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Influence of design parameters on omnidirectional sound target strength of underwater structure

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ABSTRACT

In order to reduce the probability of underwater structures being detected by active sonar, it is necessary to consider how to reduce the omnidirectional sound target strength of the structure. However, in order to weigh the overall performance of the structure, the design parameters of it can only be adjusted within a limited range. Under such conditions, a comprehensive understanding of the influence of all adjustable parameters on the sound target strength of the structure is the key to maximizing the concealment of the structure. In this paper, the planar element method (PEM) based on the high-frequency approximate Kirchhoff equation is used to study the sound target strength of the sail of the Benchmark Submarine model. The influence of design parameters such as size, shape and material on the omnidirectional target strength of the sail is analyzed. The results gained by this work can provide a reference for the design of low target strength underwater structures.

Keywords: Target strength, Planar element method, Benchmark Submarine
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

Target strength (TS) is an important parameter in the active sonar equation, which reflects the ability of underwater targets to reflect sound waves. For some underwater structure that focus on concealment, in order to reduce the probability of being detected by active sonar, the omnidirectional TS of it should be reduced as much as possible during design [1].

There are many design parameters that may affect the TS of the underwater structure, such as size, shape, material, and so on. However, the adjustment range of these parameters is usually limited, because it is also necessary to balance the strength, resistance and other performances of the structure. Therefore, it is very important to grasp the influence of the main design parameters on the TS.

Benchmark Simple model is a general model for studying the TS of submarine, which was published at the first BeTSS (iBenchmark Target Intensity Simulation) World Digital Simulation Conference in 2002 [2].This model includes all the main structures of the submarine such as hull, sail and rudders (see Figure 1). Among all of these structures, sail is the largest protru-

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-sion on the submarine and contributes significantly to the TS. In this paper, the omnidirectional TS of Benchmark Simple model was calculated by the planar element method (PEM), and the influence law of design parameters on the TS of the sail is analyzed. This work can provide a basis for the design of related structures.

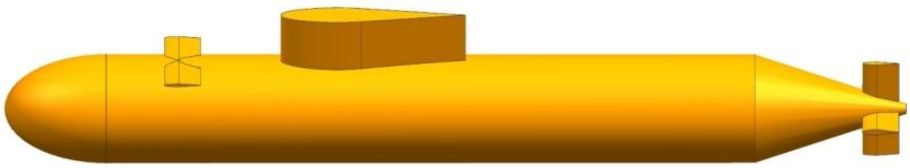

Figure 1: Benchmark Simple model

2. CALCULATION METHOD

2.1 Theoretical basis

The planar element method (PEM) is a numerical method for calculating the target strength [3-6]. This method approximates the target surface with a set of planar elements. The scattered sound field of each planar element can be calculated using the high-frequency approximate Kirchhoff equation, and the total scattered sound field of the target is approximately the superposition of the scattered sound fields of all planar elements. The theoretical basis of this method is as follows.

First, let the scattering surface of the target be S, the sound source point be M_1, and the receiving point be M_2, as shown in Figure 2.

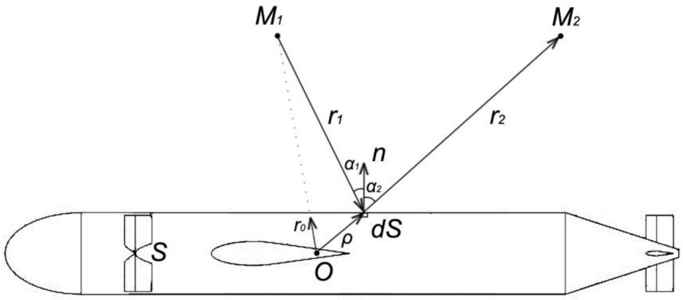

Figure 2: Schematic of the PEM method

The general expression of the Kirchhoff equation is:

$$\varphi_M = \frac{1}{4\pi}\iint_S \left[\varphi_s \frac{\partial G_s}{\partial n} - G_s \frac{\varphi_s}{\partial n}\right] dS \tag{1}$$

Here, the potential function G_s is constructed as:

$$G_s = \frac{e^{ikr_2}}{r_2} \tag{2}$$

Let φ_i be the incident wave potential function, expressed as:

$$\varphi_i = \frac{A}{r_1} e^{ikr_1} \tag{3}$$

For rigid surfaces, the boundary conditions are as follows:

$$\begin{cases} \varphi_s = \varphi_i \\ \dfrac{\partial(\varphi_s + \varphi_i)}{\partial n} = 0 \end{cases} \tag{4}$$

