork kind of machine as power source and an iron bar in the bow and another in the stern, prepared to hit boats from beneath the surface and make a hole in their sides. However, once launched, the submarine would not move.

David Bushnell, in 1775, during the Independence War of the United States, designed the “Turtle” (Figure 2-2), a one-man submarine that pumped water in or out to sink and rise and had two propellers (vertical and horizontal) hand-cranked propelled [1]. The “Turtle” is the first submarine to be used as military weapon that we know of. In this mission it had to approach the enemy’s vessels and plug a detonation device in its hull, however, once in position the “Turtle” was not able to plug it in correctly and had to retreat before running out of oxygen.

Figure 2-2. A cutaway full-sized replica of the Turtle on display at the Royal Navy Submarine Museum, Gosport, UK. [2]

The “Nautilus” is the following milestone in history of submarines, designed by the American Robert Fulton, it had a number of successful dives. It could sink up to 25 feet and could reach 4 knots under water thanks to a hand-cranked propulsion. In 1800, Napoleon granted Fulton with the funds he needed to build it, and they agreed that the payment would be a small percentage of the loot of its attacks. Nevertheless, British ships could always see it from afar enough to evade it.

The next step was taken in 1863 when the French Navy launched the “Plongeur” (Diver) [1]. The “Plongeur” was propelled by an engine based on compressed air which made it the first submarine not propelled by human power. It also used ballast tanks to go deeper or rise that would function with the same compressed air engine. The submarine was armed with a ram and with an electrically launched spar torpedo.

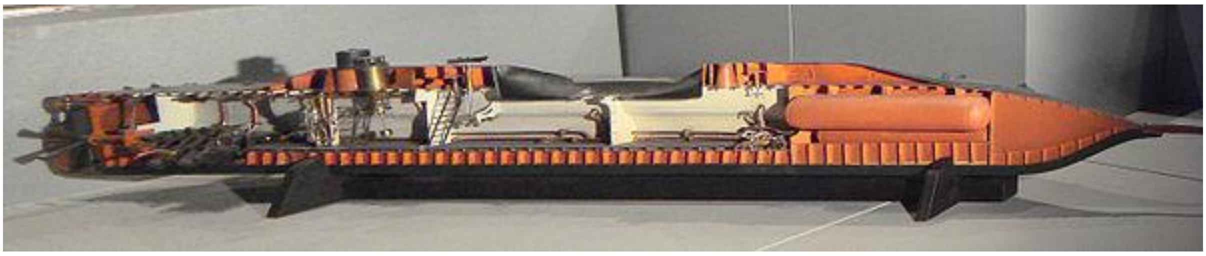


Figure 2-3. Internal view of the "Plongeur". [3]

During its first trials, it was demonstrated that the submarine was not stable enough, the front would dive first and used to hit the bottom. It was never used in an operational mission.

The first fully operational military submarine was designed by the Spanish engineer and naval officer Isaac Peral who launched it in 1888 as the “Peral”. One of its great advantages was that it used an electric motor. It also had three ballast tanks that allowed it to reach 90 feet under water. The “Peral” was armed with a torpedo launching system.

Figure 2-4. The "Peral" in 2007. [4]

The “Peral” was an inspiration to the whole world. The propulsion system that worked with a diesel engine that charged the batteries which would power the electrical propulsion engine has being used since then, in fact, conventional submarines nowadays (like Spanish S-70 class submarines) use the same system.

After this, during the World War I most countries had their own submarines [5], however, most of them were made to sail close to coast to defend the harbors, and the ones able to go further were not fully used because it was such a new technology that they did not know how to exploit it. So, it was not until the World War II that submarines took a special role in military operations.

The German U-Boats (Figure 2-5) became famous for destroying merchant convoys all throughout the Atlantic Ocean. During the first three years of war, they sunk near three thousand vessels, having lost only two and a half hundred submarines. This forced the allies to find a solution which came thanks to the Royal Navy, with the name of ASDIC [6] (acronym from Anti-Submarine Division), the first system able to detect submarines based on acoustic emissions. The Admiralty made the enemy believe it meant “Allied Submarine Detection Investigation Committee”, however, this committee never existed. Later, with the help of the United States, the system was rebranded as SONAR (Sound Navigation and Ranging). This invention made such a big change in the Atlantic Battle that Germans ended retreating the U-Boats.

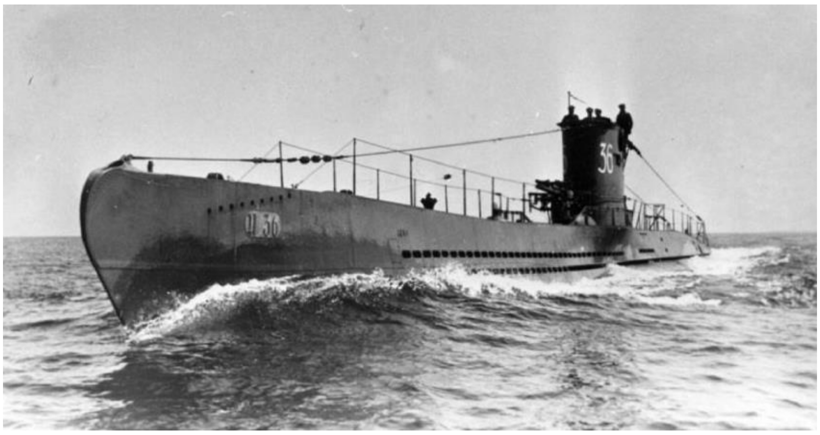


Figure 2-5. Photograph of a German U-Boat. [7]

Submarines kept evolving, and now we can find three main groups based on their propulsion system:

- Conventional: They use internal combustion engines to charge the batteries that will power the electrical rotor which will move the propellers that provide thrust to the submarine. Just like the “Peral” worked. The disadvantage is that they have to do snorkel to charge the batteries, which involves going near the surface and being exposed to enemy detection.
- AIP (Air Independent Propulsion): There are different ways to achieve this. The Spanish Navy is implementing in the S-80 Plus an AIP system based on fuel cells that obtain electricity from the chemical reaction consisted in burning hydrogen with oxygen. Their great advantage is that they do not have to go to the surface to charge the batteries which make them stealthier, however it requires a continuous flow of hydrogen and air, whose supply is limited.

- Nuclear: The nuclear reactor gives energy to the batteries, so we solve the problems of the other two groups, however, it is more expensive and, for some countries like Spain, not politically correct.

On the other hand, there are two different groups based on their purpose:

- Attack: Their purpose is to fight another submarine or ship. They mainly use torpedoes as weapon, but there are some of them able to launch missiles too.
- Ballistic: Usually with nuclear propulsion, their mission is to be at any part of the world without anyone noticing their presence. Their main weapons are nuclear missiles. Dissuasion is their actual purpose.

2.2 History of torpedoes.

The torpedo is a self-propelled and, in some cases, self-guided device that goes underwater to explode near the target. It was first invented by Robert Whitehead in 1866, who was working for the Austro-Hungarian Navy. This torpedo carried the warhead on its nose, and it was propelled by a three-cylinder compressed-air engine. It could only go straight forward during 800 yards at a maximum speed of 26.5 knots. [8]

Immediately, the US Navy showed its interest on the device not only purchasing it but also creating the Torpedo Station at Newport, where they looked for improvements. Nevertheless, it was not until 1905 that they introduced the turbine as propulsion system. By 1912, the Mark 7 measured more than 5 meters, weighed 738.4 kilograms and had a range of 6000 yards at 35 knots.

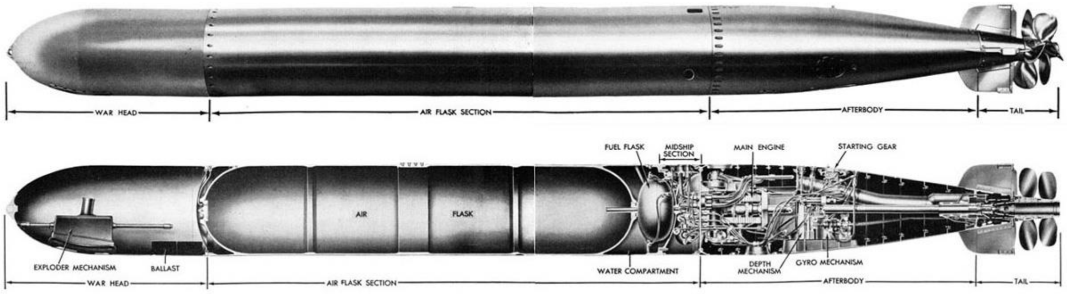


Figure 2-6. Mark 7 torpedo. [9]

After the first World War, new concepts were researched in Newport, such as oxygen or hydrogen peroxide-based propulsion systems; electric motors; air-dropped torpedoes; or magnetic exploders that allowed the torpedo to detonate under the target to achieve even more damage. However, due to the lack of budget, they could only research on the air-dropped torpedo and the magnetic exploder. The air-dropped torpedo, although it meant a great tactical advantage, posed important restrictions on the speed and flying altitude of the aircraft. Meanwhile, the magnetic exploder torpedo, did not meet all expectations and it was not intensively tested nor issued to the fleet until 1941.

When the second World War arrived, United States torpedoes showed their weaknesses. The Japanese attack on Pearl Harbor using air-dropped torpedoes showed the Americans how exposed they were to this threat that Japanese engineers improved enough to take the lead in this area. Later in Midway, U.S. aircrafts tried to use their own torpedoes, however, many of the aircrafts were lost even before dropping the torpedo due to their low-level attacks that made them an easy target for anti-air guns. In addition to this, the Mark 6, the magnetic exploder, did not work as expected either, as it would frequently fail and its backup, a contact pistol proved to be too fragile. In addition, the Mark 14 submarine torpedo was a complete failure as it used to go too deep and sometimes in circles, in fact, the submarine “Tang” was sunk by its own torpedo [8].

As the war continued, further research leaded to new air-dropped torpedoes that were less problematic to their aircrafts as the Mark 18, the first torpedo that run on electric batteries and included an acoustic homing system, rendering the Mark 6 obsolete. The first american acoustic homing torpedo was the “Mine Mark 24” [10], named this way to mislead the enemy. It had a passive sonar in its nose to track the noise made by the submarine targeted and could be thrown by either aircrafts or warships.

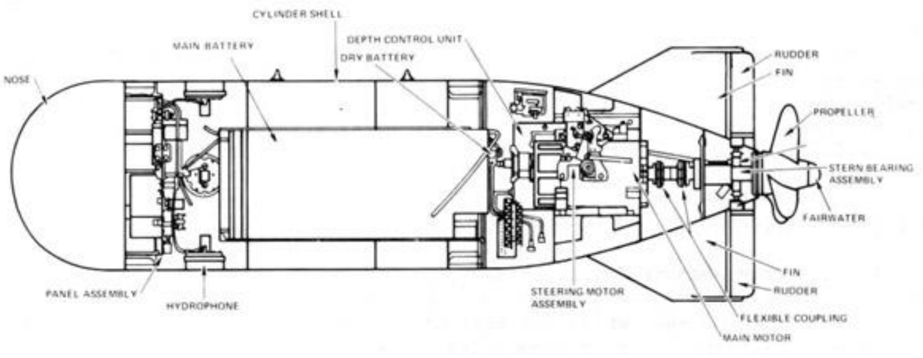


Figure 2-7. Mark 24 "Mine" torpedo scheme. [10]

It was not until the Korean War that the next step was taken, when the United States wanted to take down the Hwachon dam. After this, improvements were made to face Soviet nuclear submarines, which led them to the Mark 45 which had a nuclear warhead.

2.3 History of submarine sensors.

Back in the late 19th Century, ships had serious problems with rocks and icebergs while sailing during fog or night which resulted on the establishment of the Submarine Signal Company (SSC) in 1901. Their plan consisted on alerting ships using underwater bells that they could hear thanks to hydrophones (microphones used underwater). The idea is that sound travels much further underwater than light does through fog. [11]

Even though the system worked, it was not perfect. A system must be mounted on each vessel to detect any iceberg no matter where. And here enters Lewis Nixon, who invented the first active sonar in 1906, although, it was not until 1912 after the sinking of the Titanic that people realized the importance of Nixon’s invention. Reginald Fressenden built an experimental system this same year while working for the SSC achieving in 1914 the demonstration of depth sounding, underwater communications (in morse code) and echo ranging (detecting an iceberg two nautical miles away). The “Fressenden Oscillator” operated on a 500Hz frequency, with such a large wavelength that could not be used to determine the iceberg’s bearing.

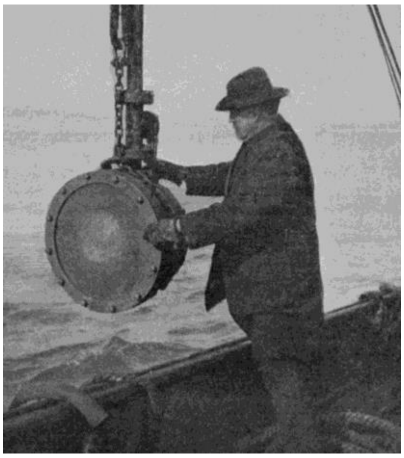


Figure 2-8. Photograph of the "Fressenden Oscillator". [12]

The start of the first World War prompted research into acoustic detection. Hydrophones were used to listen to submarines and active sound devices such as the ASDIC were developed.

In 1916, Robert William Boyle and Albert Beaumont Wood were awarded a British project on the active sound detection under the Board of Invention and Research [11]. They ended up producing the first practical underwater active sound detection device using piezoelectric crystals. To keep its secrecy, they changed its name from “supersonics” to ASDics, ASD standing from Anti-Submarine Division, but it ended up as ASDIC. By 1918, Britain and France had built some prototypes, and in 1920 they were tested on the HMS Antrim, so in 1922 the production could start.

By the outbreak of the second World War, the Royal Navy already had mounted the ASDIC system in five ships. The ASIC operation was complemented with the use of depth charges, which were dropped overboard and sunk to explode near submarines. The British shared openly the ASDIC with the United States so both countries could advance and develop new technologies based on acoustic emissions such as the sonobuoys, the dipping sonar or mine-detection sonars. Americans started to use the term SONAR (Sound Navigation and Ranging) for their own inventions, and made important discoveries such as the thermoclines and their effect on sound waves.

Until the beginning of World War II, SONAR systems were not improved much further, however the significant loss of merchant vessels in the Atlantic Battle made the Americans invest more money in SONAR research [11]. So far, SONAR devices consisted of a magnetostrictive (a property of materials that make them change its dimensions under magnetic influence) transducers and an array of nickel tubes connected to a steel plate attached to a Rochelle salt (a salt with piezoelectric properties) crystal, all packed into a spherical housing. The next step was the ADP (Ammonium dihydrogen phosphate), which replaced the Rochelle salt crystal and improved the transducer’s parameters and the reliability of the salt.

Another application to the ADP was to use it on hydrophones. They used these hydrophones to guide torpedoes, with one directional hydrophone in the vertical direction and another in the horizontal direction they could seek submarines. However, they were easily misled, the submarine only needed to drop an effervescent chemical so the torpedo targeted the generated noise instead of the submarine. On the other hand, a counter-countermeasure was made, the active sonar guided torpedo. A transmitting element was added to the torpedo’s head, and the hydrophones listened to the echo of the transmitted pulse.

At the end of the war, US Navy SONAR systems worked at 18kHz using ADP crystal arrays. Nevertheless, they wanted to achieve longer range, which could only be done with lower frequencies and the ADP could not support such big dimensions. This led to the use of lead zirconate titanate (PZT) which allowed sonars to work at 5kHz. This is the material used in the AN/SQS-23 sonar for decades. This sonar, at first, was a large array of 432 individual transducers, which demonstrated to be unreliable, out of mechanical and electrical failures that would deteriorate the system soon after installation. As a solution, they took a policy based on sealed non-repairable modules which eliminates the problem with seals and other mechanical parts [13].

Meanwhile, close to the end of war, the Imperial Japanese Navy used transducers made of quartz which made them big and heavy, especially for lower frequencies. Later they followed the German design using magnetostrictive projectors. They had two rectangular independent units in a cast iron body of 41x23 centimeters abled to expose an area half the wavelength wide and three wavelengths high. Their passive hydrophones were based on moving-coil design, Rochelle salt piezo transducers, and carbon microphones [14].

After the war, magnetostrictive transducers were pursued as an alternative to piezoelectric ones. Some transducers based on nickel could size up to 4 meters in diameter to low frequency operations, which is a real problem as it takes too much room in a warship. Finally, in the 1970s the Terfenol-D was found, with superior magnetostrictive properties was made out of rare earths and iron. It allowed hybrid magnetostrictive-piezoelectric transducers to be developed. The most recent material with these characteristics is Galfenol [15].

2.4 Active SONAR

2.4.1 Basic concepts.

Here we present the basic function of an active SONAR. A SONAR system can get information about the underwater environment by emitting a sound in a known direction and listening to its echo. Using the time difference (from the emission to the reception) and the speed of sound through water, it can be determined the distance to the surface where the wave was reflected.

