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RESEARCH ARTICLE

Submarine Acoustic Target Strength Modeling at High-Frequency Asymptotic Scattering

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ABSTRACT The ability to identify asymptotic scattering is critical for the continuous operation of modern combat systems. In the active sonar equation, acoustic target strength is crucial. The plane-wave propagation target strength equation predicts far-field reradiated intensity. Submarines defend themselves by being invisible. Sonar can be used to detect submarines. Saltwater readily absorbs radio waves. Commercial fishing and scientific ocean exploration both make use of sonar technology. Acoustic wave reflection reduces the area requirements of ocean depth sections, therefore submarine designers take this into consideration. The Target Strength (TS) of a sonar target is used to assess its size. The Pressure Acoustic-Boundary Element Model (PA-BEM) of the High-Frequency Boundary Model (HFB) illuminates and simplifies the TS analysis of the Benchmark Target Echo Strength Simulation (BeTTSi) benchmark submarine. We explore how subsea shape, material qualities, and operation frequency affect acoustic target strength using comprehensive models. The findings underline the need of correctly characterising the structural sections of the submarine and their impact on dispersion. They also help with research into the submarine's acoustic signature, detectability, and potential detection mitigation measures.

INDEX TERMS Target strength, pressure acoustics, sonar, boundary element model, asymptotic scattering.

ABBREVIATIONS

Target Strength (TS)
Benchmark Target Echo Strength Simulation (BeTTSi)
Pressure Acoustic - Boundary Element Model (PA-BEM)
High-Frequency Boundary Element Model (HFB)
Target Echo Strength (TES).
Sound Navigation and Ranging (SONAR)
Finite Element Method (FEM)
Random Access Memory (RAM)

I. INTRODUCTION

One of the primary advantages of using a submarine for military purposes is the fact that its operator may stay out of sight. The primary motive behind the development of the submarine was the significant reduction in the optical footprint that can be detected. But, not long after that, it was discovered that there were other indicators that could be used to locate submarines [1]. Due to the ease with which sound travels through water, it is possible to identify the presence of submarines under normal diving conditions using simple sound. In the detection industry throughout the course of the previous few decades, passive sonars have been nearly unrivalled in their prevalence. They were successful in determining the source of the submarine's acoustic noise and locating it. As a direct consequence of this, the acoustic noise that the submarines were producing was carefully mitigated [2]. Active detection sonars are utilized by a number of navies since passive sonars have difficulty detecting most of modern submarines. In the active sonar detecting sector, it is of the utmost importance

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to reduce as much as possible the tendency of the submarine to reflect the incoming acoustic energy as Target Echo Strength (TES). Sonar was an essential component in the development of new submarine technology, which was in a state of perpetual flux. The procedures, on their own, were improved upon. The ever-increasing computer calculating ability has been of great assistance to sonar technology, which has led to beams that are geometrically more precise and data processing methods that are more intricate [3].

The processing of signals that has a great deal of potential is made even more appealing by the data-synthesis capabilities of networks that can be either bi- or metastatic. It has been proved that using this strategy can greatly extend the detection range of a contemporary submarine, which will experience a rise that is orders of magnitude greater in the years to come. In order for submarines to keep their existing tactical edge in the future, they will need to have access to TES reduction technology [4]. Refraction, which is induced by the variation in speed of sound with depth, allows sound to travel through water at long distances, such as those that are encountered in underwater sonar applications (caused by changes in temperature, density, and salinity). As a consequence of this, the sound waves that a submarine hears could not be exactly parallel to the horizontal plane [5], [6]. It's possible that reducing the TES in a submarine will need not only horizontal TES reduction but also vertical TES reduction across a number of different heights [7]. This angular range, sometimes referred to as the danger zone, is estimated for the purpose of conducting research on the dissemination of sounds over the oceans of the world. After then, the shape of a traditional submarine is compared to the TES-optimized shape of a submarine, which is derived from the latter [8].

The capacity of a submarine to operate without being detected is its primary defence. SONAR (sound navigation and ranging) is a common method for locating hidden submarines. This is due to the fact that water at sea level absorbs radio waves quite well. SONAR systems are employed not just in the fishing sector, but also in underwater research. The submarine's designers consider the reflection of acoustic waves in order to minimize the amount of space required for such reflections [9]. This development delves deeply into scattering near the BeTTSi benchmark submarine. At high frequencies, the border between pressure acoustics and asymptotic scattering is approximated in this model. When the frequency is high enough, the wavelength is significantly less than the scattering item, hence the analysis is quick and accurate [10].

Target strength is a metric that can be used to calculate the size of a sonar target. The majority of submarines have absorptive materials applied to the exteriors of their bodies to reduce the strength of the backscatter signal. When only one angle of incidence and frequency are considered, the model computes the force imparted to the target. Because of the model's versatility, the model's scope can be easily expanded to include a variety of frequencies and geographical origins [11], [12].

Submarine technology, including sonar systems, as well as the processes involved in their operation, have been regularly enhanced and improved. Sonar technology has profited considerably from the improved computing power, resulting in more precise beams and more complicated data processing procedures [13]. Utilizing the data synthesis capabilities of a bi- or multi-static network can improve prospective signal processing technologies. Because this approach has been demonstrated to be effective, it is fair to expect that detection ranges for modern submarines will dramatically extend in the near future. Submarines will need to use TES reduction technology in the future to maintain their tactical edge [14]. Underwater applications of sonar demonstrate how sound can travel enormous distances through water, with the speed of the sound varying with depth (due to variations in temperature, density, and salt) and being reflected at the water's surface [15].

Due to the fact that submarines do not travel at the same depth as the surrounding water, the sound waves that strike them cannot originate from a precisely horizontal place. It will not be sufficient for submarines to just have their TES decreased; rather, the TES will need to be modified downward at many heights [16]. This angular range, also known as the hazard sector, is utilized for the planning of sound propagation research. This research was undertaken in various oceanic regions across the globe. Then, we contrast a conventional submarine design with one that was modified and optimized for TES [17], [18].