Then, Equation 2 can be expressed as

$$\varphi_M = \frac{-A}{4\pi}\int_S e^{ik(r_1+r_2)}\left[\frac{ikr_2 - 1}{r_1 r_2^2} cos(\alpha_1) - \frac{ikr_1 - 1}{r_2 r_1^2} cos(\alpha_2)\right] dS \tag{5}$$

In this paper, we consider that M_1 coincides with M_2 and is located at infinity. At this time, the incident wave is approximately a plane wave, and the parameters shown in Figure 2 are simplified as $r_1 = r_2 = r, \alpha_1 = \alpha_2 = \alpha$. Since $r \to \infty$, $kr \gg 1$, Equation 2 can be further simplified as:

$$\varphi_M = -\frac{ikAe^{2ikr_0}}{2\pi r_0^2}\int_S e^{2ik\Delta r} cos(\alpha) dS \tag{6}$$

The scattering cross section δ of the target is defined as:

$$\delta = \lim_{r_0 \to \infty} 4\pi r_0^2 \frac{|\varphi_s|^2}{|\varphi_i|^2} \tag{7}$$

Then the target strength of the scattering surface S can be expressed as:

$$TS = 10\log\frac{\delta}{4\pi} = 20\log\left|\frac{k}{2\pi}\int_S e^{2ik\Delta r} cos(\alpha) dS\right| \tag{8}$$

To calculate the integral in Equation 8, the target scattering surface S is discretized into a set of planar elements dS, and the area fraction of each planar element can be calculated using the Gordon formula [7]. The scattered sound fields of all the elements are superimposed to obtain the total scattered sound field as follows:

$$\int_S e^{2ik\rho \cdot r_0} dS = \frac{1}{2ik|\vec{n} \times r_0|^2}\sum_{n=1}^{N_0}(\vec{n} \times r_0 \cdot a_n)\, e^{2ib_n \cdot r_0}\frac{\sin(ka_n \cdot r_0)}{ka_n \cdot r_0} \tag{9}$$

Substituting the integral value obtained by Equation 9 into Equation 8, then the total target strength of the target can be finally obtained.

2.2 Calculation method verification

Divide the surface of the Benchmark Simple model into a series of quadrilateral meshes with a size of 0.1m. The resulting mesh model has 155,735 nodes and 155,833 cells (see Figure 3). The omnidirectional TS of this model was calculated under the conditions of incident wave frequencies of 1 kHz and 8 kHz, and the results are shown in Figure 4. It can be seen that the calculation results obtained by the planar element method agree well with the literature results [2], which proves that the calculation method used in this paper is applicable.