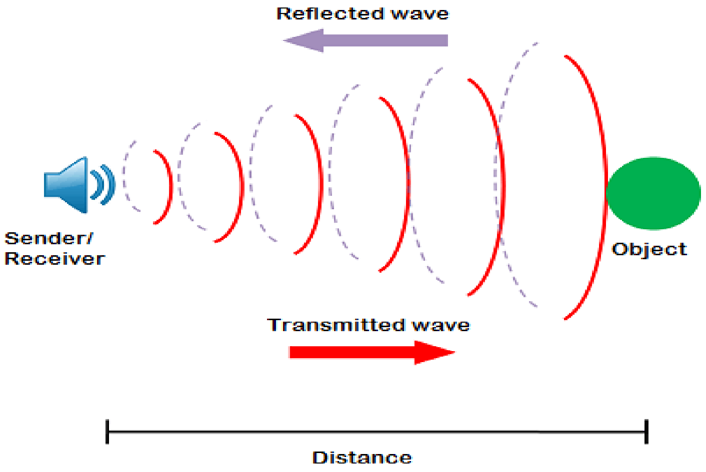


Figure 2-9 Active sonar working scheme. [16]

SONAR signals are harmonic, and therefore, can be described using the following characteristics:

- Period: time that takes to complete one oscillation.
- Frequency: number of oscillations per second, the inverse to the period.
- Amplitude: maximum value taken by the wave.
- Wavelength: distance that takes to complete one oscillation, and depends on the excitation frequency and the propagation speed, which in turn depends on the medium.

In our case, the sea is the propagating medium, which in general, is not an isotropic medium. Isotropic means that its properties do not change in space. This can be a complicated matter, because if the water properties change in space, the trajectory of sound waves becomes more complicated, due to refraction.

2.4.2 Acoustic propagation.

To understand how the sound propagates under water, we must first understand how the sound speed changes with depth. There are three facts that affect the speed of sound: salinity, temperature and pressure, however, salinity rarely changes significantly enough to make a difference. On the other hand, temperature has the strongest impact on sound speed as it accelerates sound in 3 meters per second for each centigrade grade. In addition to this, temperature often changes significantly in the first meters of depth. And last but not least, sound speed also increases with pressure, which increases constantly with depth. Usually, further than a thousand meters deep, temperature stays constant while pressure keeps increasing. Mixing both speed and pressure graphics, a celerity trace can be computed (see Figure 2-10), in which the speed of sound is represented over depth. These tables are very important because they are going to stablish how the sound will propagate. [17]

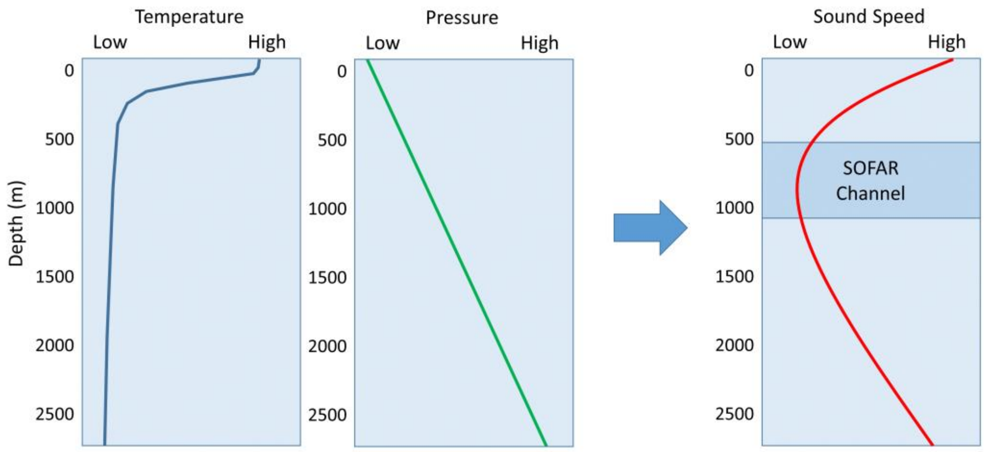


Figure 2-10. Variation of temperature and pressure and how it affects speed of sound. [18]

Another characteristic of sound is that it tends to travel through the zones with lower speed due to the Snell's law of refraction. This leads to different zones and propagation paths depending on the ocean, sea, time of the year or even on weather conditions.

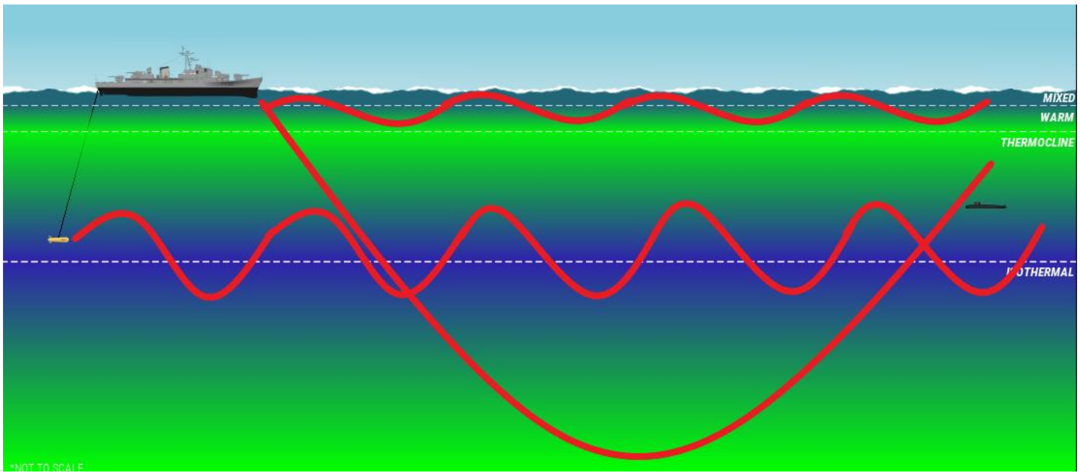


Figure 2-11. Representation of propagation of sound in cold waters. [19]

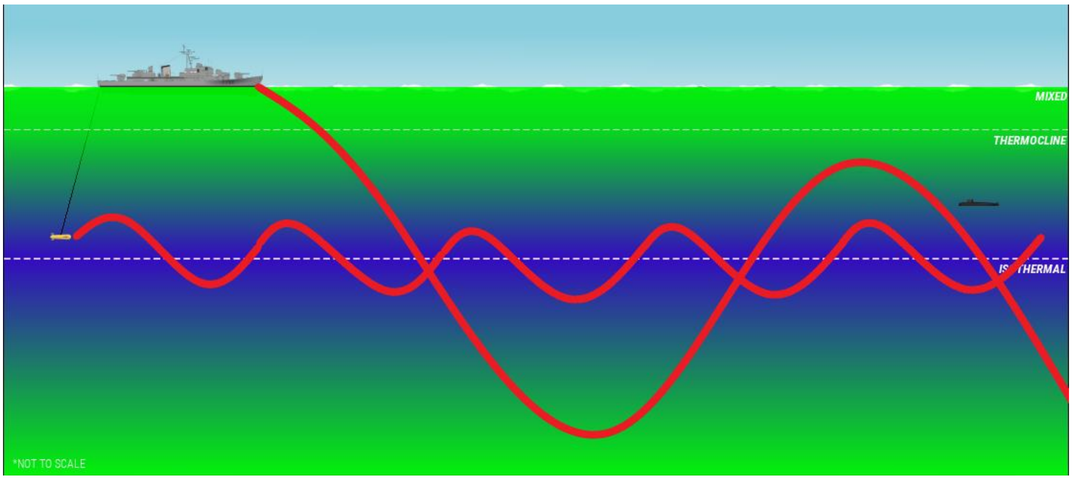


Figure 2-12. Representation of sound propagation in warm waters. [19]

These changes in temperature result in different layers. Taking a look at Figure 2-11, it can be appreciated the surface channel, where most of the hull sonar waves will get stuck in, which can be a real problem in antisubmarine warfare. Below the beginning of the thermocline region, the deep sound channel can be found. This is one of the most important layers, any wave sent in this channel will stay in and will propagate for great distances, however, for a surface vessel to explore this channel it is needed a variable depth sonar. Another characteristic in propagation of waves underwater is the generation of shadow zones where the acoustic waves do not propagate, leaving a space for submarines to hide from SONAR. Under the right circumstances the trajectory of sound waves underwater come back to the surface at a regular distance, giving rise to the phenomenon known as convergence.

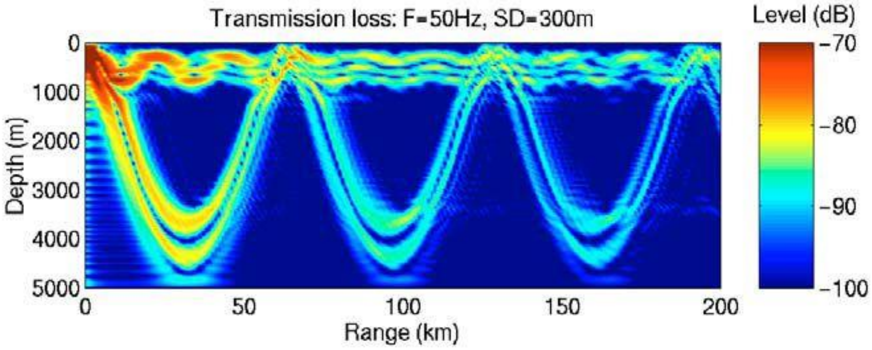


Figure 2-13. Underwater acoustic model. [20]

2.4.3 Modes of operation.

Active SONARs work using pulses limited in time, and these pulses can be transmitted in two modes: Continuous Wave or Frequency Modulated.

- Continuous Wave (CW): a continuous wave is a single frequency wave, which means it stays constant. It is the simpler kind of wave as it is not modulated, plus, it has good Doppler sensitivity.
- Frequency Modulated (FM): a frequency modulated wave is a pulse modulated so it ends with a different frequency to which it started with. Commonly known as chirp, it is good for long range detection and gives much better resolution.

2.5 Modern active military sonars.

This section describes current SONAR systems used by different navies, especially the Spanish Navy, in both FFGs and F-100 frigates and the systems that are expected to be mounted on the F-110 frigates.

2.5.1.1 SQS-56.

The SQS-56 is a both active and passive hull sonar made by Raytheon company able to detect either submarines and torpedoes installed in the FFGs frigates. [17]

It counts with a cylindric shaped transducer formed by 36 vertical arrays of 8 elements each covering 360 degrees installed into a rubber dome. A baffle is installed at its stern covering 90 degrees to cancel the ship’s noises.

Figure 2-14. SQS-56 transducer. [17]

Property	Value
Power	36 kWs
Source Level	222/236 dB re 1µPa
Range	20 kyds (18.3 km)
Number of frequencies of transmission	3
Passive reception	Ability to detect noises from torpedoes or propellers
Number of elements	288
Distance scales	2.5/5/10/20 kyds
Pulse length CW	5/40/160 ms
PCC (Polary Coincidence Correlator)	
Pulse length FM	160 ms
PDPC (Post Detection Pulse Compression)	

Table 2-1. SQS-56 characteristics. [17]

This sonar counts with the following modes of transmission:

- Omnidirectional mode: the 36 columns of elements transmit at the same time covering the 360 degrees. Used for close detection it is the lowest source level mode.
- Single RDT mode: covers a sector between 20 and 120 degrees with steps of 10 degrees. Takes more time to transmit, however it is the mode with higher source level which allows it to do long range search, classification and tracking.
- Triple RDT mode: three simultaneous beams of 10 degrees separated 120 degrees to each other cover the 360 degrees by changing the bearing at a time. Takes the same time to transmit as single RDT, but has a lower source level.
- Wide RDT mode: covers a sector between 30 and 120 degrees with steps of 30 degrees. Used for detection and tracking but not for searching due to its lower source level.

In addition to this, this sonar has the following reception modes:

- Active reception: listens to the echoes from the active transmission.
- Active listen: listens to any noise in a bandwidth of 600Hz centred in the transmission frequency. It has 36 lobes of reception separated 10 degrees to each other.
- Passive reception: listens to any noise in lower frequencies using 18 lobes separated 20 degrees to each other.

2.5.1.2 DE-1160LF.

The DE-1160LF is a low frequency sonar installed in the first series of F-100 frigates that can work in either active or passive mode to detect, track and classify contacts. Another particularity of this sonar is the ability to use the convergence zones.

Property	**Value**
Frequency Tx	3.05-3.75-4.45 kHz
Power	108 kWs
Vertical Lobe/MCC[1]	16.5º/25º
Scale	2.5-5-10-20-40 kyds
Pulse length	CW: 40-160-1000 ms LFM[2]: 12-40-160 ms
Number of elements	216
Source Level	ASW: 238 dB re 1µPa SOA: 226 dB re 1µPa

Table 2-2. DE-1160LF characteristics. [17]

The DE-1160LF has four different modes of transmission:

- Omnidirectional transmission: for Antisubmarine Warfare (ASW) and Small Objects Avoidance (SOA).
- Single RDT mode: for ASW.
- Triple RDT mode: for ASW.
- Wide RDT mode: for SOA using up to 4 simultaneous beams.

Although it looks similar to the SQS-56, it has some improvements such as:

- A specialized wave shape that improves navigation in shallow waters and a longer CW pulse for more precise doppler measures.
- Simultaneous processing of different active receptors.
- Computer assisted detection and tracking: up to 20 active targets.
- Detailed simultaneous displays: up to four windows of tracked targets displays.

On the other hand, there is the PASS mode (passive mode):

- Listens to any noise related to ASW.
- Detection in wide bandwidth, thin bandwidth and DEMON (Demodulation Noise).

---

[1] *MCC (Maintaining close contact): to keep contact with close targets, the sonar turns off the two first elements of each column to widen the vertical lobe.*

[2] *LFM (Linear Frequency Modulation): a transmission pulse of a bandwidth of either 500Hz or 1200Hz centred in the transmission frequency.*

- Estimates the torpedo threat and recommends manoeuvres.
- Automatic tracking of up to 8 contacts.
- Classifying.

In addition, it counts with other operation modes: ASW/PASS (passive and active at the same time); SOA (for detection of small objects in close range); anti-torpedo alert (working as passive sonar recognises a torpedo and alerts); PP mode (to analyse the reverberations in the working frequency and recommend transmission parameters).

2.5.1.3 LWHP53SN.

It is a hull-mounted sonar (HMS) that is installed in the F-105 Cristobal Colón has been made by Indra Systems and Lockheed Martin as an improvement from the one of the first series frigates (F-101, F-102, F-103, F-104).

It brings the following improvements:

- Increased capability to detect by bottom bounce.
- An integrated acoustic prediction tool.
- Improved management of integrated resources. Notices of any failure or malfunctioning and alerts the operator.
- A new operating console.

The most important feature might be the acoustic range prediction which works with the program WADER, which determines the acoustic range from the probability of detection, transmission losses and acoustic beam trajectories. In addition to this, historical data can be used to predict the medium acoustic conditions, allowing the operator to select month, coordinates, environment and historic SVP (Sound Velocity Probe: measurement of the speed of sound in the water column). Finally, it can also make an in-situ prediction by selecting coordinates, current SVP and type of bottom.

2.5.1.4 Captas-4 Compact (S2087).

One of the most modern towed sonars is the Captas-4 developed by the British company Thales Group that will be mounted in the Spanish F-110 frigates as well as in the most modern frigates of Europe. It bestows an ultra-long range simultaneous active and passive modes covering 360º with permanent all-around torpedo alert. Two versions have been designed:

- Independent towed version: that enables simple and safe deployment and recovery, optimizes the depth for receiver and transmitter.
- Dependent towed version: a lighter and more compact device for specific platforms. A single towing line to facilitate simultaneous operation with other towed system.

Figure 2-15. Captas-4 towed sonar representation. [21]

This sonar can work in a multi-static operation when used with Captas family variable depth sonars, HMS family, FLASH dipping sonar and SonoFlash sonobuoys.

Main features:

- Integrated on-board training capabilities.
- Performance prediction capabilities to optimize sonar use.
- User-friendly HMI, with 3D analysis and chart overlay to improve visualization.
- Guard depth function.
- Adjustable source level.
- Mission module for cross decking.
- Four Free Flooded Rings transmit array, very high source level.
- Omni-directional low frequency transmission.
- Reduced reverberation due to limited vertical directivity and wide bandwidth.
- Triple array to instantly resolve left/right ambiguity.

Property	**Value**
Detection Range	150 km (2nd oceanic convergence zone in Atlantic Ocean)
Functions	Concurrent Active and Passive surveillance and torpedo warning + analysis + audio
Operating depth	Up to 235 m
Frequency (active)	Below 2 kHz
Bandwidth (active)	Wide FM
Pulse modes	FM, CW, COMBO
Pulse length	Up to 16 s
Passive frequency	Exceeding 4 kHz
Footprint (Dependent Tow)	43 m^2
Footprint (independent Tow)	45 m^2
Footprint (original version)	84 m^2

Table 2-3. Characteristics of Captas-4 towed sonar. [21]

2.5.1.5 BlueMaster UMS 4110.

The Thales group also developed the BlueMaster HMS which will be installed in the F-110 frigates complementing the Captas-4. This sonar permanently provides to the surface ship the capability to detect, localize an classify submarines either in rough sea states or shallow waters. It also counts with SOA and torpedo detecting systems.

Figure 2-16. BlueMaster HMS transducer. [22]

Main features:

- Panoramic and directional active transmission.
- Panoramic permanent torpedo alert.
- Very long-range detection and tracking in any environmental condition.

- Limited reverberation effect due to its wide bandwidth.
- Multi-static mode operations with Captas family VDS.
- User-friendly HMI, with 3D analysis and chart underlay to increase situation understanding.
- Integrated on-board training capability.
- Performance prediction function to optimize sonar use.
- Adjustable source level.
- Underwater telephone and bathythermograph.

Property	**Value**
Detection range	35 km
Functions	Active and passive surveillance + analysis + audio + torpedo alert + SOA
Frequency (active)	From 4.6 to 6.1 kHz
Bandwidth (active)	Wide FM
Pulse modes	FM, CW, COMBO
Pulse length	Up to 4 s
Passive frequency	From 1 to 6.1 kHz
Adaptive beam forming processing	Own ship noise cancellation + reverberation effect reduction

Table 2-4. Characteristics of BlueMaster hull sonar. [22]

2.6 Torpedo’s guidance system.

There are four main types of torpedoes based on their systems of guidance: wire-guided homing, active sonar homing, passive sonar homing and wake-homing. In this project we are going to talk about the first three types, as they are the only ones that can be perturbated by a sound cancellation technique.