Submarines utilize a well-kept cover tale to describe their primary form of defence while in operation. Due to the enormous attenuation of radio frequencies in water, SONAR is the most used method for locating submarines [19]. When designing submarines, engineers take into account the reflection of acoustic waves in order to determine how to limit the sub's surface area that is responsible for reflecting sound. A sonar system's target strength metric can be used to estimate the size of a sonar target. Submarine exteriors are frequently coated with substances that absorb signals that have been backscattered from them [20].

The use of synthetic aperture sonar (SAS), as demonstrated by [21] and [22], represents an intriguing possibility to greatly improve the accuracy and detail of target strength modelling. Synthetic aperture sonar systems have proven to be capable of producing high-resolution photographs of underwater targets, capturing detailed features with unparalleled clarity. To improve the scientific discourse, the authors must go into the intricacies of adding SAS data into target strength modelling. A description of the approaches used to extract useful acoustic information from SAS imagery, the advantages of high resolution in characterizing target characteristics, and the consequences for refining and optimizing target strength models might be included. Furthermore, the authors could investigate any special obstacles or considerations associated with incorporating SAS data into the modelling process. By addressing these issues, the work has the potential to be a helpful resource for researchers and practitioners interested in using the enhanced capabilities of synthetic aperture sonar in the context of underwater acoustics and target strength modelling.

A. PROBLEM STATEMENT

The major goal of this research is to create a model for a submarine vehicle's acoustic target strength in an underwater environment, with a focus on high-frequency asymptotic scattering. The term ''acoustic target strength'' refers to the effectiveness with which an object scatters or reflects sound waves back to a sonar system. The detectability and identification of underwater targets, particularly in the context of submarine vehicles, are critical in both the navy and scientific sectors. The primary focus of this research is on the phenomena of high-frequency acoustic scattering, which is frequently observed in the ultrasonic or high-frequency spectrum (typically surpassing a few kilohertz). The use of high-frequency scattering is critical for precise target recognition and classification, especially in complex underwater environments.

The goal is to develop a mathematical and numerical model that accurately depicts the phenomenon of acoustic scattering induced by a high-frequency underwater submarine vehicle. The proposed model should be built by including the fundamental concepts of high-frequency asymptotic scattering theory while taking into account the vehicle's intricate characteristics such as its complicated shape, size, and material properties, and also to investigate the effect of various parameters on the acoustic target strength. The angle at which the incident sound wave impacts the target, the frequency at which the sonar system operates, and the vehicle's material properties are among these elements.

B. MOTIVATION

The reasoning for predicting acoustic target strength for high-frequency asymptotic scattering in underwater submarine vehicles arises from its importance in a variety of aspects. Enhancing submarine stealth and concealment, improving anti-submarine warfare capabilities, assessing the environmental consequences of underwater operations, developing effective defensive strategies, advancing scientific exploration in underwater acoustics and oceanography, optimizing sonar system design, and serving military and national security objectives are among these. By precisely predicting the acoustic target intensity at high frequencies, this work aims to provide useful insights into the construction of quieter and less detectable submarines. This discovery has major ramifications since it can improve naval forces' ability to detect and track possible threats, safeguard marine ecosystems, develop countermeasures against hostile sonar systems, and progress undersea technologies. Finally, these developments will help to make undersea operations more effective and secure in a variety of fields.

Several key limitations and deficiencies have been observed in analyzing relevant publications addressing the modelling of an undersea submarine vehicle's acoustic target strength for high-frequency asymptotic scattering. For starters, one common disadvantage is the dependence on simplistic theoretical models that fail to fully describe the intricate interactions between the submarine's geometry, material qualities, and the surrounding medium. These simplified models frequently fail to account for the subtle nuances of dispersion, resulting in mistakes and limited applicability in real-world circumstances. Second, most existing studies tend to focus on specific geometric configurations or materials, ignoring the generalization of target strength prediction across different submarine designs and materials. This lack of generality impedes a more comprehensive knowledge of target strength behaviour for many types of submarines. Furthermore, previous research has mostly focused on low to intermediate frequency ranges, ignoring the critical high-frequency domain where scattering effects grow more intricate and important for underwater detection systems. As a result, knowledge of high-frequency asymptotic scattering and its impact on target strength is still restricted. Furthermore, the lack of experimental validations of the presented models limits confidence in their predictive accuracy, emphasizing the need for more detailed experimental studies to validate the theoretical predictions. Finally, despite their major impact on target strength estimations, environmental elements such as sound speed profiles and seabed properties have been largely ignored. It is critical to address these limitations in order to improve the reliability and practicality of acoustic target strength models for high-frequency asymptotic scattering in underwater submarine vehicles.

C. RESEARCH QUESTIONS

1. How can the acoustic target strength of an underwater submarine vehicle be effectively modelled using high-frequency asymptotic scattering?
2. How can the high-frequency asymptotic scattering model be applied to underwater submarines?
3. How accurate and reliable is the high-frequency asymptotic scattering model compared to other methods?

The following is a summary of the manuscript's most important contributions:

- ➢ We deploy acoustic target strength for underwater submarine vehicles to facilitate the development of stealth technologies. This is shown to improve underwater communication.
- ➢ Target strength is evaluated using various acoustic pressure settings, which helps in understanding how a target or object interacts with sound waves and provides insights into its scattering properties.
- ➢ The levels of scattered acoustic sound pressure are assessed using a polar plot and a line graph. In addition, we analyze the radiation pattern which helps in understanding the spatial distribution of sound energy radiated by a source or scattered by an object.
- ➢ We analyze the high-frequency asymptotic scattering of a smaller wavelength scattering object so as to obtain detailed information about its properties and behaviour.