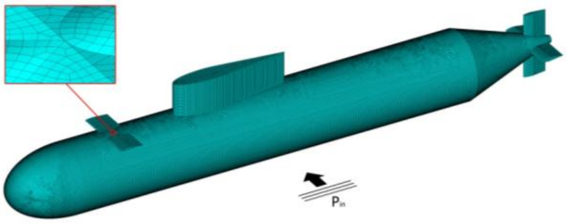

Figure 3: Schematic of the calculation model

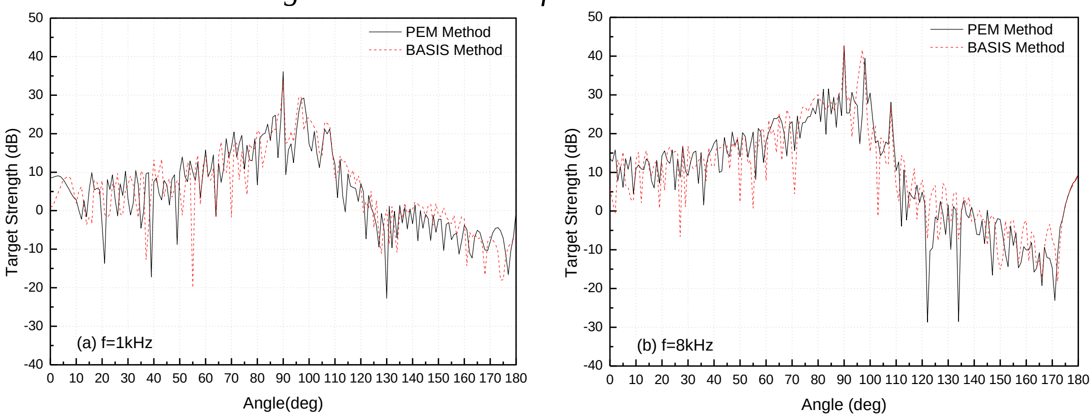

Figure 4: Comparison of PEM calculation results with literature values

3. OMNIDIRECTIONAL TARGET STRENGTH

In order to analyze the composition of the omnidirectional TS of the Benchmark Simple model, the model is divided into five parts: bow, rudder, sail, amidships, and stern (as shown in Figure 5). The omnidirectional TS of these parts are calculated separately, and the results are shown in Figure 6.

As shown in Figure 6, the TS of the model is the largest (more than 20dB) in the range of 75°～110°, a little lower (about 0dB~20dB) in the range of 0°～75°,and the lowest (basically less than 0 dB) in the range of 110°～180° .

Among all the substructures, the sail contributes the most to the omnidirectional TS and has a dominate position in the range of 0°～97°. At 97 °, a large area of the sail is vertically incident by sound waves, thus forming a strong target intensity peak.

The rudder's contribution to the omnidirectional TS is second only to the sail, and it has a dominant position in the range of 97°～165°.

The TS of the amidships at most incident angles is very low, only one strong peak appears when the sound waves are incident at 90 °. However, this peak determines the maximum value of the TS of the entire model in the positive direction.

The TS of the stern is only large at 108° and 165°～180°. At these angles, the incident wave is approximately perpendicular to the surfaces of the stern. The TS of the bow is very low in magnitude and contributes little to the omnidirectional TS of the entire model.

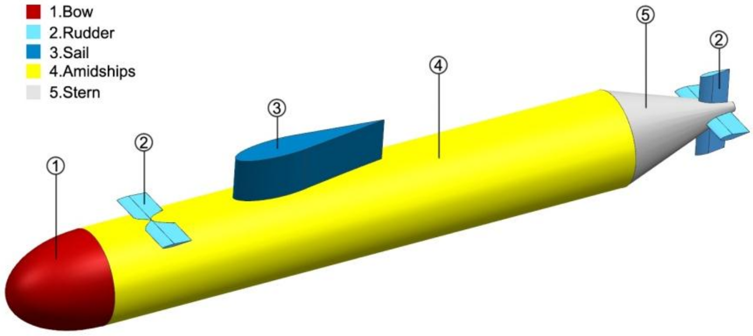

Figure 5: Substructure division of the model

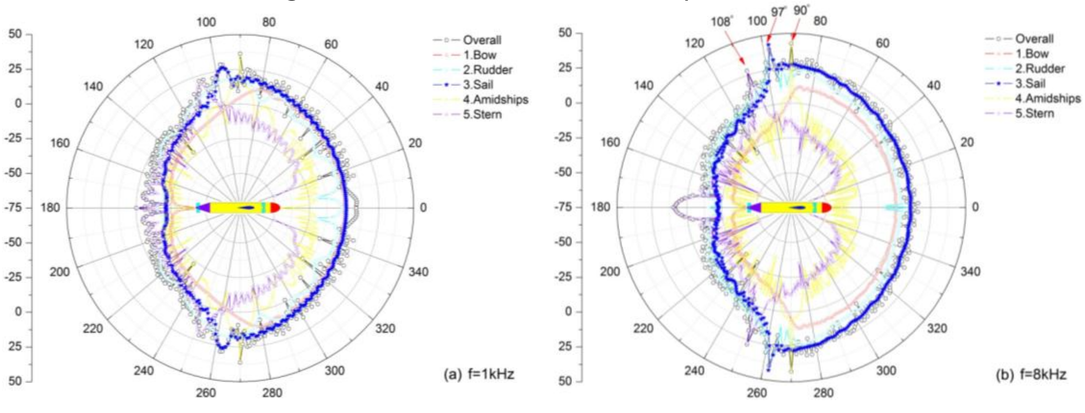

Figure 6: Omnidirectional target strength of the substructures

According to the above analysis, although the area of the bow, the amidships and the stern is large, the contribution of these structures to the omnidirectional TS is limited. This is because the curvature of the surface of these structures is so large that the area that can be vertically irradiated by the incident wave is small. On the contrary, although the sail and the rudders are not large in size, they are easy to form strong echoes because of the large-area plane on these structures. It can be seen that in order to reduce the omnidirectional TS of the submarine, special attention should be paid to the design of the sail and the rudders. This article mainly takes the sail as an example for discussion.