We will consider first the active sonar guidance, which is our main objective. This kind of guidance system uses an active sonar to seek and home in on the target. Secondly, the passive sonar guidance system consists in a passive sonar that listens to noise and pursues the platform producing it. And last but not least, the wire-guided homing torpedo which may use either or both passive and active sonar is attached to its launching platform (usually a submarine) so an operator can make decisions when necessary; for example, when the target uses acoustic countermeasures the torpedo may not distinguish between a vessel noise and a countermeasure noise, however, the operator may.

In addition to this, nowadays, the most advanced torpedoes use these three guidance systems at the same time, for example, the Mark 48 mod 7 [23], the Spearfish [24], the F21 and the SeaHake Mod 4 torpedoes.

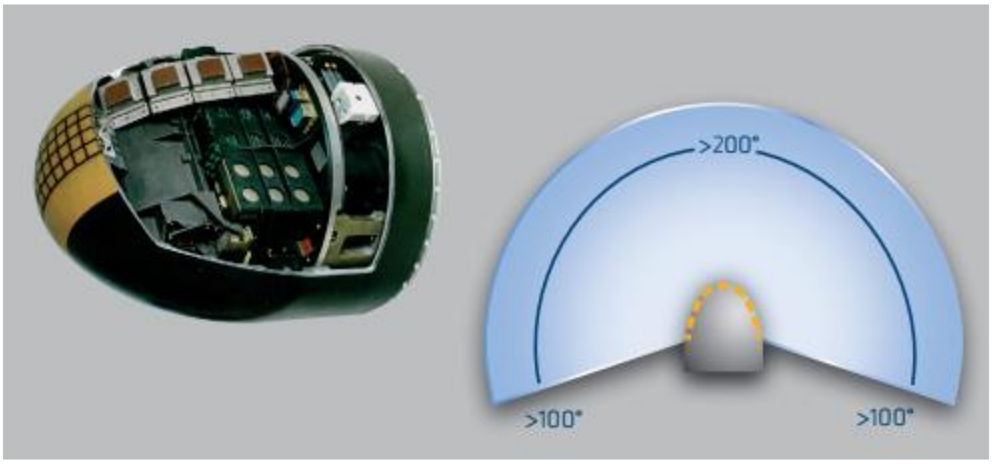


Figure 2-17. SeaHake mod 4 front. [25]

Currently, in Spain, our surface vessels are equipped with the lightweight Mark 46 torpedo, which uses both active and passive acoustic-homing, as will be the Mk 54 which its purchase has been confirmed by the Spanish government. On the other hand, Spanish submarines are armed with ECAN L5 mod 3 (active and passive acoustic-homing) and the ECAN F17 mod 2 which is also wire-guided. In addition to this, the future S-80 Plus submarine is expected to support the electrically propelled SeaHake mod 4 heavy weight torpedo which combines the four guidance systems mentioned above: active and passive sonar, wire-guided system and wake-homing system.

2.7 Torpedo countermeasures.

Torpedo countermeasures are tools used to avoid torpedo attacks, these can be either hard-kill or soft-kill measures. The first ones are designed to destroy the menace before it homes in. Between the second ones we find decoys based on perturbation of active or passive sonar seekers, or even both at the same time so they cannot home in on the correct target. [26]

Broadband passive SONAR systems listen to any noise and compares it with the signal-to-noise ratio (SNR) to identify the target and seek it. Maskers are the simplest torpedo countermeasures which interferes with the sonar’s ability to differentiate the vessel’s noise from the background noise. An example is the Mark 3 which is thrown to the water and produces noise to lure the passive sonar of the torpedo. However, they are useless against an active-sonar-torpedo, and as we already know, most torpedoes nowadays use both active and passive sonar homing systems.

To address this issue, we find jamming devices that try to perturb the active sonar of torpedoes by creating multiple false targets. An example of this kind of countermeasures is the Mark 4 mod 1 which produces broadband tones designed to confuse the torpedo’s processing system. Nevertheless, this crude countermeasure is ineffective if the torpedo has also a passive sonar homing system or a wire-homing system.

We also find decoys that use both kinds of countermeasures such as the Russian Vist-E, which combines broadband noise masking and active sonar jamming, or the LESCUT (Launched Expendable Scutter), which can be automatically launched when a torpedo is detected and can hover at a depth between 10 and 300 metres. This device also listens to the torpedo active sonar analysing its ping and classifying it so it can transmit a customized pulse to confuse that specific torpedo. The SUBCUT is the submarine launched counterpart. A very similar countermeasure device is the SCAD used by the Royal Navy which has to be programmed before launch.

Figure 2-18. LESCUT, SUBCUT, SCAD and Mark 4 mod 1 devices. [26]

Modern torpedoes such as the Spearfish can be almost immune to the countermeasures seen in Figure 2-18 thanks to wire-homing technology.

Another way the torpedo’s CPU has to differentiate a decoy from the vessel is to analyse the speed of the different possible targets detected, mostly using the doppler effect. A way to avoid this is using a towed decoy such as the AN/SLQ-25 Nixie. This system uses both broadband masker, that transmits more acoustic energy than the vessel itself and an active pulse transmitter that can reproduce the torpedo’s active sonar ping in a higher amplitude than the received. One of its greatest advantages is that as it is towed from the vessel, it will not lose power and also, it can be reused as many times as needed. In addition to this, towed decoys can also work as early-warning devices, plus, they can also activate torpedo’s magnetic fuses.

Another valid way to countermeasure a torpedo is engaging it with another one. The Russian Packet-E/NK system can attack torpedoes or submarines closer than 800 metres, and it consists in an externally mounted ring of eight intercept devices, a control system and a sonar set. The system automatically detects the torpedo, calculates its path and launches the anti-torpedo torpedo. This has been made to be used if the rest countermeasures fail.

A similar system is Rafael’s Torbuster (from Israel), which is an automotive decoy capable of luring torpedoes by imitating their active sonar pulses, calculating the CPA (closest point of approach) and destroying it with a detonating charge.

2.8 Acoustic Signature and Target Strength.

We have been talking about passive sonars and how they can be used, however, we have not talked about how they identify and track a target yet. To understand this, we must explain what the acoustic signature is.

The acoustic signature is the collection of every noise produced by a vessel. However, the most significant ones are: the on-board machinery such as, propulsion engines, generators, air conditioning systems; the hydrodynamic perturbances like cavitation or vortex shedding; the intakes; the exhausts and other non-persistent noises produced by a particular activity on board. Every one of these noise sources produce a different sound at different frequencies that can be studied by a passive SONAR system to classify and identify the contact. [27]

Warship designers use different techniques to minimize the acoustic signature of the vessel, such as:

- Mounting machinery separated from the hull by an absorbent layer such as rubber.
- Designing propellers to reduce their cavitation levels.
- Hydrodynamic efficiency of the hull.

In addition to this, vessels can reduce the acoustic signature by, for example: moving under the cavitation speed (speed from which cavitation starts) or turning off as many engines as possible without compromising the integrity and security of the vessel and its crew. Another way to reduce acoustic signature is using systems such as the praire-masker, which consists in several outtakes of air in the hull and in the propeller blades that reduce the hydrodynamic and cavitation noise. [17]

Conventionally, the acoustic signature is analysed by a SONAR operator who has been trained to identify and classify the target. However, nowadays, acoustic signature classification software is also available based on DEMON (Demodulation of Noise) algorithms, capable of doing this automatically, which makes this an issue of great importance.

The counterpart of the acoustic signature for active sonars is the target strength which is defined as the intensity ratio of a reflected wave at 1 yard of distance to the incident sound wave. In other words, the target strength is a property of each vessel which depends on the materials and the shape in which it has been made.

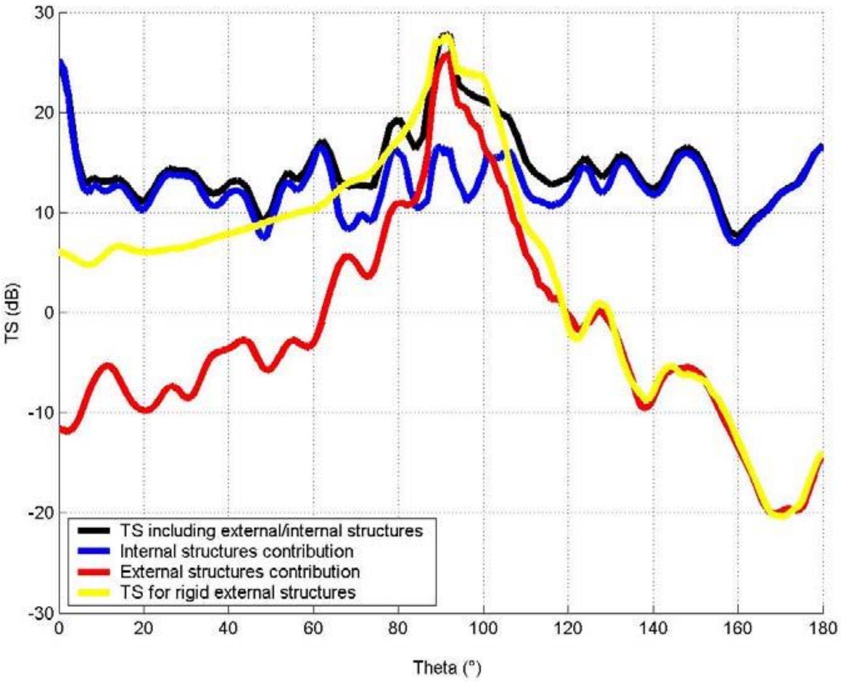


Figure 2-19. Mathematical analysis of the target strength of a virtual submarine (TS vs. Bearing). [28]

2.9 Noise cancellation.

Noise cancellation, also known as Active Noise Control (ANC) or Active Noise Reduction (ANR), is a method used to reduce unwanted noise, that is commonly used in modern headphones. The system is based on the transmission of a soundwave designed to cancel the noise.

Noise cancellation speakers emit an anti-phased wave (that is the opposite phase of the received noise) to cancel the noise by destructive interference. Ideally, this can be accomplished by placing a ANC speaker right next to the origin of the sound, however, this is always possible. On the other hand, if the speaker is far from the noise source, it would only need as much power as the wave carries itself. In this project the objective is to cancel the pulse reflected by the vessel, and thus the ANC transducer must be placed on the vessel's hull. This is advantageous as the ANC acoustic power must only be comparable to the SPL of the reflected wave.

In addition, the same transducer (or set of transducers) could be used to cancel the vessel's acoustic signature, reducing the enemy's ability to locate our vessel using passive SONAR.

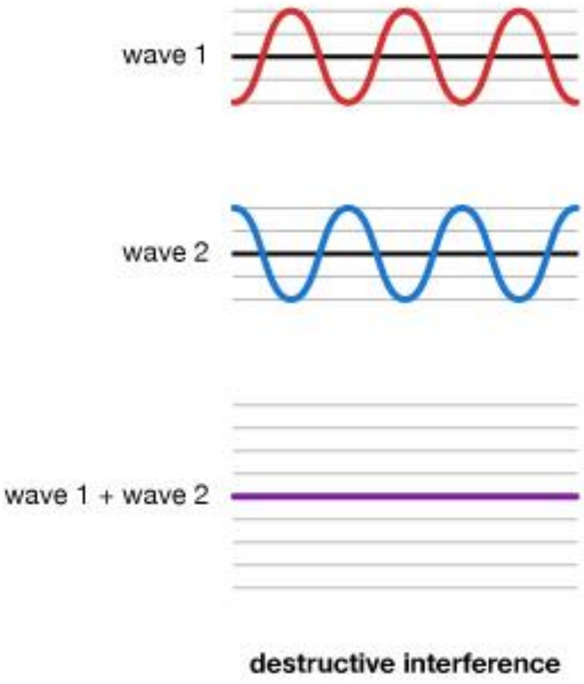


Figure 2-20. Graphical description of destructive interference. [29]

2.10 SONAR echo cancellation.

The concept of ANC has been already applied to SONAR warfare, taking the name of SONAR echo cancellation. However, the number of publicly available sources is scarce. The only reference we could find is the work by Riddle and Murray [30], but the idea may have been explored in classified projects.

The system described by Riddle and Murray performs SONAR echo cancellation over a wide band using a frequency scheduled control architecture. Performing wide band echo cancellation is difficult, and hence expensive, given the real-time constrains that exist over the cancellation error estimator. Riddle and Murray, reduce those constrains by dividing the frequency range of operation into small sub-bands that can be handled by a narrowband echo cancellation system (see in Figure 2-21). This solution has been successfully applied on CW and FM pings (see in Figure 2-22).

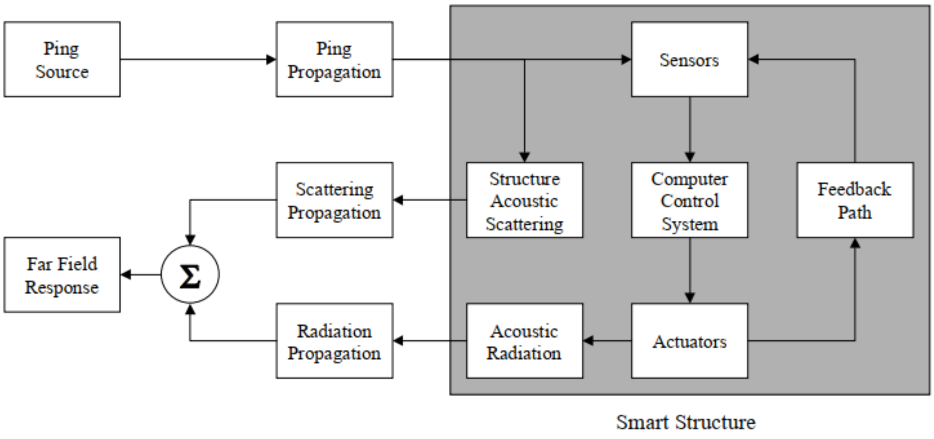
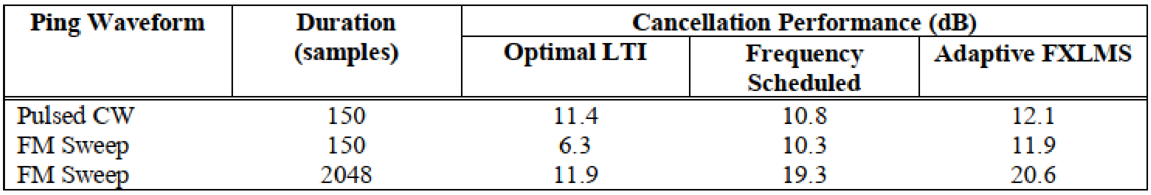


Figure 2-21. SONAR echo cancellation by frequency scheduled control diagram [30].

The results show how the frequency scheduled method works even better with FM pings than the an optimal LTI system. However, the best algorithms is the adaptive filtered-X least mean squares (FXLMS).



Ping Waveform	Duration (samples)	Cancellation Performance (dB)		
		Optimal LTI	Frequency Scheduled	Adaptive FXLMS
Pulsed CW	150	11.4	10.8	12.1
FM Sweep	150	6.3	10.3	11.9
FM Sweep	2048	11.9	19.3	20.6

Figure 2-22. Echo controller performance comparison [30].

3 THEORY

In this chapter we lay out the basic equations that describe the phenomenon that we aim to validate and exploit. Here we derive two equations: one that defines the phase needed to cancel a signal depending on the relative position between the reflection point and the transmitter, and the expected SPL reduction depending on those two positions; and the equivalent range of the active sonar once it has been perturbated by the echo cancellation device.

3.1 Cancelling phase and error signal.

Let us assume that the acoustic pressure generated by the torpedo seeker, at a distance of one meter, can be written as:

$$p_{1m}(t) = A\sin(\omega t) \qquad [1]$$

where A [Pa] is the amplitude of the wave, measured in Pascals, and ω [rad/s] is the pulse centre frequency, measured in radians per second. The amplitude of the wave is given by:

$$A = 10^{SL/10} \qquad [2]$$

where SL [dB re 1 μPa] is the source level of the torpedo active SONAR system. Let us assume the medium in front of the torpedo head is isotropic and homogenous, and that acoustic pressure at any point could be written as:

$$p(\vec{r},t) = \frac{A\sin(\omega t + kr)}{r} \qquad [3]$$

where $\vec{r} = (x, y, z)$ is any position in front of the torpedo, r[m] is the modulus of $\vec{r}$ in meters, and $k = \omega/c$ is the wave number, measured in radians per meter.

On the other hand, in terms of sound pressure, it is important to calculate the sonar equations. The sound pressure level SPL_{IN} that impinges on the vessel hull is given by:

$$SPL_{IN} = SL - TL \qquad [4]$$

where TL[dB] is the transmission loss suffered by the wave while travelling from the torpedo to the vessel location. The reflected sound pressure level SPL_{OUT} , at the hull location, is therefore:

$$SPL_{OUT} = SL - TL + TS \qquad [5]$$

where TS[dB] is the target strength of the vessel or, more simply put:

$$SPL_{OUT} = SPL_{IN} + TS \qquad [6]$$

For clarity let us call B [Pa] to the amplitude of the pressure wave reflected by the vessel, so that

$$B = 10^{SPL_{out}/10} \qquad [7]$$

As we have assumed an isotropic and homogenous medium, we can write the expression of the reflected acoustic pressure wave as:

$$p_{ref}(\overrightarrow{r_1}, t) = \frac{B}{r_1}\sin(\omega t + kr_1) \qquad [8]$$

Where r_1 is the distance between the vessel and the torpedo location. Let us assume that an ANC transducer has been installed on the vessel´s hull. Let us assume for a moment that the ANC transducer is on the exact same position where the reflections occurred. To successfully cancel this reflected wave the sound wave generated by the ANC transducer must be:

$$p_{anc}(\overrightarrow{r_1}, t) = \frac{B}{r_1}\sin(\omega t + kr_1 + \alpha) \qquad [9]$$

It can be shown that for $\alpha = \pi$ the coherent sum of the signals $p_{ref}(\overrightarrow{r_1}, t)$ and $p_{anc}(\overrightarrow{r_1}, t)$ yields a null signal and cancellation is perfect.