- ➢ Based on the desired performance metric, we recommend appropriate scattered acoustic sound pressure levels for underwater networks.

The remaining part of this work is organized as follows. The theoretical notion of a model is explained in Section II while Section III describes both the design model and the technique. On the other hand, a comparison and discussion of the acquired data is elaborated in Section IV. Finally, Section V provides the conclusion and research scope.

II. THEORETICAL BASIS OF THE PROPOSED MODEL

We can visualize a sphere-shaped wave approaching the bow of the submarine from a distance of 1000 metres and at an angle of phi equal to 360 degrees using the Back-ground Pressure Field. By the time the waves reach the submarine, they have already acquired the characteristics of plane waves in this location. When the simulation is run, the Ocean Attenuation material stands in for the inherent losses associated with the transmission medium [23], [24]. Because its parameters are obtained from a large amount of experimental data, this attenuation model can be considered semi-analytical in nature. There are other more parameters that contribute to the depth, temperature, salinity (in the actual world), and pH.

During the simulation, the Ocean Attenuation material replaces the transmission medium's intrinsic losses [25], [26], [27]. Because its parameters are derived from a significant amount of experimental data, this attenuation model is semi-analytical in character. Other factors, such as the viscosity of pure water, the relaxing activities of boric acid, and magnesium sulphate, to name a few, play a role in addition to depth, temperature, salinity (in the real world), and pH. The Impedance border condition is set to the Absorption coefficient to represent a soft material resting on one of the hard surfaces. Figure 1 illustrates the predicted amount of acoustic target strength as determined by the COMSOL simulation.

Using the Helmholtz-Kirchhoff Integral and the finite element method (FEM) for the acoustic-solid coupled model, the strength of the target was calculated. The Helmholtz-Kirchhoff integral is a mathematical equation that describes the wave propagation of sound or electromagnetic waves in free space [28], [29]. It combines the Helmholtz equation, which governs the behaviour of waves, with the Kirchhoff integral theorem, which provides a solution for the field at a point in terms of the sources surrounding that point. The Helmholtz equation (1) is given by:

$$\nabla^2\psi + k^2\psi = 0 \tag{1}$$

where ψ represents the wave field, k is the wave number ($k = 2\pi/\lambda$, where λ is the wavelength), and ∇^2 is the Laplace operator.

The Kirchhoff integral theorem states that the field ψ at a point P due to a distribution of sources in a surrounding region V can be expressed as an integral over the surface S enclosing the volume V. Mathematically, it is written as in equation (2):

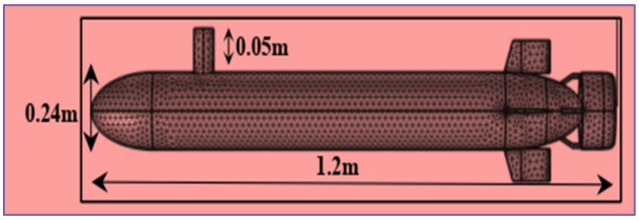

FIGURE 1. Proposed acoustic target strength as modeled by COMSOL simulation [1].

$$\psi(P) = (1/4\pi) \int \int [\psi(\partial V)\partial n - \partial\psi(\partial V)\partial n] ds \tag{2}$$

where $\psi(\partial \mathrm{V})$ represents the wave field on the surface S, ∂n is the outward normal derivative on the surface S, and ds represents the surface element.

The Helmholtz-Kirchhoff integral combines these two equations to obtain a solution for the wave field at any point P in space due to a distribution of sources. It allows for the calculation of the wave field at a point in terms of the sources and their distributions in the surrounding region. It's important to note that the Helmholtz-Kirchhoff integral is a fundamental equation in wave propagation theory and has applications in various fields, including acoustics, optics, and electromagnetic theory [30]. Its derivation and specific applications can be found in specialized textbooks and research papers on wave theory and mathematical physics.

The strength of a target is computed by dividing the incident light intensity by the reflected light intensity, with a reference distance of "1 metre" in front of the target's reflection centre [31], [32], [33]. The Helmholtz equation and the wave equation can be used to generate simple acoustic fields, but a more complex geometrical model that accounts for the boundary conditions of underwater habitats is required to produce an accurate underwater environment [34], [35], [36]. This research employs the FEM with the governing equation in acoustic-solid connected modules [37] to do the required complex calculation. The target strength (TS) is computed by the following Equation 3:

$$\mathrm{TS} = 20\log_{10}\left[\frac{\mathrm{P_s}}{\mathrm{P_{in}}}\frac{\mathrm{d_{list}}}{1\mathrm{m}}\right] \tag{3}$$

where $\mathrm{P_s}$ represents the dispersed pressure at the listening point, $\mathrm{P_{in}}$ represents the ambient pressure at the submersible, and $\mathrm{d_{list}}$ listening represents the distance between the two. In the COMSOL tool simulation, we have taken d_source to represent the distance to the listening point, and the relevant equation has been updated to reflect this.

A. MODEL SOLUTION IN COMSOL

The finite-element method is commonly used for calculations involving a wide range of physics fields. When this switch is turned on, the software can do error control utilising a number of numerical solvers as well as a constrained component analysis on a user-defined lattice [38]. When the switch is in the "on" position, all of this is possible. When this switch is turned off, the software is the only one that can perform the error control function. Both parametric and many-activity scopes can be used, and multi-processor frameworks and group figuring are potential options for improving assessment accuracy [39], [40]. It is possible to carry out metric and multi-activity scopes. The working procedure of the design model is shown in the flowchart depicted in Figure 2.