4. INFLUENCE OF DESIGN PARAMETERS ON SAIL

4.1 Height

The design of the cross-sectional shape of the sail is generally determined by its hydrodynamic performance and is difficult to change easily. In contrast, the height of the sail is a more adjustable parameter. In order to investigate the influence of height on the TS of the sail, a set of models with the same cross-sectional shape and different heights are calculated. The omnidirectional TS of the sails with a height of iH ($\mathrm{H}=3.5\mathrm{m},\ \mathrm{i}=0.5, 1.5, 2.0$) are shown in Figure 7.

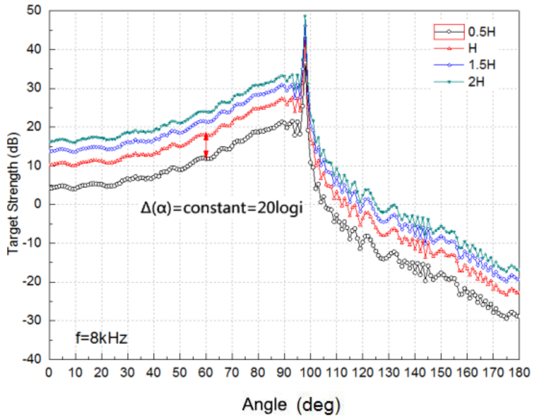

Figure 7: Influence of height on the omnidirectional target strength of the sail

It can be seen that the omnidirectional TS of the sail increases with height and the magnitude of the increase in all angles is the same. To explain this phenomenon, the sail scattering surface is discretized into a series of rectangles with a width of a and a height of H (see Figure 8). When the elevation angle is not considered, the TS of each rectangle can be expressed as [8]:

$$\mathrm{TS}=20\log\left|\frac{\mathrm{aH}}{\lambda}\frac{\sin(\beta)}{\beta}\cos(\alpha)\right| \tag{10}$$

Here, $\beta=\mathrm{ka}\sin(\alpha)$, Equation 10 can be simplified as:

$$\mathrm{TS}=\begin{cases}20\log|\mathrm{aH}/\lambda| & \alpha=0,\pi\\ 20\log|\mathrm{H}\sin(\beta)\cot(\alpha)| & \alpha\neq 0,\pi\end{cases} \tag{11}$$

It can be seen from Equation 11 that when the height changes from H to iH, the target intensity will increase by $20\log i$, which is consistent with the PEM calculation results shown in Figure 7.

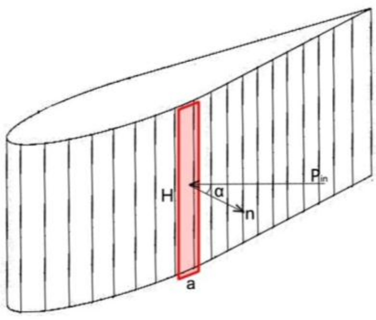

Figure 8: Discrete scattering surface of the sail

4.2 Tilt angle

As discussed in Section 3, an effective measure to reduce TS is to reduce the area that is normally incident on the sound wave. As shown in Figure 6, the TS of the sail has a peak at 97°, but sharply decreases at 96° and 98°, which indicates that changing the tilt angle of the sail wall is an effective method. Figure 9 shows the effect of different tilt angles θ(1°，3°，5°，10°，15°) on the omnidirectional TS of the sail. It should be noted that due to the increase of the tilt angle, a transition surface is added to the tail of the sail, resulting in no comparability between 120° and 180°. However, some laws can be observed in other angles.

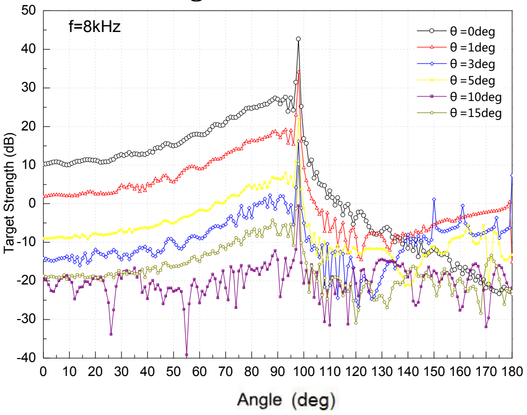

Figure 9: Influence of tilt angle on the omnidirectional target strength of the sail