Let us consider what would happen if the ANC transducer were located at a slightly different location $\overrightarrow{r_2}$. On that circumstance the coherent sum would be, in general, different from zero, yielding an error signal:

$$e(t) = \frac{B}{r_1}\sin(\omega t + kr_1) + \frac{B}{r_2}\sin(\omega t + k(r_2) + \alpha) \qquad [10]$$

Let us denote as $\bar{r} = (r_1 + r_2)/2$ as the mean distance. Since we have assumed that the reflection position is close to the location of the ANC transducer, it follows that,

$$\frac{B}{r_1} \approx \frac{B}{r_2} \approx \frac{B}{\bar{r}} \qquad [11]$$

And hence we can write:

$$e(t) = \frac{B}{\bar{r}}(\sin(\omega t + kr_1) + \sin(\omega t + kr_2 + \alpha)) \qquad [12]$$

Applying the trigonometric identity of the sum of the sines:

$$e(t) = \frac{2B}{\bar{r}} \sin\left(\frac{2\omega t + k(r_1 + r_2) + \alpha}{2}\right) \cos\left(\frac{k(r_1 - r_2) - \alpha}{2}\right) \qquad [13]$$

We notice that the first term is a signal with the same frequency and a slightly different phase. The second term does not depend on time, and only depends on the difference of the distances $(r_1 - r_2)$. That term is often referred as the interference factor. In order to have perfect cancellation that term must be cero, so

$$\cos\left(\frac{k(r_1 - r_2) - \alpha}{2}\right) = 0 \qquad [14]$$

$$\frac{k(r_1 - r_2) - \alpha}{2} = \frac{\pi}{2} \qquad [15]$$

$$\alpha = k(r_1 - r_2) - \pi \qquad [16]$$

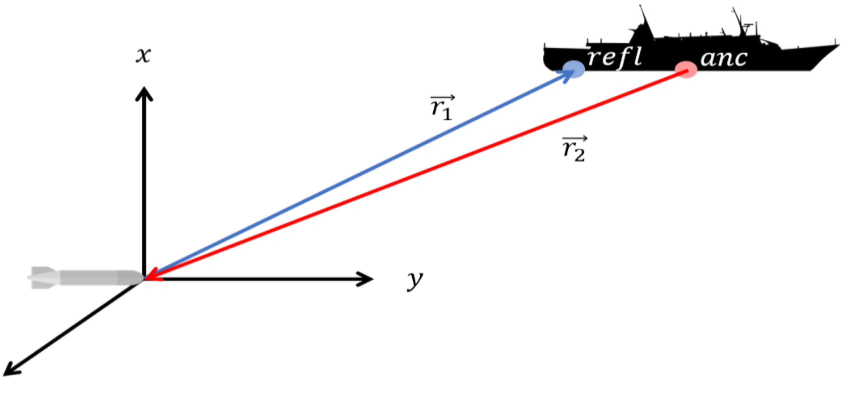


Figure 3-1. Scheme of the situation for the understanding of the equations.

For a given alpha, it is possible to estimate the error signal by evaluating the Eq. [13]. Figures Figure 3-2 and Figure 3-3 show the map of the amplitude of the interference factor for two different frequencies.

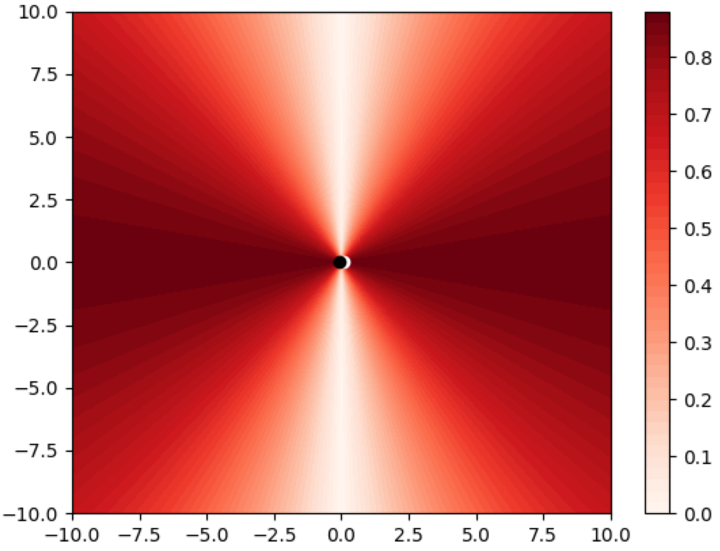


Figure 3-2. Value of the cosine for cancelling signal of 1kHz frequency, in air and with a distance between the ANC and the reflection point of 11.5 centimetres.

It can be appreciated how the map gets simpler as the speed of sound increases, the frequencies lower and the reflection point and the ANC are closer, as we see in Figure 3-3.

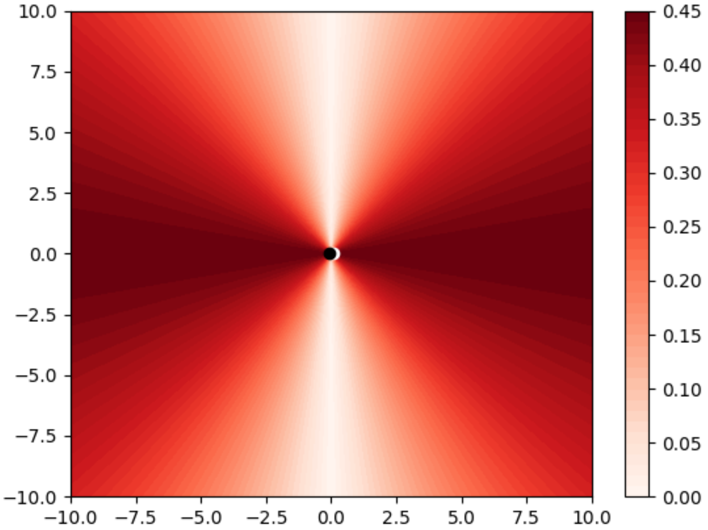


Figure 3-3. Value of the cosine for cancelling signal of 440Hz frequency, under water and with a distance between the ANC and the reflection point of 11.5 centimetres.

3.2 Equivalent SONAR range.

Let us take the equation of the active SONAR and introduce the effect of the SONAR cancellation device:

$$SL - 2\,TL + TS + DI - NL - ANC > DT \qquad [17]$$

Where SL is the Source level of the active sonar, TL is the transmission loss, TS is the target strength, DI is the directivity index, NL is the noise level, DT is the Detection threshold, and ANC is the TS reduction factor caused by the echo cancellation system.

Now, let us solve for the TL to derive the maximum range of the system.

$$TL = \frac{SL + TS + DI - NL - ANC - DT}{2} \qquad [18]$$

This equation can be rearranged as:

$$TL = \frac{SL + TS + DI - NL - DT}{2} - \frac{ANC}{2} = TL_0 - \frac{ANC}{2} \qquad [19]$$

where TL_0 is the transmission loss in absence of a ANC system. Since the SONAR range is given by:

$$R = 10^{TL/20} \qquad [20]$$

The range of the enemy SONAR system will be:

$$R = \frac{10^{\frac{TL_0}{20}}}{10^{\frac{ANC}{40}}} = \frac{R_0}{10^{\frac{ANC}{40}}} \qquad [21]$$

Which means that the enemy SONAR range will be reduced by a factor of:

$$\frac{R}{R_0} = 10^{-\frac{ANC}{40}} \qquad [22]$$

And thus, for instance, an ANC factor of 20 dB would reduce the enemy maximum range down to 31% of the original range. An ANC factor of 10 dB reduces the enemy maximum range down to 56% of the original range.

4 MATERIALS AND METHODS

4.1 Materials.

Two types of experiments were conducted: in air experiments whose aim was to validate mathematical expressions in a controlled situation, and experiments under water, carried out both in a swimming pool and in the sea.

For the in air experiments the following instruments were used:

4.1.1 Hardware.

4.1.1.1 Microphone TONOR.

To record the samples used to analyse the results of the experiments has been used the microphone TONOR TC30 (Figure 4-1), which has an input sample rate of 48kHz, a bit rate of 16Bit and a frequency response from 50Hz to 20kHz. It also has a sensitivity of -32dB referred to 1V/Pa at 1kHz with an error of ±3dB. The output impedance is of 2.2kΩ, its maximum SPL is 100dB and it has a 68dB SNR [31].

Figure 4-1. Microphone TONOR.

4.1.1.2 EBTOOLS speakers.

The speakers from Figure 4-2 have been used in the first three experiments in air in the laboratory at frequencies between 400Hz and 18kHz showing an appreciable power decay under the 400Hz, due to their shape can be inferred that they work better with higher frequencies.

These speakers work with 12V, they have a power capacity of 150W and a frequency response from 2000Hz to 22000Hz.

Figure 4-2. Speakers used in the first experiment in air.

4.1.1.3 Kinter Amplifier.

This amplifier from Figure 4-3 has been used in the lab and has two channels with 20 watts each and allows the user to select low pass or high pass filters. It has been used with the speakers from Figure 4-2.

It has an input impedance of 47kΩ, an output impedance of either 4Ω or 16 Ω, a frequency response between 20Hz and 20kHz, an input voltage from 9V to 14.4V and an input current from 1A to 5A.

Figure 4-3. Amplifier of 500 Watts.

4.1.1.4 KKmon power source.

In Figure 4-4 can be seen the KKmon power source from the fluids laboratory which has powered the 500W amplifier from Figure 4-3 at 12V.

This power source supports up to 32V and 5.2A and must be plugged to a 220V plug in.

Figure 4-4. Power source.

4.1.1.5 Pyle Amplifier.

The amplifier from Figure 4-5 has been used for outdoors experiments plugged to a 12V battery. It is the Pyle PLMRA410BT model and counts with an output power of 100 watts for each of its four channels. It has an input gain impedance from 1mV to 300mV, a frequency response between 15kHz and 30kHz, an input impedance of either 10kΩ or 100Ω, an input sensitivity of 250mV or 2.5V and a SNR of 95dB.

Figure 4-5. Amplifier of 400W.

4.1.1.6 FIAMM battery.

Thanks to the battery in Figure 4-6 we have been able to take the experiments outdoors. The FG21803 battery, manufactured by FIAMM, is a 12V battery with a nominal capacity of 18Ah and a 20mΩ resistance when fully charged. It has been connected to the amplifier from Figure 4-5 to power it and so the speakers.

Figure 4-6. 12V battery.

4.1.1.7 JVC speakers.

The CS-J620X JVC (Figure 4-7) speakers of 16cm have a power capacity of 300 watts maximum and 30 watts minimum and an impedance of 4Ω.

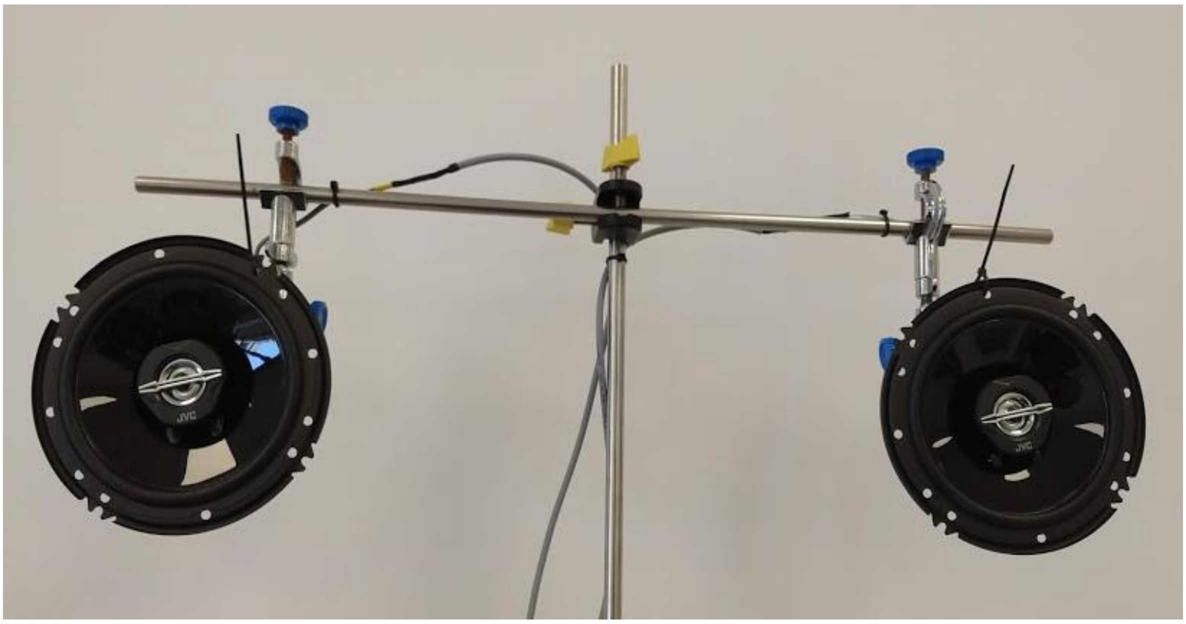


Figure 4-7. JVC speakers mounted on its rig.

4.1.1.8 Transducers.

The transducers used in the underwater experiments had a resistance of 8Ω and needed a power of 20W each as we can see in Figure 4-8.

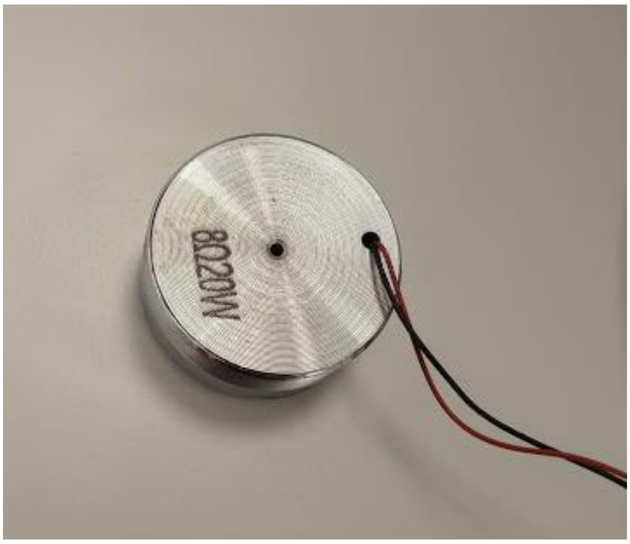


Figure 4-8. Transducer used in underwater experiments.

These transducers have been attached to a waterproof plastic box which had a hole made for the cables to go through as shown in Figure 4-9. In addition to this, we also inserted in the box, behind the transducer, a plastic piece made in a 3D printer to make pressure between the back wall of the box and the back of the transducer. This way, we can get more power out of the system.

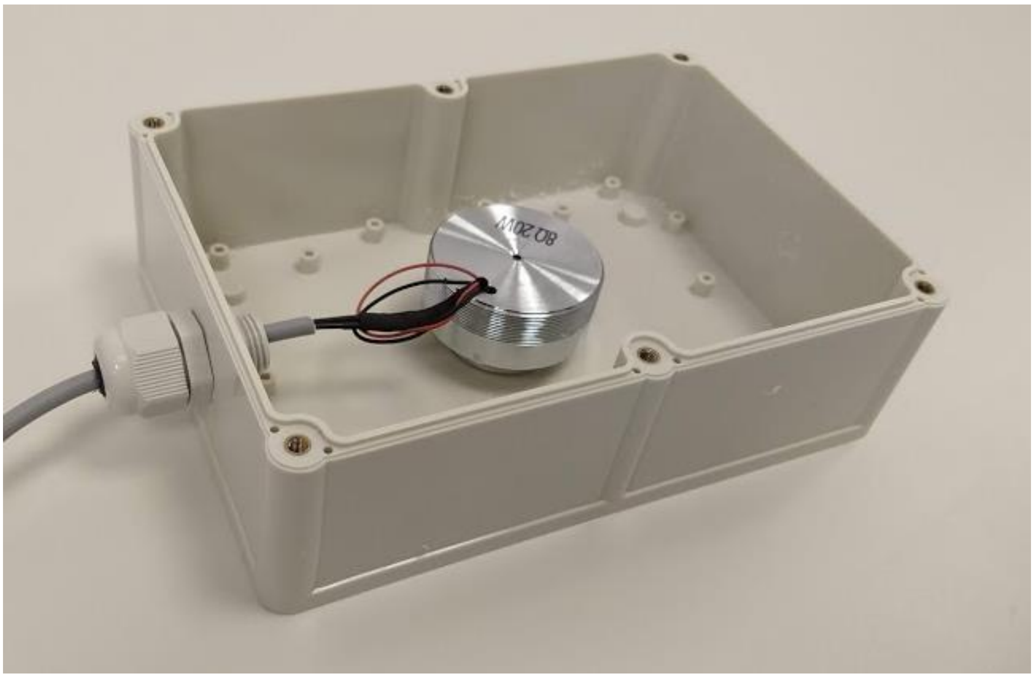


Figure 4-9. Transducer attached to a waterproof box.

These transducers have been attached to a wooden piece and tied up to a concrete brick to have them submerged in the desired position as we can see in Figure 4-10.

Figure 4-10. Final set up of the transducers.