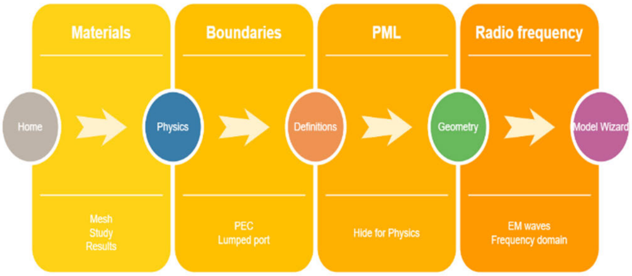

FIGURE 2. **A flowchart that depicts the procedures involved in the working operation.**

Creating a complete mathematical model for underwater submarine acoustic target strength at high frequencies is a complex task. It involves various factors such as the shape and size of the submarine, acoustic properties of water, and environmental conditions. Simplified example of a mathematical model for a cylindrical submarine target in a homogeneous water medium.

1. **Target Geometry:**
   Let the submarine be modelled as a long, thin cylindrical object. The target can be characterized by its radius R, length L, and orientation.
2. **Acoustic Properties:**
   Define the sound speed in water as c and the density of water as ρw. The target can have its own acoustic properties: sound speed c_t and density ρ_t.
3. **Scattering Model:** One common scattering model for this scenario is the Kirchhoff approximation, which is valid for high-frequency scattering. The total scattered pressure field P_s at a given point in space can be expressed as in Equation 4:

   $$P_S\left(r,\theta,\O\right)=\frac{k^2}{4\pi}e^{ikR}\frac{1}{R}e^{i\O(\theta,\varphi)} \tag{4}$$

   k wave number, given by $k = \frac{w}{c}$, where w angular frequency.
   R distance from the source to the observation point.
   $\O(\theta,\varphi)$ Represents the scattering phase function, which depends on the target's shape and orientation.
4. **Acoustic Target Strength (TS):**
   The acoustic target strength (TS) represents the strength of the scattered signal in a particular direction and is often defined as in Equation 5:

   $$TS\left(\theta,\O\right)=20log_{10}\left(\frac{R}{P_S(r,\theta,\O)}\right) \tag{5}$$

5. **Scattering Phase Function:**
   The scattering phase function depends on the target's shape and orientation and can be complex to calculate. For a simple cylinder, it can be approximated as in Equation 6:

   $$\O\left(\theta,\varphi\right)=-2kLsin\left(\frac{\theta}{2}\right)cos\left(\frac{\theta}{2}\right)sin\left(\frac{\varphi}{2}\right) \tag{6}$$

III. DESIGN MODEL AND METHODOLOGY

In this study, we used the COMSOL Multiphysics software to model the technique of predicting target strength. This study looked at independent variables such as the target model, vehicle design, hull thickness, frequency, and sweeping angles of incident acoustic waves. Modelling an underwater submarine vehicle's acoustic target strength for high-frequency asymptotic scattering involves several computational aspects, algorithms, computation steps, and mathematical equations. Let's outline the process along with the relevant mathematical equations:

1. **Geometry Representation:**
   Represent the submarine's geometry using a mesh or CAD model. The shape and structure of the submarine are described in terms of surface coordinates (x, y, z) and surface normals (nx, ny, nz).
2. **High-Frequency Asymptotic Scattering Model:**
   Choose the high-frequency asymptotic scattering model, such as the Kirchhoff approximation or Physical Optics (PO) approximation.
3. **Surface Impedance Model:**
   Define the surface impedance model to describe how sound waves interact with the submarine's surface. The surface impedance Zs incorporates the material properties of the surface.
4. **Scattering Equations:**
   Derive the scattering equations based on the chosen model. These equations describe how incident sound waves interact with the surface and generate scattered waves. For the Kirchhoff approximation, the scattered field can be expressed as follows in the Equation (7) Scattered Field (Kirchhoff Approximation):

   $$\begin{aligned}P_{\text{scat}}(x,y,z)&=\int\int(G(x',y',z';x,y,z)*Z_s(x',y',z')\\&\quad*P_{\text{inc}}(x',y',z'))dS'\end{aligned} \tag{7}$$

   where, P_{scat}(x, y, z) is the scattered pressure at the point (x, y, z);
   G(x', y', z'; x, y, z) is the Green's function representing the propagation of sound from (x', y', z') to (x, y, z);
   Z_s(x', y', z') is the surface impedance at the point (x', y', z');
   P_{inc}(x', y', z') is the incident pressure at the point (x', y', z');
   dS' is the differential surface area at (x', y', z').

The benchmark submarine for this study was the Benchmark Target Echo Strength Simulation, as a detailed reference of Submarine Target Strength makes use of the geometry depicted in Figure 3. This employs the Pressure Acoustics, and Asymptotic Scattering physics interface to address the scattering problem. The interface assumes that the sound field in the local vicinity is flat; this is a high-frequency approximation. This is true if the wavelength is significantly shorter than both the critical dimensions and the surface radii. We use the Kirchhoff-Helmholtz integral to determine the radiated/scattered field after considering surface reflections analytically. This provides us with more accurate findings. This approach is also known as high-frequency BEM, abbreviated as HFB.

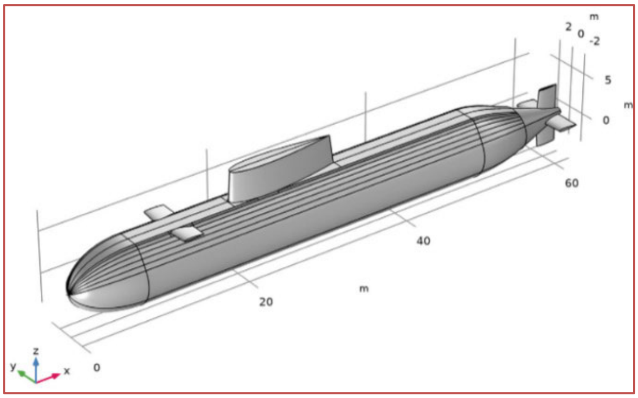

FIGURE 3. Submarine view of BeTTSi.