Within this setup, the transducers have been tested in the swimming pool by doing a frequency sweep (see Figure 4-11) in which we can see how the SPL drops at frequencies higher than 12kHz.

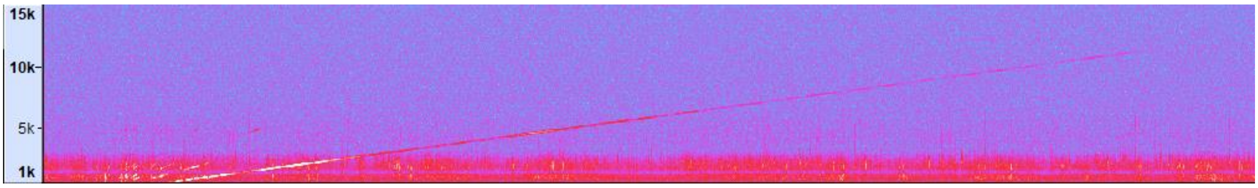


Figure 4-11. Frequency sweep of the transducer from 0Hz to 15kHz analysed in audacity.

Therefore, we made another sweep from 0Hz to 5kHz (Figure 4-12) in which can be appreciable the harmonic effect producing sounds with double frequency to the original. However, the most important data we got from this sweep is that the transducer has its maximum SL at frequencies between 2kHz and 2.5kHz.

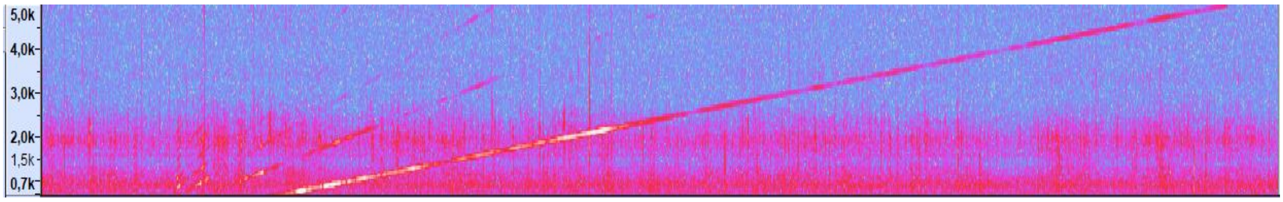


Figure 4-12. Frequency sweep of the transducer from 0Hz to 5kHz analysed in audacity.

4.1.1.9 DolphinEar DE200 Hydrophone.

The hydrophone used in the experiments underwater shown in Figure 4-13 has an amplifier which it is connected to that allows the user to modify the gain and has a type jack output for better compatibility.

This omnidirectional hydrophone has a frequency range from 7Hz to 22kHz and an output of just one channel (MONO). [32]

Figure 4-13. Hydrophone used in the underwater experiments.

4.1.1.10 Behringer sound card.

To connect the hydrophone to the computer we have used an external sound card Behringer UCA202 (see Figure 4-14).

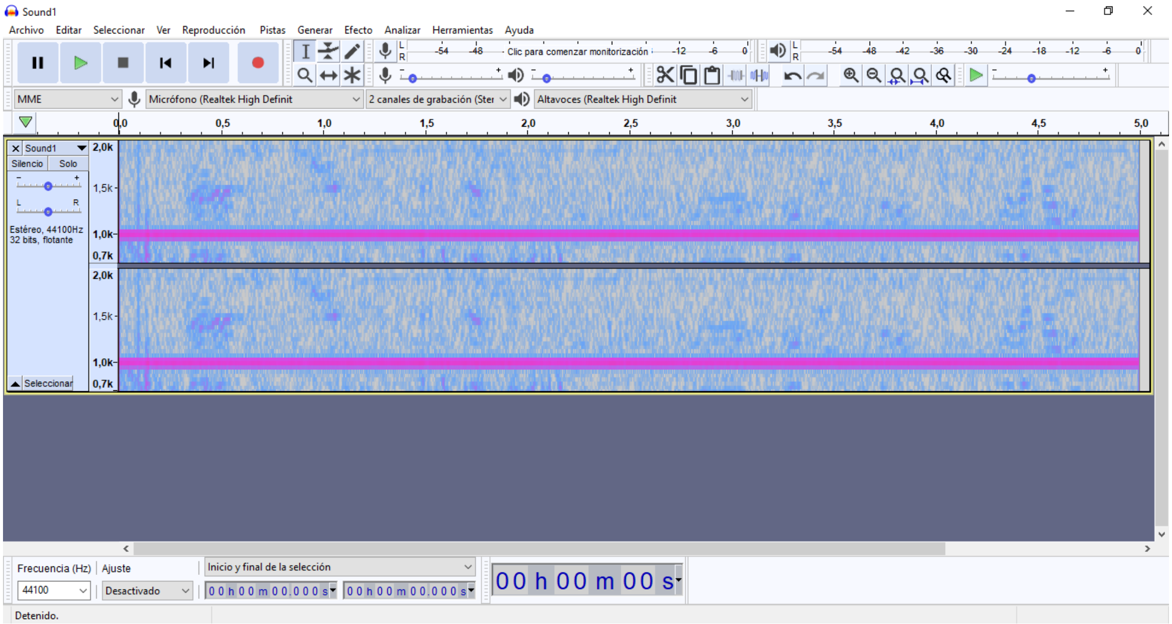
This sound card has connectors RCA as input with an impedance of 27kΩ and a maximum input level of 2dBV. On the other hand, as outputs, it counts with connectors RCA of 400Ω impedance and 2dBV maximum input level, a stereo jack type output of 50Ω. It is connected and powered by an USB cable to the computer. It has a 16bit converter, sample rates of 32kHz, 44.1kHz or 48kHz, a frequency response from 10Hz to 20kHz with 44.1kHz sample rate and from 10Hz to 22kHz with 48kHz sample rate. Finally, it has a SNR of either 89dB or 96dB.

Figure 4-14. External sound card.

4.1.2 Software.

4.1.2.1 Audacity.

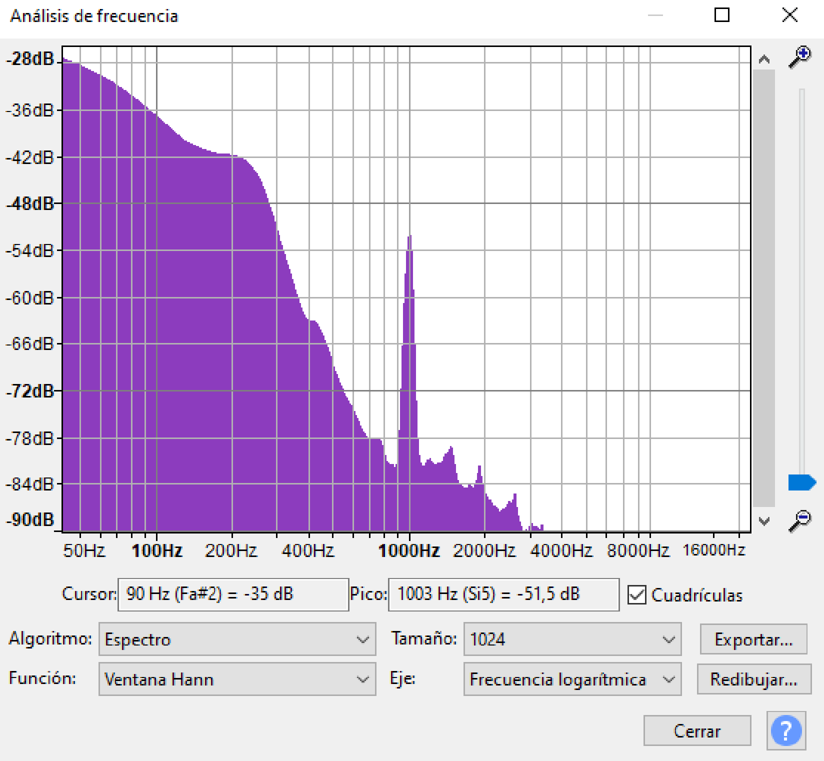
Audacity is a free program used to record, generate and edit audio that we used to test the transducers and to analyse results from audio samples. This software allows the user to explore and analyse the audio files obtaining the frequency spectrum (see Figure 4-15) and wave shape graphics.



MME
Micrófono (Realtek High Definit
2 canales de grabación (Ster
Altavoces (Realtek High Definit
Estéreo, 44100Hz
32 bits, flotante
Frecuencia (Hz): 44100
Ajuste: Desactivado
Inicio y final de la selección: 00 h 00 m 00.000 s – 00 h 00 m 00.000 s
00 h 00 m 00 s
Detenido.

Figure 4-15. Screen shot of audacity showing the spectrogram of an audio sample of 1kHz.

In addition to this, audacity has a tool that analyses also the frequency against the SPL as we see in Figure 4-16.



Cursor: 90 Hz (Fa#2) = -35 dB
Pico: 1003 Hz (Si5) = -51,5 dB
☑ Cuadrículas
Algoritmo: Espectro
Tamaño: 1024
Función: Ventana Hann
Eje: Frecuencia logarítmica

Figure 4-16. Screenshot of audacity's analysis of frequency of an audio sample of 1kHz.

4.1.2.2 Python.

Python is a programming language characterized by its easy comprehension that we have used to create programs needed for the experiments.

One of the key features of python it is the availability of open-source libraries, or modules, created by the other users, that are easy to integrate in your own projects. These modules are basically a group of functions that can be called as long as the module has been imported. Some of the modules used in this project are:

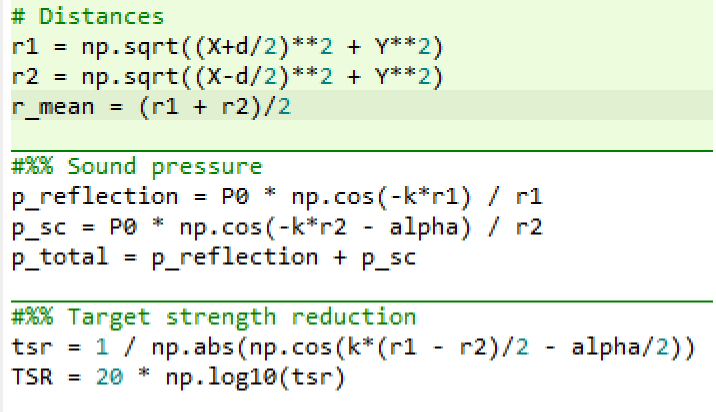
- Matplotlib: a comprehensive library for plotting and making graphs.
- Numpy: a library for handling multidimensional arrays and vectors.
- Sounddevice: a library for playing and recording audio.
- Scipy: a library for signal processing containing functions such as the FFT.

These modules have been used to develop the following computer programs:

4.1.2.2.1 Simulation.py

This program was implemented to simulate and represent the SPL in space when applying sound cancellation with a given relative position between the reflection point and the transmitter.

The most important part of this piece of code the definition of the relative positions, the pressure fields produced by each source and the reduction of target strength (see Figure 4-17).

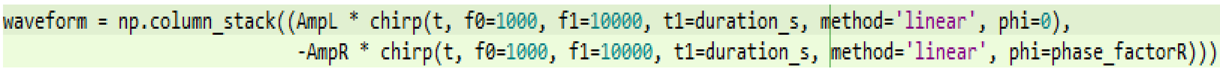


```
# Distances
r1 = np.sqrt((X+d/2)**2 + Y**2)
r2 = np.sqrt((X-d/2)**2 + Y**2)
r_mean = (r1 + r2)/2

#%% Sound pressure
p_reflection = P0 * np.cos(-k*r1) / r1
p_sc = P0 * np.cos(-k*r2 - alpha) / r2
p_total = p_reflection + p_sc

#%% Target strength reduction
tsr = 1 / np.abs(np.cos(k*(r1 - r2)/2 - alpha/2))
TSR = 20 * np.log10(tsr)
```

Figure 4-17. Extract of "simulation.py" code.

4.1.2.2.2 Chirp_cancellation.py

This program generates two simultaneous signals modulated in frequency with opposite phases, each signal to be sent to either the right or left audio channel of the computer. To achieve this, we generate them with the function "chirp" from the Scipy library (see Figure 4-18).

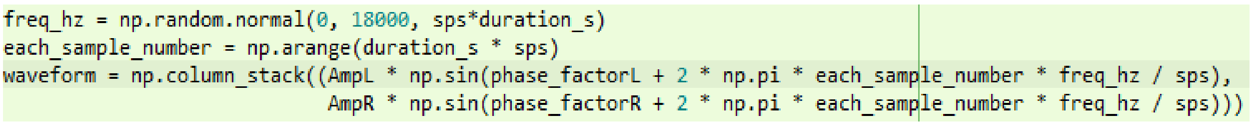


```
waveform = np.column_stack((AmpL * chirp(t, f0=1000, f1=10000, t1=duration_s, method='linear', phi=0),
                           -AmpR * chirp(t, f0=1000, f1=10000, t1=duration_s, method='linear', phi=phase_factorR)))
```

Figure 4-18. Extract of "chirp_cancellation.py" code.

4.1.2.2.3 White_noise_cancellation.py

This program was used to experiment with white noise using a random Numpy array (see Figure 4-19).

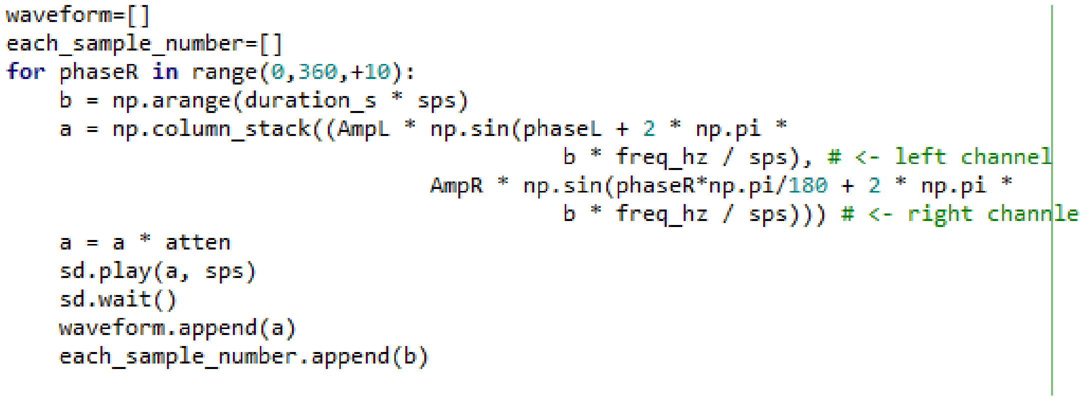


```
freq_hz = np.random.normal(0, 18000, sps*duration_s)
each_sample_number = np.arange(duration_s * sps)
waveform = np.column_stack((AmpL * np.sin(phase_factorL + 2 * np.pi * each_sample_number * freq_hz / sps),
                            AmpR * np.sin(phase_factorR + 2 * np.pi * each_sample_number * freq_hz / sps)))
```

Figure 4-19. Extract of "white_noise_cancellation.py" code.

4.1.2.2.4 PhaseSweep.py

To increase the efficiency of the experiments we developed a program that generates continuous wave pulses with different phases by steps of 10 degrees. This is done using a loop in which the phase changes in each repetition and that plays the continuous wave pulse (see Figure 4-20).

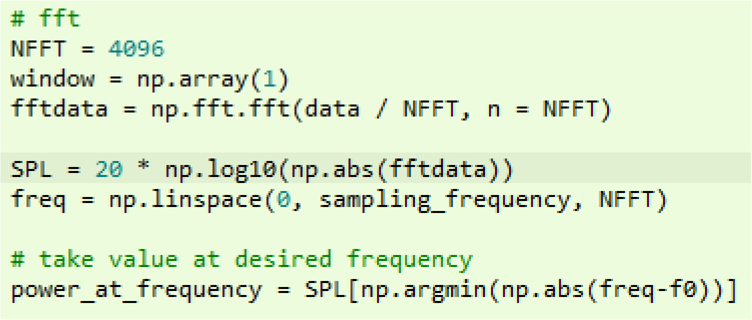


```
waveform=[]
each_sample_number=[]
for phaseR in range(0,360,+10):
    b = np.arange(duration_s * sps)
    a = np.column_stack((AmpL * np.sin(phaseL + 2 * np.pi *
                                       b * freq_hz / sps), # <- left channel
                             AmpR * np.sin(phaseR*np.pi/180 + 2 * np.pi *
                                       b * freq_hz / sps))) # <- right channle
    a = a * atten
    sd.play(a, sps)
    sd.wait()
    waveform.append(a)
    each_sample_number.append(b)
```

Figure 4-20. Extract of "PhaseSweep.py" code.

4.1.2.2.5 ResultsPlot_440.py and ResultsPlot_1000.py

To analyse the results, we used several pieces of code that read each sound file, compute the Fourier Transform, obtain the SPL at the required frequency, and represent the values in a graph comparing it with the expected results. The most important part of this set of programs is the computation of the Fourier Transform using the Numpy function "fft" and acquiring later the SPL from the desire frequency (see Figure 4-21).

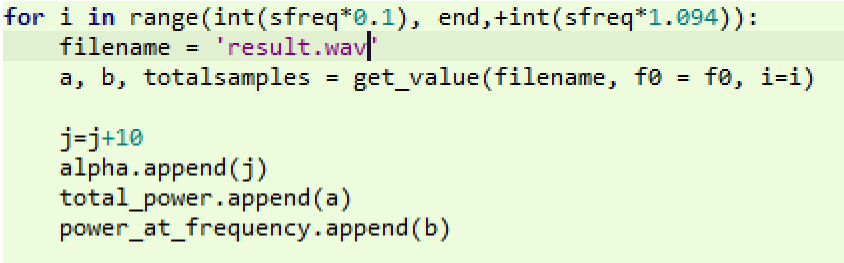


```
# fft
NFFT = 4096
window = np.array(1)
fftdata = np.fft.fft(data / NFFT, n = NFFT)

SPL = 20 * np.log10(np.abs(fftdata))
freq = np.linspace(0, sampling_frequency, NFFT)

# take value at desired frequency
power_at_frequency = SPL[np.argmin(np.abs(freq-f0))]
```

Figure 4-21. Extract of "ResultsPlot_440.py" code.