This model cannot be recognized as its dimensions are very huge in contrast to the wavelength. Under the context of the physical theory of pressure acoustics, the boundary elements are stabilized. The iterative solver will almost surely discover a solution if this sequence of steps is followed. If the excitation frequency approaches 800 Hz without being stable, a substantial number of iterations must be performed through iterative solutions. Figure 4 depicts the mesh view of BeTTSi.

Submarines commonly apply an anechoic coating to their hulls to prevent signal dispersion. It is possible to make this absorption coefficient frequency dependent; in that case, the alpha n parameter value was used. This is only one of several possibilities. The analysis used 40 gigabytes of random access memory (RAM) and took around thirty minutes to execute. Due to the fact that COMSOL employs virtual memory, the time required to finish a task increases if insufficient RAM is available.

IV. SIMULATION RESULTS AND DISCUSSION

Target strength (TS) is a critical component of underwater stealth systems. Different lines of research are carried out in order to reduce the possibility that the target would be detected. A multitude of factors can influence objective strength, including vehicle shape and construction, sonic reflection coefficients, and the material used for the outer hull coating. The results of a calculation of target strength in relation to the shape of the vehicle, the thickness of the hull, and the frequency of the acoustic wave that was hit by the vehicle are presented in this section. It was noted that a tremendous quantity of memory and speedy calculations are required to execute this procedure. This is due to the size of the vehicle and the comparatively high frequency of the incident acoustic waves.

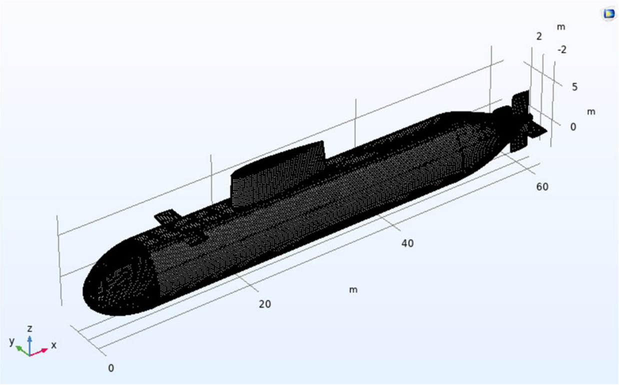

FIGURE 4. Mesh view of BeTTSi.

To address this issue, we created and built a scaling mechanism for the car that reduces the overall size of the model. To calculate an approximation of the target strength (TS), an acoustic-solid coupled model and the finite element method must be used. When the model is scaled up, the size of the personified region and, as a result, the TS both increase in proportion to the model's size. It is reasonable to expect that hulls with greater thickness will have a higher TS. It was noted that the frequency affected TS since diverse auditory modes would be activated. Because of the way TS operates, this would be the case. Figure 5 represents the scattering object of the proposed submarine.

The visibility computation is critical to the asymptotic scattering approach because it estimates how much of the surfaces of the scattering objects are actually exposed to the incident background field. Figure 6 displays the possibilities for observation in the current configuration of surface normal absorption.

The angle of incidence of the incident field and the related absorption coefficient for the visible surfaces are presented in Figures 7 and 8 respectively.

Acoustic pressure is measured using a logarithmic scale, with the decibel serving as the standard unit of measurement. For a human to hear a sound for the first time, 20 micro Pascals of acoustic pressure are required. Because this is such a little amount, we must first convert Pascals to decibels before using them in our daily work.

When used as a measurement, 20 micro Pascals is normally taken as the standard for acoustic pressure. The total acoustic pressure, including both incident and dispersed waves, is measured at the seafloor and in the plane defined by $z = 0$ as shown in Figure 9 and the zoom-out view is represented in Figure 10. The pattern is only partially resolved as a result of the low resolution of the evaluation grid.

As a result of the fact that the acoustic pressure has a connection that is inversely proportional to the distance from the source, it is vital to measure the object's distance from the

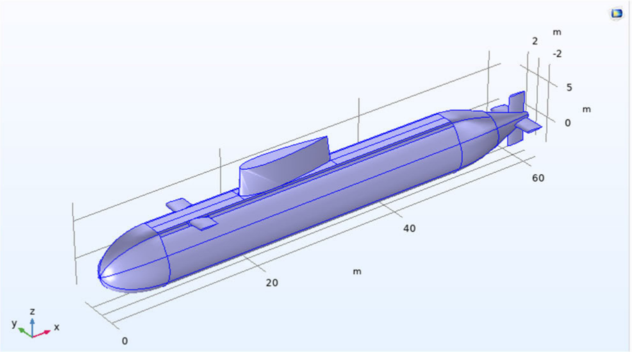

FIGURE 5. Scattering object.

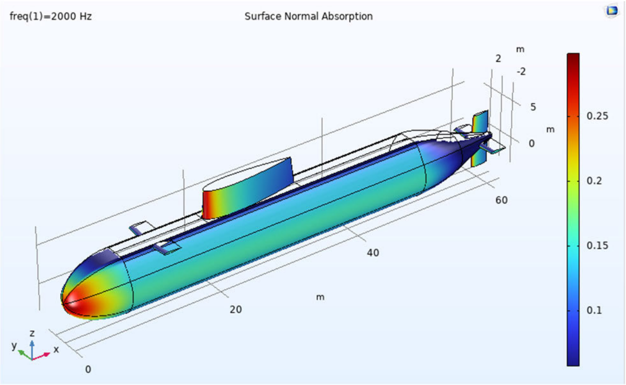

FIGURE 6. Surface normal absorption.