4.1.2.2.6 ResultsTambo.py

To analyse the results from just one audio file we used the same functions to get the SPL at the frequency but we used a loop to extract the data from the audio file (see Figure 4-22).



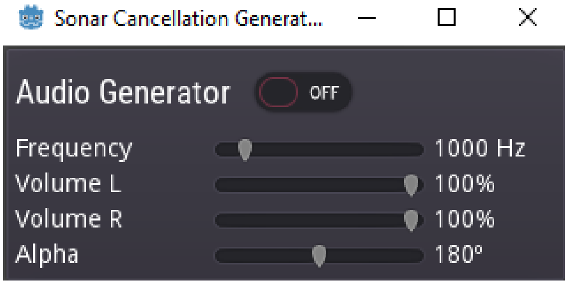
```
for i in range(int(sfreq*0.1), end,+int(sfreq*1.094)):
    filename = 'result.wav'
    a, b, totalsamples = get_value(filename, f0 = f0, i=i)

    j=j+10
    alpha.append(j)
    total_power.append(a)
    power_at_frequency.append(b)
```

Figure 4-22. Extract of "ResultsTambo.py" code.

Where the variable “sfreq” is the sampling frequency which means one second of the audio and the value that multiplies the sampling frequency to define the steps is the time between each pulse in the audio file.

4.1.2.3 Sonar Cancellation.

Sonar Cancellation is a program created by Prof. Rodríguez Molares, supervisor of this project. This application (see Figure 4-23) allows the user to generate a tone in any frequency, with any volume for both right and left channel independently and with any phase difference between the channels.



Audio Generator OFF

Frequency 1000 Hz

Volume L 100%

Volume R 100%

Alpha 180º

Figure 4-23. Sonar Cancellation program by Prof. Rodríguez Molares.

4.2 Experiments in air.

4.2.1 Experiment I.

In this experiment we aimed to cancel different kind of sounds in a particular bearing, starting with a tone, followed by a Chirp and white noise to finish.

4.2.1.1 Continuous tone.

The objective of this first experiment was to cancel a continuous tone. To achieve this objective, we used the JVC speakers, the microphone TONOR, the FIAMM battery and the Pyle amplifier.

The idea is that the left speaker emits a single frequency tone with zero-phase while the right speaker emits the exact same tone with a π-phase. According to the theory presented in Section 2.9, both waves should cancel each other at bearing 0º as long as the experiment takes place in an anechoic environment, this is an environment where free-field conditions are met. We can see in the simulations of the program “simulation.py” how the SPL changes with the bearing (see Figure 4-24).

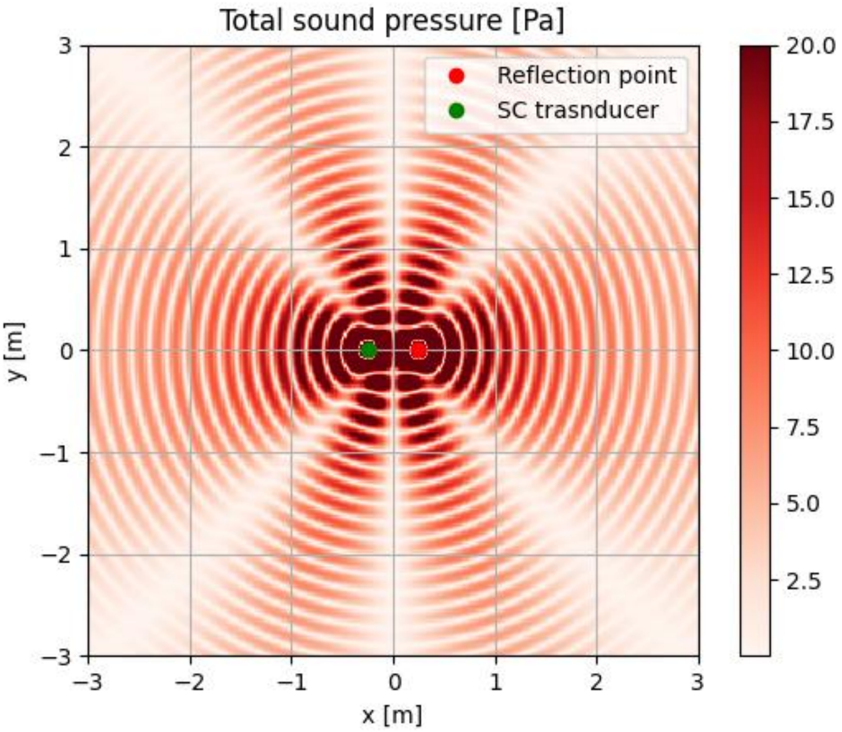


Figure 4-24. Simulation of sound cancelling for a distance between speakers of 50cm and a frequency of 1kHz.

However, the experiments were not performed under free-field conditions. The 1kHz experiment took place in the training yard facing the sea and the 440Hz experiment was made on the roof of the research building (Figure 4-26). Although our intentions were to minimize the influence of nearby structures, on both locations there could have been sound bounces that complicated the sound cancellation. Nevertheless, destructive interference could be observed to some extend by adjusting the phase and/or the amplitude of one of the speakers.

Figure 4-25. Scheme of the Experiment I with 1kHz frequency in the training yard of the Spanish Naval Academy.

Figure 4-26. Picture of the execution of Experiment I with 440Hz frequency on the roof of the investigation building.

Once the instrumentation was set, using the personal computer, we executed the program "Sonar Cancellation". This program has been made to generate the same tone with each speaker allowing us to change the phase and amplitude on both channels.

The loudspeakers were not calibrated so the phases set for each channel may be different from the real ones. This means that for each frequency we needed to find the virtual phase in which sound cancels at bearing 0º.

This experiment was carried out with both 1kHz and 440Hz frequency and the recorded samples were analysed in Audacity.

4.2.1.2 Chirp.

We also aimed to cancel a frequency modulated pulse (Chirp). To achieve this, we used the set up shown in Figure 4-27, and this time, the program "chirp_cancellation.py" was developed to generate a soundwave modulated in frequency (FM) from 3kHz to 4kHz (Figure 4-28) and plot what was recorded by the microphone.

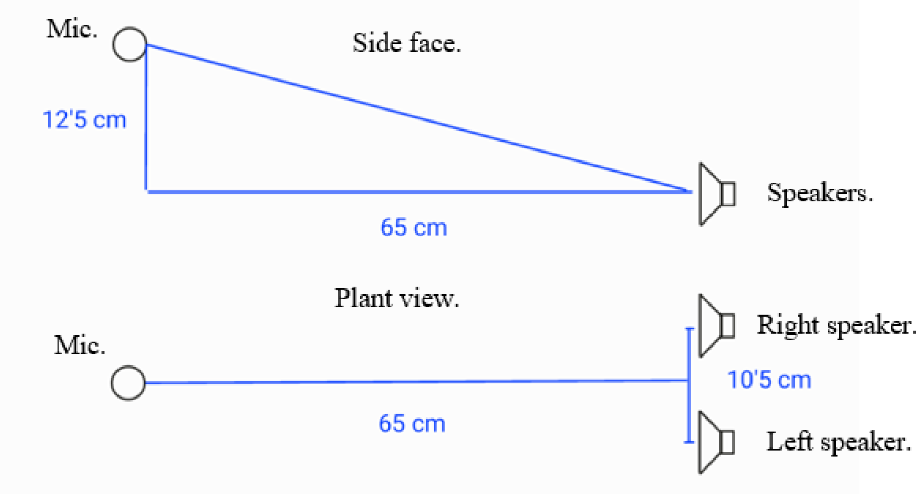


Figure 4-27. Scheme of the set up for second and third experiments in air.

The materials used are the EBTOOLS speakers, the microphone TONOR, the Kinter amplifier and the KKmon power source. This experiment took place inside the Fluidics laboratory.

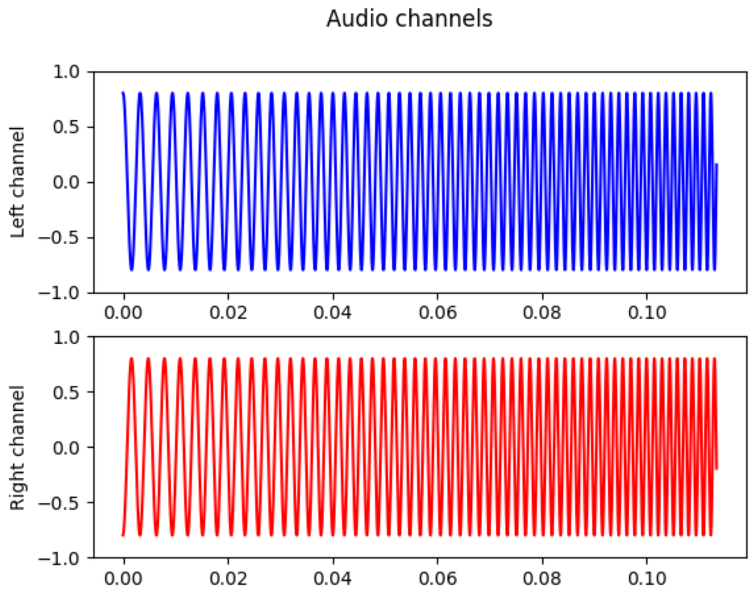


Figure 4-28. Example of two chirp signals in anti-phase.

4.2.1.3 White Noise.

Thinking about the possibility of extrapolating this idea to passive sonars, we have done the same experiment emitting white noise (Figure 4-29) instead of a chirp or a tone using the program "white_noise_cancellation.py". The materials, set up and place are exactly the same as in the chirp experiment.

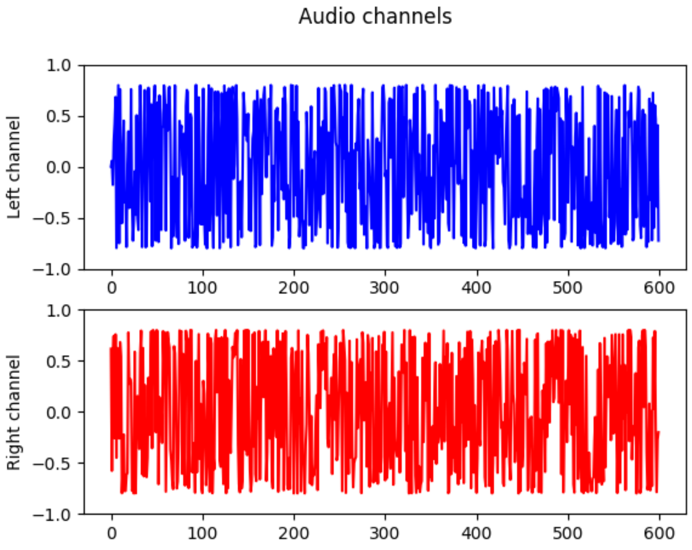


Figure 4-29. Representation of two signals of white noise.

4.2.2 Experiment II.

This experiment was also carried out on the training yard of the Naval Academy facing the sea to have fewer reflections, with the following materials: the Pyle amplifier, the FIAMM battery, the JVC loudspeakers and the TONOR microphone.

The objective of this experiment was to verify the results predicted by Eq. [13] with the bearing shown in Figure 4-30 for a given alfa.

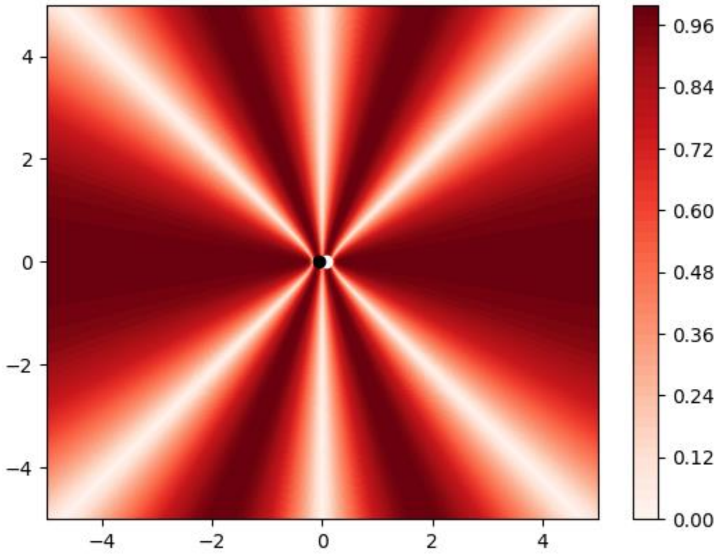


Figure 4-30. SPL for cancelling signal of 1kHz frequency, in air and with a distance between the ANC and the reflection point of 50 centimetres.

In order to achieve this goal, we set the speakers one next to the other and the microphone right in front of them as shown in Figure 4-32.

The procedure was the following: the program "Sonar Cancellation" was used to emit a tone of 1kHzm a frequency where the wavelength in air is similar to that of a 4kHz active underwater SONAR. Then, we moved the microphone to measure the SPL at different locations at a perpendicular distance of 4 m. The results were compared with the predictions given by Eq. [13].

The experiment was also carried out using a frequency of 440Hz to see the difference (Figure 4-31).

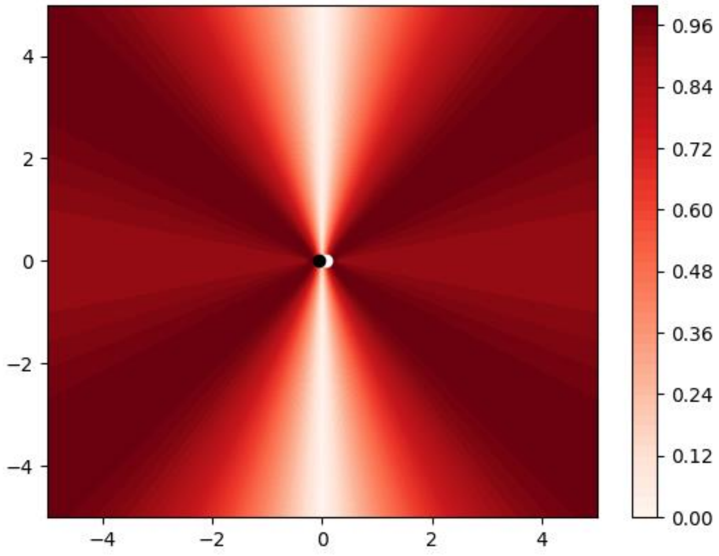


Figure 4-31. SPL for cancelling signal of 440Hz frequency, in air and with a distance between the ANC and the reflection point of 50 centimetres.

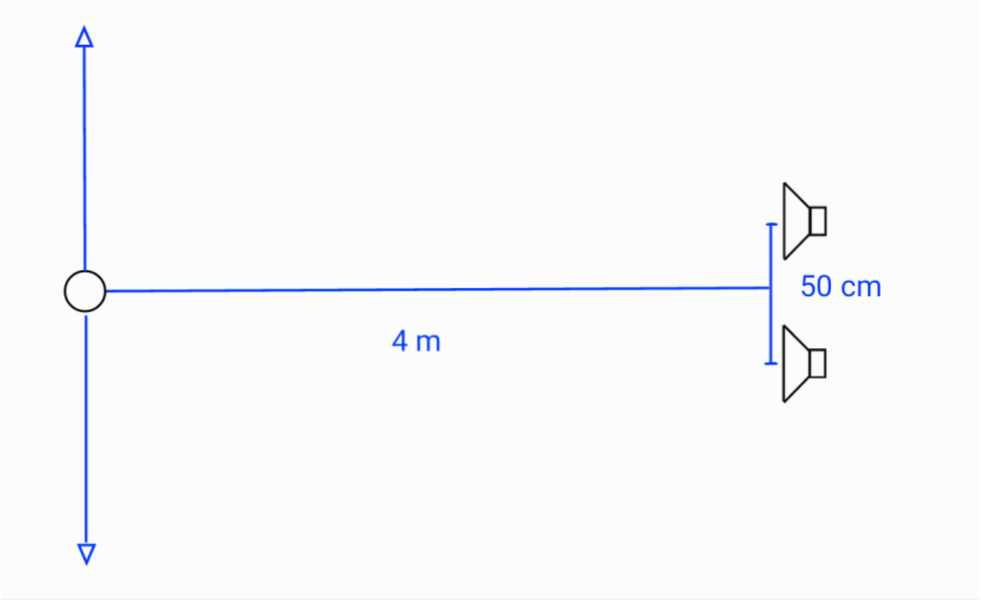


Figure 4-32. Scheme of the second experiment in air.

In this experiment no calibration was performed prior to measurement, and due to that the cancellation bearing did not match the 0º bearing.

4.3 Experiments in water.

With the available resources and time, it was unfeasible to evaluate the whole SONAR process, including the generation and reflection of the SONAR pulse on a suitable target. For that purpose we would have needed not only strong SONAR projectors, but also highly sensitive hydrophones and an appropriate experimental setup. Because of that, we decided to focus on the evaluation of the cancellation emulating the reflected sound wave with an acoustic source. This way, one sound source was used to emulate the reflection at the vessel’s interface, and the other as the echo cancelling transducer.

4.3.1 Experiment III.

In this third experiment we tried to replicate the first experiment in water. The experiment was carried out in the swimming pool of the Naval Academy using two computers, two transducers, the DolphieEar DE200 hydrophone, the Pyle amplifier and the FIAMM battery.

One computer was taken to one side of the pool and connected through the Behringer external sound card to the hydrophone which was under water (see in Figure 4-33). The other computer was set on the other side of the swimming pool connected to the amplifier, which was then powered by the battery and connected to both transducers (see in Figure 4-34 and Figure 4-35). See a drawing of the experimental set up in Figure 4-36.

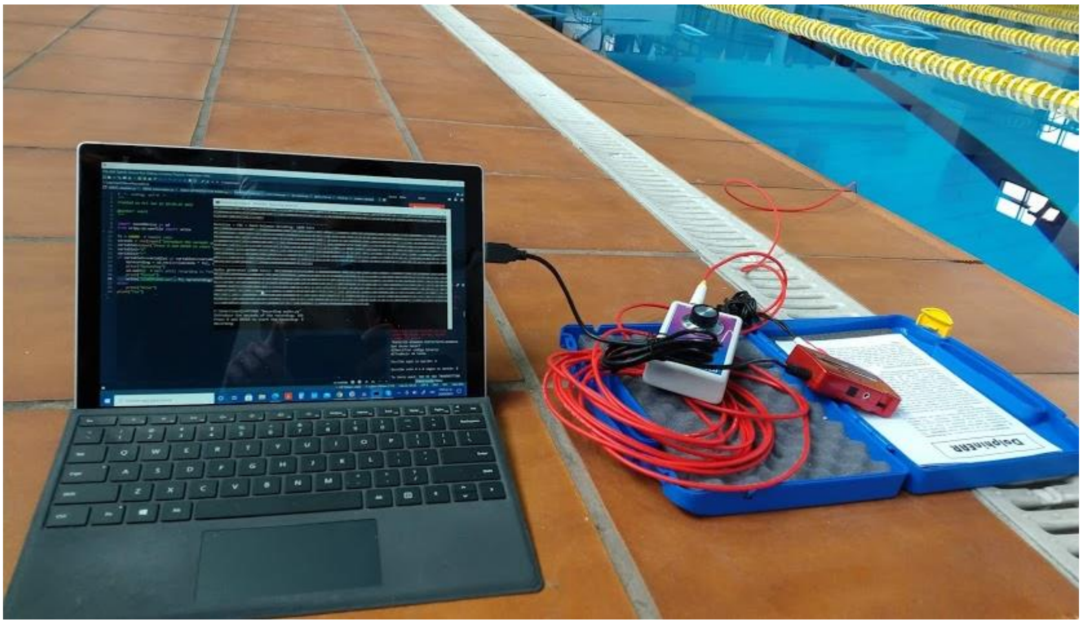


Figure 4-33. Picture of the hydrophone connected to one of the computers.

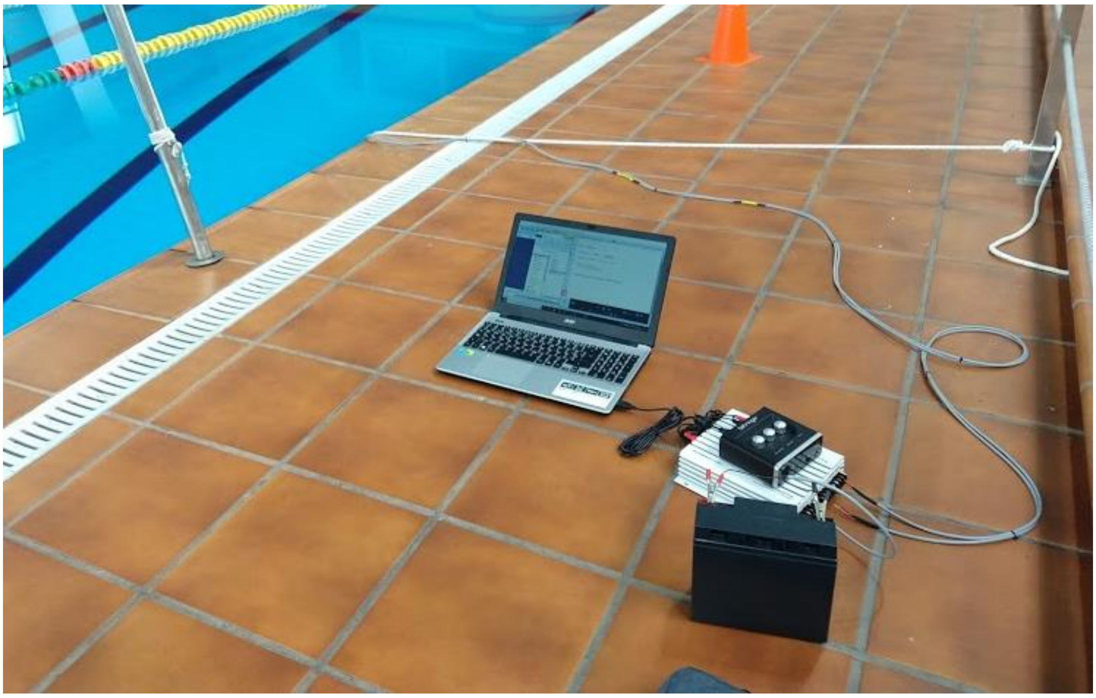


Figure 4-34. Picture of the transmitter computer connected to the amplifier and transducers.

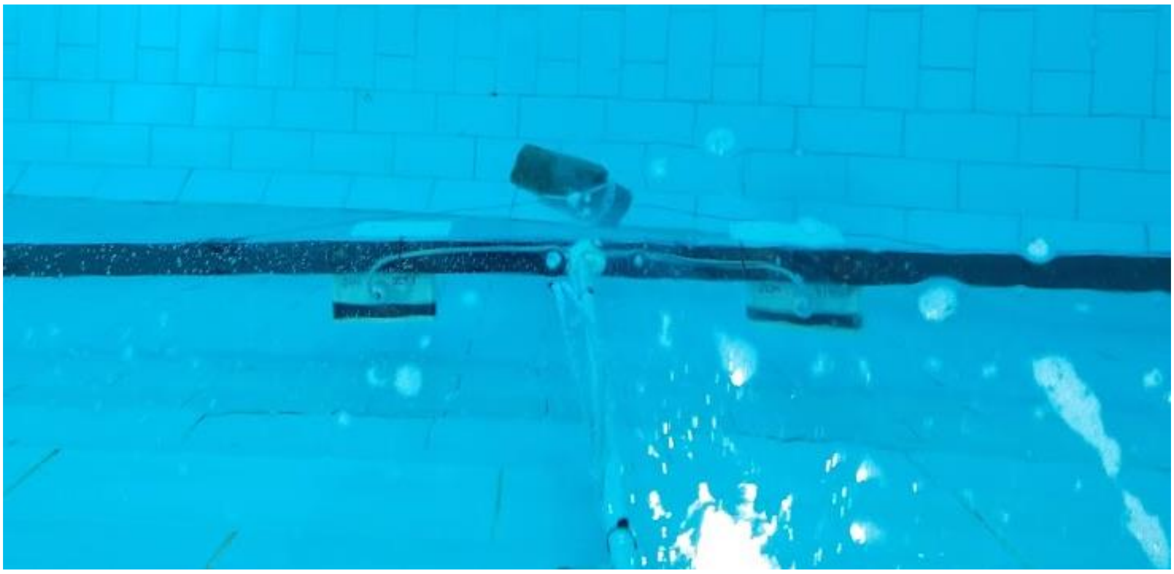


Figure 4-35. Picture of the transducer's rig in the pool.

Using Audacity to record the audio files and the “phase_sweep.py” program to emit the signals while changing the phase, we try to accomplish the same objectives as in the first experiment in air: cancelling the sound in the hydrophone position by changing the phase of one of the generated tones.

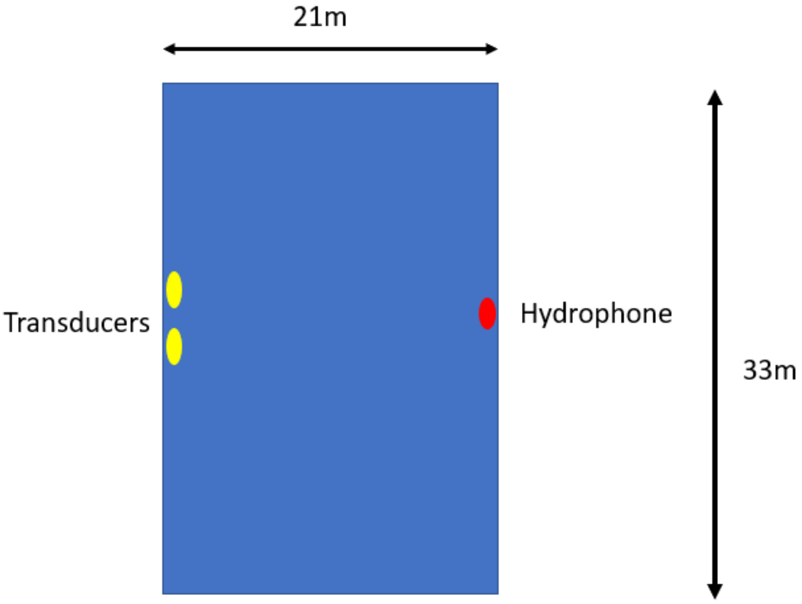


Figure 4-36. Scheme of the experiment in the swimming pool.

4.3.2 Experiment IV.

We repeated Experiment III but this time in the harbour of the Spanish Naval Academy, between the locations shown in Figure 4-38. We used two laptops, two transducers, the DolphinEar DE200 hydrophone, the Pyle amplifier and the FIAMM battery.

One computer was set on the “Chereguini” dock and connected through the Behringer external sound card to the hydrophone which was under water. The second computer was placed on the “Torpedos” dock connected to the amplifier, which was powered by the battery and connected to both transducers (Figure 4-37).

Figure 4-37. Transducers submerged in water in "Torpedos" dock.

We used the program "phase_sweep.py" to generate the tones with different phase and recorded the samples using Audacity commercial software.

In this experiment we transmitted a 5 kHz tone with both speakers, sequentially changing the phase of one of the channels in 10 degrees steps.

Figure 4-38. Scheme of the experiment in the Naval Academy's docks.

4.3.3 Experiment V.

A last experiment was carried out from a longer distance (985 metres), from the Tambo island to the "Torpedos" dock of the Spanish Naval Academy. The locations are shown in Figure 4-39.

Figure 4-39. Scheme of the Experiment V.

The transmission laptop was located on the “Torpedos” dock, connected to the Pyle amplifier, that drived the two transducers immersed in water as shown in Figure 4-40 and Figure 4-41.

Figure 4-40. Transmission equipment set up.

Figure 4-41. Transducers being submerged in "Torpedos" dock.

In the island we mounted the receiver computer connected, through the Behringer sound card, to the DolphinEar hydrophone. The hydrophone was mounted on a wooden pole to avoid it hitting the nearby rocks (see in Figure 4-42).

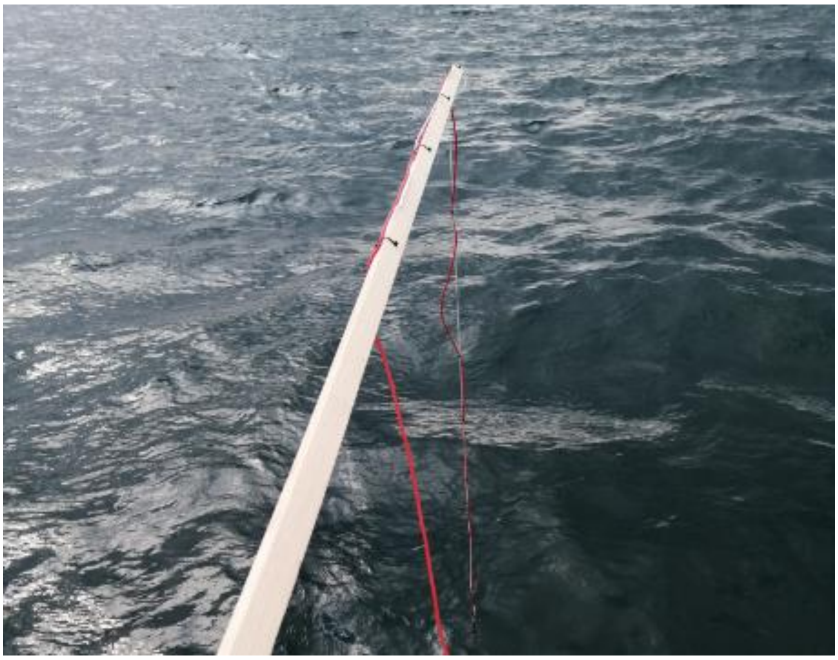


Figure 4-42. Picture of the DolphinEar hydrophone submerged in water held by a wooden piece.

In this experiment we transmitted both CW and FM pulses in different frequencies. Phase sweeps where also carried out to characterize the channel and find the best frequencies to carry out the experiments. The FM pulses were centred in 5kHz and in 8kHz while the CW pulses where in 5kHz, 8kHz and 10kHz.

4.4 Summary of experiments.

Experiment	**Description**
Experiment I	Experiment carried out on the roof of the Research Building of the University Defence Center to demonstrate sound cancellation by changing the phase of one of the channels. Divided in three parts: continuous wave (CW), frequency modulated wave (FM) and white noise (WN).
Experiment II	Experiment carried out on the training yard of the Naval Academy's to evaluate the SPL in space for a stablished phase value. Divided in two parts: a 1kHz tone and a 440Hz tone.
Experiment III	Experiment carried out in the Naval Academy's swimming pool to measure the SPL for different cancelling phase using a 2 kHz frequency tone.
Experiment IV	Experiment carried out in the Naval Academy's harbour to measure the SPL for different cancelling phase using a 5 kHz frequency tone.
Experiment V	Experiment carried out between the "Tambo" island and the "Torpedo" dock of the Naval Academy for different cancelling phases, frequencies and both CW and FM pulses.

Table 4-1. Summary of Experiments.

5 RESULTS

5.1 Experiments in air.

5.1.1 Experiment I: Training yard and rooftop of the investigation building.

Using a 1 kHz tone, we observed that ANC resulted in a reduction in SPL of 11.54 dB at bearing 0º. Using a 440 Hz tone, we observed that ANC resulted in a reduction in SPL of 25.17 dB at bearing 0º. This reduction in SPL can be regarded as an effective reduction in the target strength of the vessel.

The results in the experiment with the FM pulse and the white noise signal were not successful, in fact, we did not get cancellation.

5.1.2 Experiment II: Training yard and rooftop of the investigation building.

In the Figure 5-1 we can see, represented in a blue line, the expected SPL as predicted by Eq. [13], and adjusted for the microphone directivity pattern. The red dots represent the measurements of the SPL for the 1kHz tone. In this figure, the SPL units are referred to a reference sound sample which was recorded using a single channel, and hence, without any kind of sound cancellation. We observe a decrease of around 11 dB at bearing 0º, and additional minima at points x = -1.8m, and x = 1.8 m.

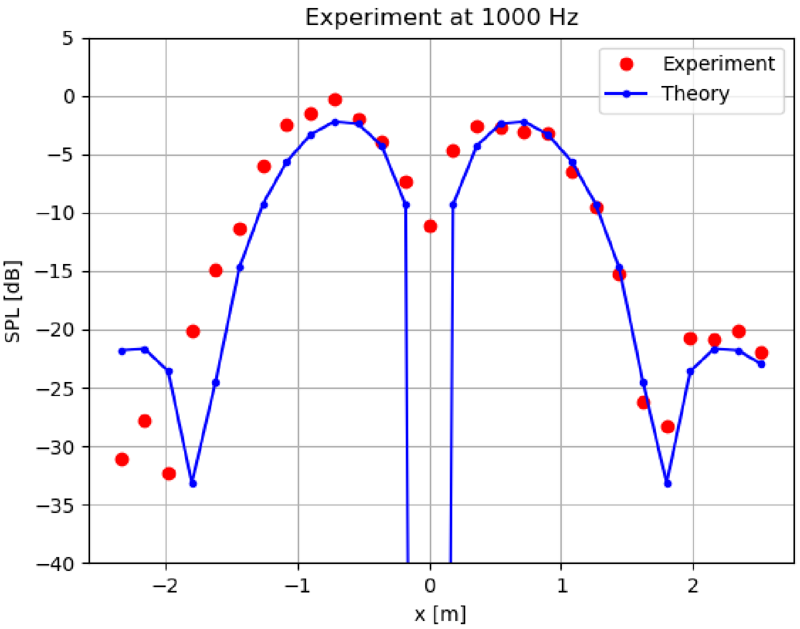


Figure 5-1. Representation of the results of the experiment against the theory for 1kHz.

Figure 5-2, shows the same results for the experiment done using a 440 Hz tone. We observe a decrease in SPL of around 27 dB at bearing 0º.

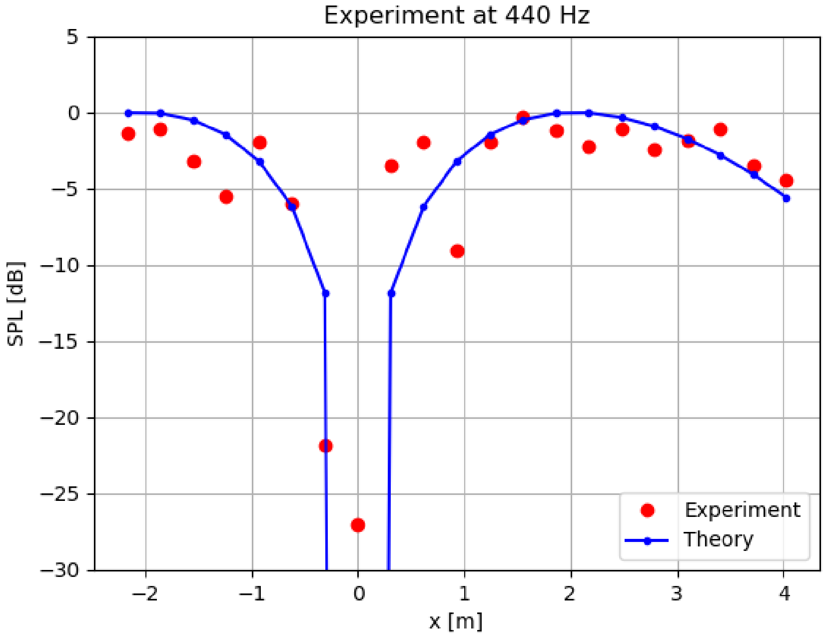


Figure 5-2. Representation of the results of the experiment against the theory for 440 Hz.