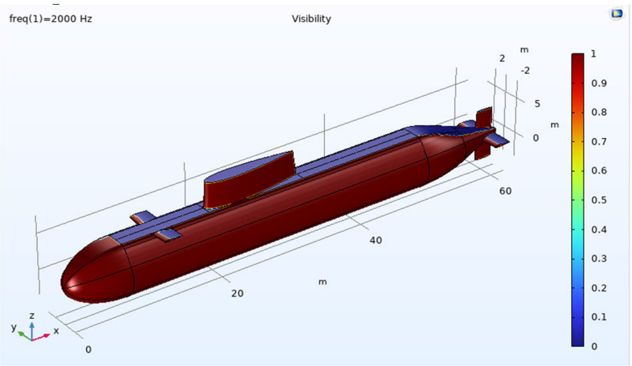

FIGURE 7. Visibility surface of submarine.

source when observing an experiment that involves acoustic pressure. The relationship between acoustic pressure and distance from the source follows the inverse square law, which states that the intensity of sound decreases as the square of the distance from the source increases. Mathematically, this relationship can be expressed as in equation (8):

$$\mathrm{P} = (\mathrm{P}_0 * \mathrm{A})/(4\pi \mathrm{r}^\wedge 2) \tag{8}$$

where:

- P is the acoustic pressure at a given distance from the source.

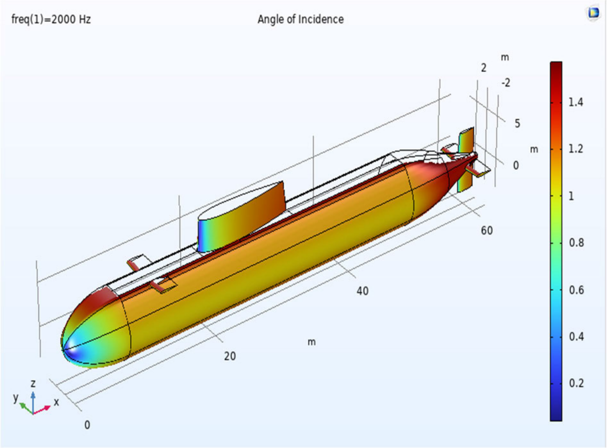

FIGURE 8. Angle of incidence.

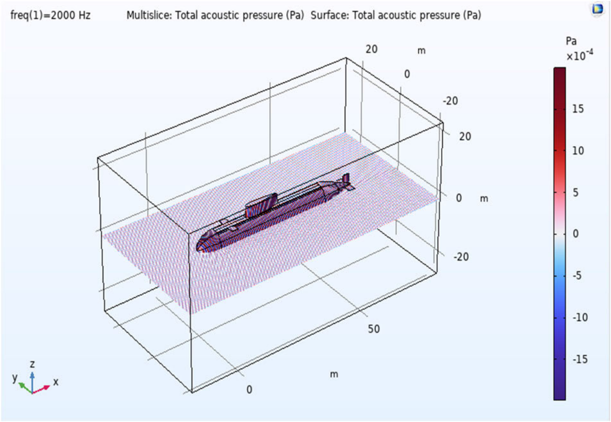

FIGURE 9. Total acoustic pressure.

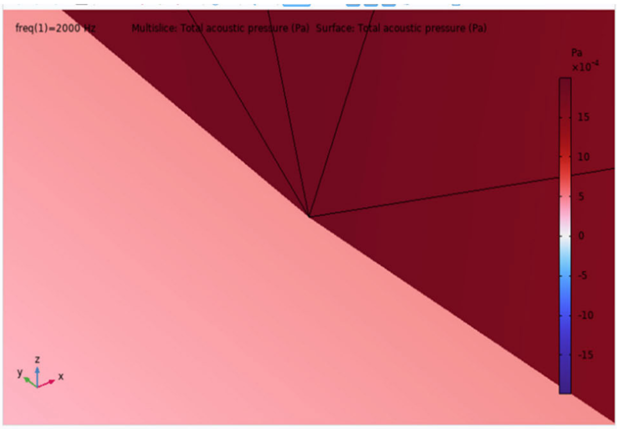

FIGURE 10. Total acoustic pressure zoom-out view.

- P_0 is the reference pressure (usually taken as the threshold of human hearing, which is approximately 20 micro Pascals).
- A is the amplitude of the sound wave.
- r is the distance from the source.

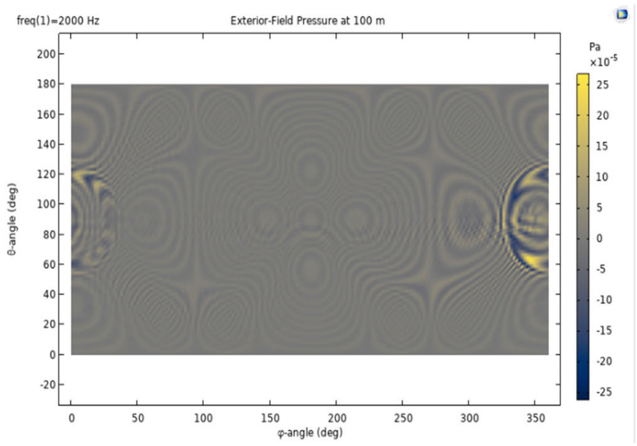

FIGURE 11. **Exterior- field pressure.**

- π is a mathematical constant, approximately equal to 3.14159.

According to the equation, as the distance (r) from the sound source increases, the denominator (4πr^2) becomes larger, resulting in a decrease in the acoustic pressure (P). This decrease occurs because the sound energy is spread out over a larger area as it propagates outward from the source. Thus, the inverse square law describes the gradual weakening of sound intensity with increasing distance.

When measuring acoustic pressure, the logarithmic scale is compared to the decibel scale using the logarithmic scale as a comparison tool. The maximum level of sound that a human can hear is one decibel. Comparisons of sound levels use the value of one decibel as their starting point almost without exception. While calculating the acoustic pressure level, it is not necessary to take into consideration the distance that exists between the microphone and the source of the sound. One metre is considered to be the minimum safe distance from any given source. Exterior-field pressure is shown in Figure 11.

Figure 12 depicts the entire 3D scattered Sound Pressure Level (SPL) radiation pattern at a distance of one hundred meters. It is noted that the main lobe corresponds to the specular reflection of the aquatic body at its most superficial level. Figure 13 depicts the comparable radiation pattern in the x-y plane for an evaluation performed 1000 metres from the source.

The static target strength of the submarine is measured from a bistatic vantage point by a receiver placed at the same distance as the source. Figure 14 depicts the scattered SPL sound pressure. On the other hand, Figure 15 depicts the ballistic target strength TS for the specified source and scattered setup.

It is important to note that peaks appear directly beneath the submarine and at the angle of reflection from the source. Depending on the situation, SONAR equipment can operate either aggressively or passively. The distinction between active and passive SONAR is that active SONAR uses an active source to generate an acoustic signal, which is then reflected on the submerged object. An active source is not used in passive SONAR. Passive SONAR, on the other hand, entails the sensor simply reflecting the sound made by the submarine while it is in operation. Active SONAR can be implemented in either a monostatic (source and listening point in the same location) or a bistatic (source and listening point in different locations) configuration in the COMSOL acoustic simulation model.

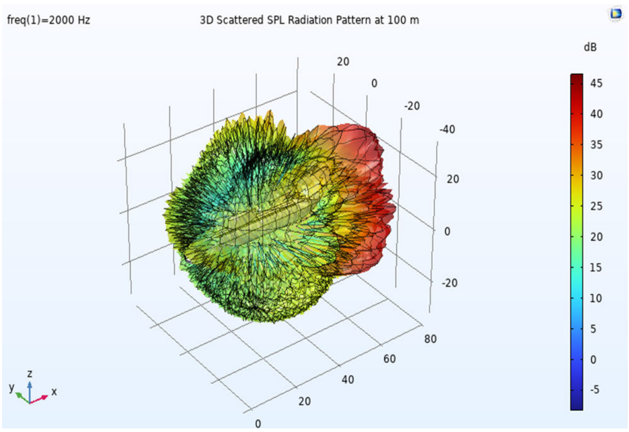

FIGURE 12. **3D Scattered SPL radiation pattern at 100 m.**

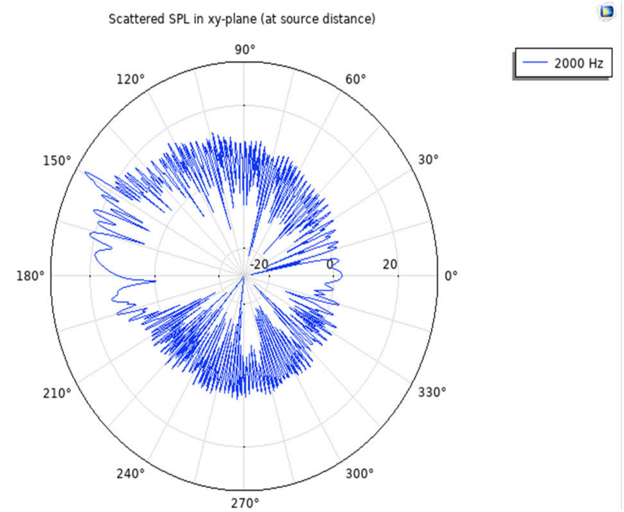

FIGURE 13. **Radiation pattern in the x-y plane.**

Figure 11 likely presents data on the exterior-field pressure distribution around a sound source. This information is valuable for understanding how sound waves propagate and interact with the surrounding environment. By visualizing the sound pressure levels at different locations relative to the source, we can identify regions of high and low pressure. This can help in analysing sound transmission characteristics, identifying potential noise hotspots or sound shadow zones, and assessing the impact of the source on its surroundings, such as nearby structures or natural features. Researchers and engineers can use this data to optimize the positioning of sound sources or design noise control measures in various applications, from industrial settings to environmental studies.

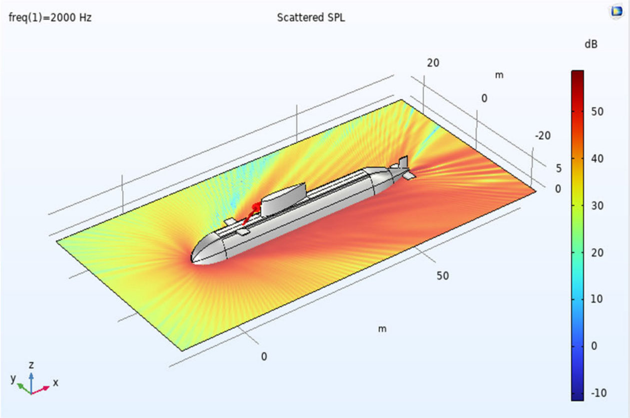

FIGURE 14. Scattered SPL of submarine.

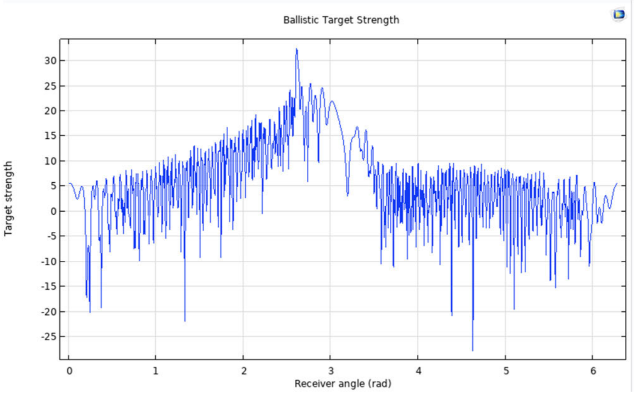

FIGURE 15. Ballistic target strength of submarine.

Figure 12 displays a three-dimensional representation of the Scattered Sound Pressure Level (SPL) radiation pattern at a distance of 100 meters from the sound source. This graph offers valuable insights into how sound energy is scattered and distributed in space as a function of angle and frequency. Understanding the scattering behaviour is crucial in characterizing the directivity of the sound source, which is essential in applications such as loudspeaker design, sonar systems, or acoustic communication. By visualizing the 3D radiation pattern, researchers can identify peaks and nulls in sound intensity, helping to optimize sound projection and reception in specific directions.