5.2 Experiments in water.

5.2.1 Experiment III: Swimming Pool

Figure 5-3 shows, in a blue line, the expected SPL as predicted by Eq. [13]. The red dots indicate the SPL measured for each phase value using a 2 kHz tone. In this figure, the SPL units are referred to a reference sound sample which was taken without any kind of sound cancellation. We observe a decrease in SPL of around 20 dB for a phase difference of 30º between both channels.

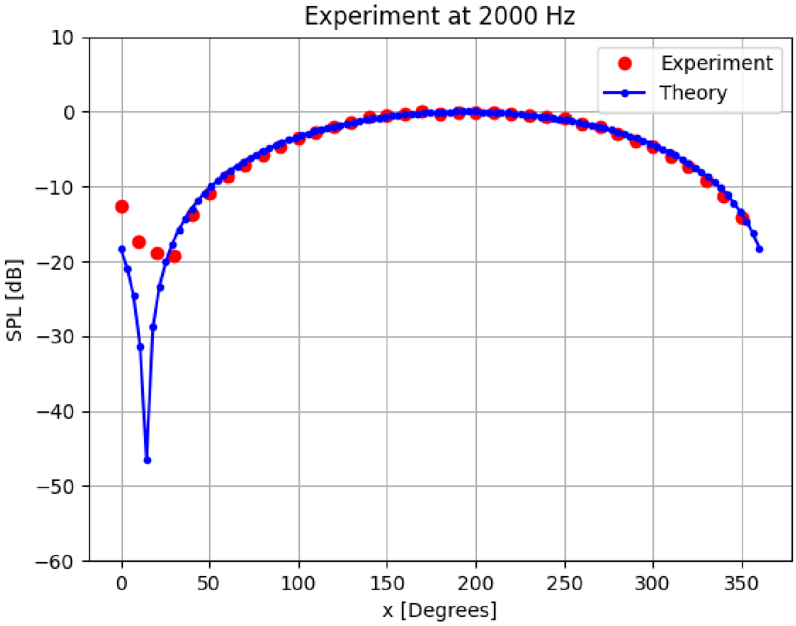


Figure 5-3. Results of Experiment II carried out in the swimming pool of the Spanish Naval Academy.

5.2.2 Experiment IV: Harbour of the Naval Academy

In Figure 5-4 the blue line is the expected SPL as predicted by Eq. [13]. The red dots represent the measured SPL for each phase tested using a 5 kHz tone. In this figure, the SPL units are referred to a reference sound sample which was taken without any kind of sound cancellation. We observe a maximum reduction of the SPL of 18 dB, for a phase difference of 200º between both channels.

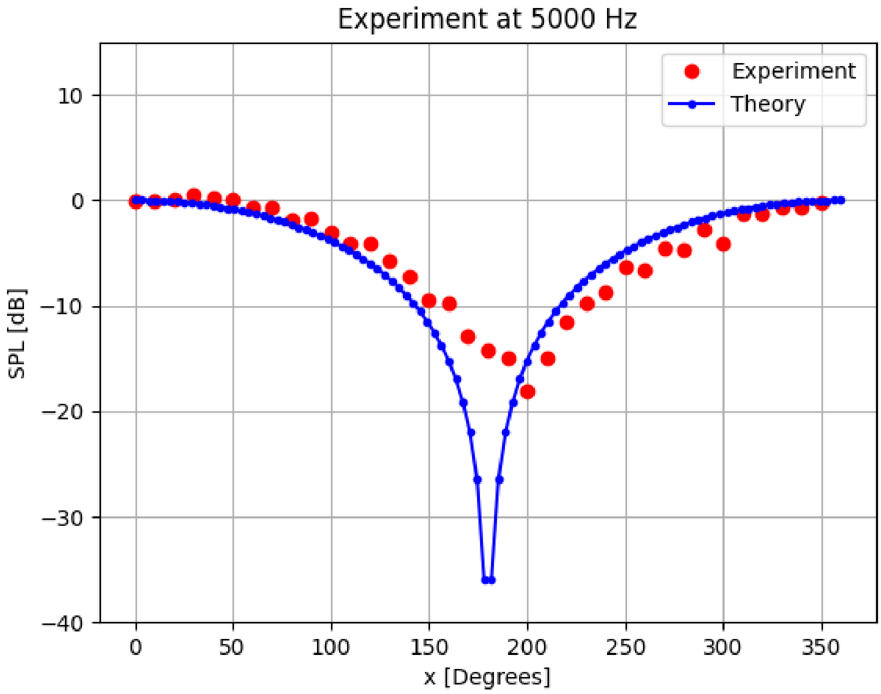


Figure 5-4. Results of the first experiment in the harbour of the Spanish Naval Academy.

5.2.3 Experiment V: Tambo island

In Figure 5-5 the expected SPL is shown as predicted by Eq. [13] for the Tambo-Torpedos link using a 5 kHz tone. The red dots represent the SPL measured for different phases. The SPL is measured in dB referred to a reference sound sample took without cancellation. No clear cancellation is observed.

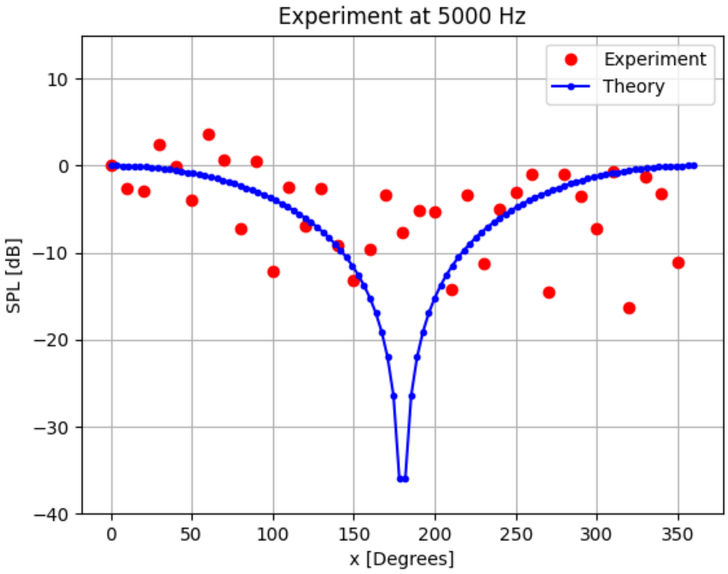


Figure 5-5. Result of Experiment V, transmitting 5kHz CW pulses.

In Figure 5-6 the predicted SPL values are shown, in blue, together with the measured SPL, in red dots, for the FM pulses centred at 5kHz. The SPL is measured in dB referred to a reference sound sample took without cancellation. A slight cancellation is observed reaching a maximum reduction of around 8 dB at a phase difference of 130º between both channels.

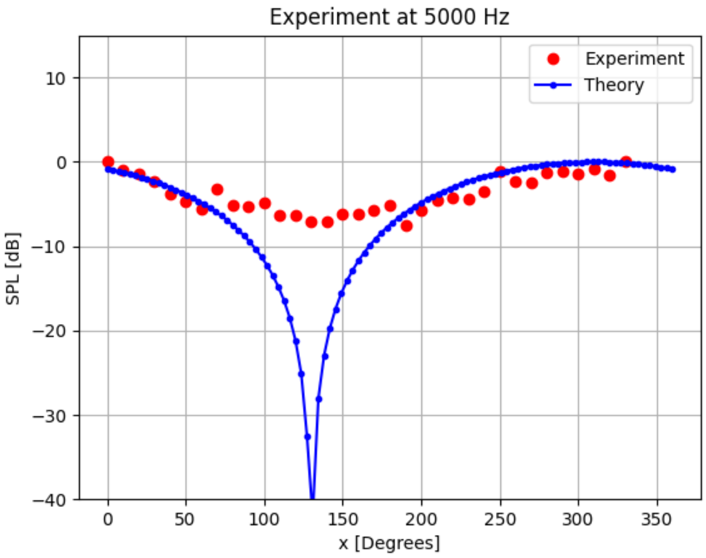


Figure 5-6. Result of Experiment V, transmitting 5kHz centred FM pulses.

6 DISCUSSION AND CONCLUSIONS

In general, the obtained results seem to support our hypothesis that it is possible to cancel a SONAR pulse using an echo cancelling transducer. In this chapter we discuss the result of each experiment in detail and we provide some general conclusions and future work.

6.1 Discussion of the experimental results.

6.1.1 Experiments in air.

In Experiment I the objective was to achieve sound cancellation at a particular bearing modifying the phase difference of one of the speakers: the one simulating the echo cancelling transducer. The results obtained seem to confirm that cancellation was in effect possible. In the first case, using a frequency of 1 kHz, we obtained a reduction in SPL of 11.54 dB, and in the second case, using a frequency of 440 Hz, the SPL reduction was 27.17dB. However, the reduction obtained with the 1 kHz tone was much less than the predicted value. This could be motivated by the presence of surrounding walls and building elements where sound could have been reflected. These results could be further improved by performing the experiment inside an anechoic chamber, and using calibrated sound sources, both in phase and amplitude.

In Experiment II, that took place in the training yard, the objective was to map the measurements spatially to better understand the physical phenomenon. In this experiment we obtained a reduction of the SPL of 11.6dB, which means a 93.08% decrease in the received SPL, using a 1 kHz tone. Although the result was positive, the actual number differed significantly from what it was predicted by Eq [13]. In this case the deviation could be easily explained by the presence of ambient noise, as wind intensity increased during the completion of the experiment, being clearly noticeable in the resulting recording.

On the other hand, in the 440 Hz tone experiment, that took place on the roof of the Research building, we obtained a reduction in the SPL of 26.9dB, which means a 99.79% decrease in the transmission loss. This result clearly matched the prediction by Eq. [13].

We could illustrate how this result could be applied to the SONAR detection problem. Let us assume that a given active SONAR systems bestows a submarine with the capacity of detecting a vessel from a 40 NM range. If the reduction in SPL is in effect 26.9dB, then using Eq. [22] we can predict what would be the effective detection range of the torpedo if we activate the ANC system:

$$R = \frac{40}{10^{\frac{26.9}{40}}} = \frac{40}{4.704} = 8.5\ \text{NM}$$

That means about a 79% reduction of the active sonar range.

In spite of the general good results from the experiments in air, the attempts to cancel FM pulses and white noise were unsuccessful. This could be due to the lack of calibration of the used sound sources. Having a different phase response to each frequency would hinder the cancellation of broadband signals such as FM pulses and white noise. In other words, an uncalibrated sound source may change phase as we change frequency and those changes must be compensated to ensure that the correct phase is emitted by both sources at all frequencies. Performing that calibration requires of equipment that was not available to us, and because of that we decided to focus on narrowband cancellation.

6.1.2 Experiments in water.

Experiment III was carried out underwater using the swimming pool of the Spanish Naval Academy. The swimming pool cannot be assumed to be free field, but rather a diffuse reverberant field, since it is a relatively small body of water. Despite this, the obtained results fitted remarkably well the predictions of Eq. [13], with a reduction in SPL of around 20 dB. This is the case because we swept across all possible phase differences, and acoustic cancellation can also be achieved in reverberant fields. However, the prediction of the needed phase difference is problematic, as it depends not only on the torpedo location, but also on the geometry of the surrounding space. This means that, although theoretically possible, the cancellation in shallow waters and at close distances, will require a more complete description of the acoustic phenomena involved.

Experiment IV, which took place in the harbour of the Naval Academy, presented more realistic conditions. However, the location was still shallow waters and surrounded by docks and piers that would effectively reflect sound in several directions. Therefore free-field conditions were not met. The background noise in the harbour was noticeably higher than in the swimming pool, covering the lower frequency range up to approximately 3 kHz. That background noise would have masked the tones generated by our transduced and forced us to use a frequency of 5 kHz to conduct the experiment.

The results obtained in Experiment IV were very similar to the ones obtained in the swimming pool, achieving a reduction in the received SPL of up to 18 dB. This result further supports the hypothesis that SONAR cancellation could be applied to reduce the target strength of a vessel in open waters, where the medium characteristics are closer to free-field conditions.

In order to get closer to free-field conditions, we carried out Experiment V between the island of Tambo and the “Torpedos” dock at the Naval Academy. With a separation of around a kilometer between both locations and a maximum depth of water of 17 meters, we expected that this experiment would finally show the feasibility of the proposed solution. However, the background noise observed during the experiment was much higher than the experienced inside the Naval Academy harbour. That noise masked the transmission of almost all the signals transmitted, with the exception of the FM pulses centred at 5 kHz, where a SPL reduction of up to 8 dB was observed.

It must be noted that Experiment V took place during the evening, coinciding with high tide to facilitate the immersion of the sound sources. During the evening of that particular day, most of the vessels of the Naval Academy were in operation in the vicinity of Tambo, including all the instruction boats, the “Tabarca” patrol boat, the “Intermares” training ship, plus a number of civilian ships such as a tugboat, and half a dozen small sized boats provided with outboard motors. Due to lack of time (as we had a two-hour window to carry a number of experiments), we could not wait for the vessel to finish operation. In addition, the transduces used in this project had limited power, due to budgetary limitations, and most of it concentrated between 2 kHz and 3 kHz. Had we had an actual SONAR system, able to produce an SL of 200 dB, we wouldn’t have been stopped by such limitation.

In the few CW transmissions that were received, the SPL of the received pulses was very similar to the level of the background noise and hence we cannot easily discern any cancellation effect. However, using FM pulses centred in 5 kHz, a relatively good cancelation is observed yielding the reported 8 dB reduction in SPL. In spite of the difficulty, and the lack of specialized equipment, this result seems to confirm that not only that echo cancellation is possible underwater, but also that the cancellation of FM pulses can be achieved.

This result in Experiment V also puts into question the failure in cancellation of FM pulses that we experienced during Experiment I. Perhaps with a different experimental setup or configuration of the FM pulses, we should have validated the results obtained in air also for FM pulses.

At higher frequencies than 8 kHz, the power of the transducers dropped drastically, making any observation unfeasible, either for CW or FM pulses.

Table 6-1 summarizes the results obtained underwater. As we can see, in the cases where the background noise allowed us to make any observation, reductions between 8 and 20 dB were obtained, giving rise to reductions in the vessel target strength, in natural units, ranging from 99% and 84%. This is equivalent to a reduction of the enemy effective detection range, as shown in Table 6-1.

Experiment	SPL reduction [dB]	Reduction in natural units [%]	Enemy effective detection range, from a reference of 40 NM
III	20	99%	12.64NM (reduction of 68.4%)
IV	18	98.41%	14.19NM (reduction of 64.53%)
V	8	84.15%	25.24NM (reduction of 36.9%)

Table 6-1. Analysis of the results of experiments in water.

6.2 Conclusions

The experimental results seem to support the feasibility of the proposed system. However, in practice the system must be implemented using a series of sensors and transducers distributed along the vessel hull. The sensors, a collection of broadband hydrophones, would locate the bearing of the incoming SONAR ping. Using a low latency hardware and algorithms, the incoming SPL and the known TL of the vessel, would be used to produce an echo cancelling signal. The signal would be generated by one or several ANC transducers depending on the bearing of the incoming ping.

In this way the ANC system can reduce remarkably the target strength of the vessel. A reduction of 20 dB in TS is significant, and this reduction was achieved using low budget equipment and very simple processing. Using state-of-the-art SONAR equipment, the reduction in TS could be even more, specially if we consider an open sea situation, where propagating conditions are closer to free-field, and fewer problems with reflections are to be expected.

In addition, this array of transducers could be also used to reduce the acoustic signature of the vessel, which can be used as countermeasure against passive SONAR homing or to reduce detection probability in stealth missions.

6.3 Future lines.

In this project we have studied the feasibility of a device capable of reducing the target strength of a vessel when illuminated SONAR pulse. Taking this into account, probably the best option to carry on with this investigation would improving the results for FM pulses, that have only been tested partially and are, in fact, the most common mode of operation of modern SONAR. The investigation could start with experiments in a swimming pool, and later replicate in the harbour, just as carried out with CW pulses during this project.

Probably the best course of action would be to acquire high power SONAR transducers, able to overcome the noisy conditions around the harbour area and get them phase calibrated so as to improve the repeatability of the results under different conditions. In addition to this, it would be necessary to invest in a new power source, amplifiers and acquisition equipment, enabling us to carry out long range experiments out in the sea, not only from Tambo island, but also using the instruction ships of the Naval Academy both as seeker and target.

Also, the reflection phenomenon must be studied in detailed. The performance of the implementation in a real vessel should be analysed depending on the hull geometry, and the number and distribution of sensors must be optimized. Finally, the system must be tested in a real situation using an active SONAR and verifying if the proposed system is effectively able to make the target disappear from the enemy SONAR screen.

Finally, passive SONAR is the favourite mode of operation of submarines, and it is also implemented in most modern torpedoes. The ability of the ANC system to reduce the passive noise generated by the vessel is of highly interest and deserves to be studied separately. It would increase the safety of our boats, by equipping them with countermeasures, increase the vessel’s stealth capabilities, and difficult the enemy’s ability to classify and our forces.

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