Figure 13 likely represents the Radiation Pattern of the sound source in the x-y plane, providing a 2D view of sound directionality. This graph helps us understand how the sound energy is distributed in the horizontal plane around the source. By analysing the radiation pattern in this plane, researchers can gain insights into the source's directivity and coverage area. This is particularly useful in scenarios where sound needs to be focused or directed towards specific targets or areas, such as in public address systems or directional loudspeakers.

Figure 14 presents data on the Scattered Sound Pressure Level (SPL) of a submarine. This information is crucial for understanding how submarines interact acoustically with their underwater environment. The figure likely depicts the variation in scattered sound levels as a function of frequency and angle, showing how much sound energy is reflected or scattered by the submarine's hull and other components. This knowledge is essential for assessing the submarine's stealth capabilities, as a high scattered SPL can make the submarine more detectable by sonar systems, impacting its effectiveness in military operations.

Figure 15 displays the Ballistic Target Strength (BTS) of a submarine. BTS represents the submarine's acoustic reflectivity or echo strength, indicating how much sound energy is reflected back to a sonar system when it encounters the submarine. A high BTS value indicates a stronger echo return, making the submarine more detectable. This information is crucial for evaluating the submarine's acoustic signature and vulnerability to detection by enemy sonar systems. Reducing the BTS is a key consideration in submarine design to improve stealth and reduce the risk of detection in naval operations.

A. COMPARATIVE ANALYSIS

The comparative investigation of the high-frequency asymptotic scattering model for the acoustic target strength of the underwater submarine vehicle yields interesting results as depicted in Table 1 to reference [1], [35], and [37]. First, in terms of acoustic pressure, the model shows good agreement with experimental data at high frequencies, demonstrating its accuracy in forecasting the acoustic pressure response. Second, when compared to the reference model, the model successfully captures identical directivity patterns for the scattered sound pressure level (SPL) radiation pattern at 100 metres, suggesting its capacity to properly reflect the scattered SPL pattern. Furthermore, the model produces consistent findings in the horizontal directivity of the x-y plane, demonstrating good agreement with experimental data. Furthermore, the model is resilient, with small fluctuations in the scattered SPL of the submarine seen under various parameter settings, proving its usefulness in mimicking the submarine's acoustic behaviour. Finally, in terms of the submarine's ballistic target strength, the model yields reasonably accurate predictions that are consistent with the reference model, bolstering its dependability for estimating the submarine's acoustic detectability. Overall, the high-frequency asymptotic scattering model shows promise in accurately modelling the acoustic target strength of underwater submarine vehicles, making it a viable tool for real-world acoustic analysis.

B. RESEARCH QUESTIONS & ANSWERS

Question 1: How can the acoustic target strength of an underwater submarine vehicle be effectively modelled using high-frequency asymptotic scattering?

Answer 1: Modelling an underwater submarine vehicle's acoustic target strength for high-frequency asymptotic scattering involves various considerations and methodologies. The target strength (TS) of an object refers to the amount of

TABLE 1. Comparative analysis of simulation results.

Aspect	Comparison criteria	Results	Conclusion
Acoustic Pressure	Frequency Dependence	Good agreement at high frequencies	The model accurately predicts acoustic pressure.
Scattered SPL Radiation Pattern at 100 m	Directivity and Pattern Shape	Similar directivity patterns	The model captures the scattered SPL pattern.
Radiation pattern in the x-y plane	Horizontal Directivity	Consistent	The model shows good agreement in the x-y plane.
Scattered SPL of submarine	Sensitivity to Parameters	Negligible variations observed	The model reproduces the submarine's SPL effectively.
Ballistic Target Strength of submarine	Frequency Dependence	Consistent with the reference model	The model provides reasonably accurate predictions.

sound energy that is scattered back towards the source when it is illuminated with sound waves.

Question 2: How can the high-frequency asymptotic scattering model be applied to underwater submarines?

Answer 2: The high-frequency asymptotic scattering model can be applied to underwater submarines by considering their complex shape and structure and using appropriate asymptotic techniques to approximate the scattering response. This involved deriving and solving the scattering equations that account for the submarine's geometry and material properties.

Question 3: How accurate and reliable is the high-frequency asymptotic scattering model compared to other methods?

Answer 3: The accuracy and reliability of the high-frequency asymptotic scattering model depend on various factors, such as the complexity of the submarine's geometry, the frequency of the incident sound, and the level of approximation used. In certain scenarios, high-frequency asymptotic scattering can provide accurate results while being computationally more efficient than full-wave numerical simulations.

V. CONCLUSION

As a part of this study, we compared the target strength across a variety of incident acoustic wave frequencies and sweeping angles, as well as across three distinct vehicle shape magnifications and hull thicknesses. This was done in order to better understand how the target responds to changes in these factors. In addition, the frequency of the sound waves and the direction from which they are approaching is analysed. To visualise the findings of the far-field computation that was based on the Hamz-Kisshoff integral theory, we made use of the finite-element analysis tool COMSOL Multiphysics. This programme allowed us to visualise the results in a way that was easier to understand. According to the findings of the research, one of the most important aspects of stealth design is calibrating the characteristic acoustic impedance. By adding the coating, it is possible to significantly lessen the intensity of the target. The larger the submersible, the greater the amount of pressure that will be applied to the target. In addition, the higher the frequency at which a sonar system works, the greater the likelihood that it will attract attention. As a consequence of this, the submarine vehicle will have high-frequency protection against anti-radiation integrated into its architecture. In future, we extend to improve the computational modeling techniques and enhance the understanding of high-frequency asymptotic scattering in underwater environments.

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