It can be seen that even if the tilt angle is small, the omnidirectional TS of the sail can be significantly reduced. However, TS does not monotonically decrease as the tilt angle increases. For example, the TS value at θ=5° is smaller than at θ=1°, but larger than at θ=3°. To explain this phenomenon, we still discretize the scattering surface of the sail into a series of rectangles (as shown in Figure 10). For each rectangle, the TS can be expressed as [9]:

$$TS = 20\log\left|\frac{aH'}{\lambda}\frac{sin\big(kasin(\alpha)cos(\theta)\big)}{kasin(\alpha)cos(\theta)}\frac{sin\big(kH'\sin(\alpha)sin(\theta)\big)}{kH'\sin(\alpha)sin(\theta)}cos(\alpha)\right| \tag{12}$$

Here, $H' = H/cos(\theta)$. It can be seen from Equation 12 that the influence of θ on TS is very complicated. For ease of discussion, let $\alpha = 0$, then the situation at this time is similar to Equation 11, which can be expressed as:

$$TS = 20\log|a| + 20\log\big|sin\big(kH\tan(\theta)\big)cot(\theta)\big| \tag{13}$$

In Equation 13, $cot(\theta)$ is a monotonically decreasing function, and $\big|sin\big(kH\tan(\theta)\big)\big|$ is a function with a period of $\arctan(j\pi/kH), (j = 0,1,2,\ldots)$. The result of multiplying these two functions is shown as Figure 11. Obviously, as θ increases, the value of Equation 13 has a downward trend, and the rate of decline is mainly dominated by the $cot(\theta)$ term, which means that the rate of deceleration in the range of $\theta < 10°$ is the fastest. The decrease in the value of Equation 13 is fluctuating due to the $\big|sin\big(kH\tan(\theta)\big)\big|$ term, which explains the result in Figure 9.

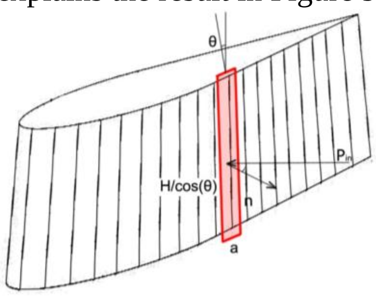

Figure 10: Discrete scattering surface of the sail

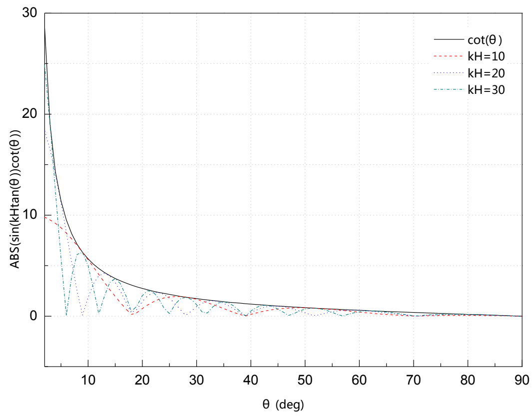

Figure 11: Influence of tilt angle on the TS

4.3 Round corner

For the sake of hydrodynamic performance, the corners of the sail are generally designed to be rounded. This design also provides a partial improvement in the omnidirectional TS. As shown in Figure 12, adding a round corner with a radius of R = 800 mm at the top of the sail can reduces the omnidirectional TS by about 2 dB. Obviously, this kind of partial improvement is easier to implement and also has considerable benefits.

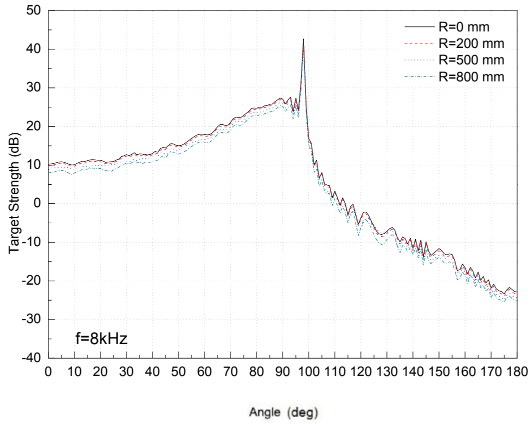

Figure 12: Influence of round corner on the omnidirectional target strength of the sail

4.4 Material

The above discussion is based on the fact that the sail is a rigid body, which is similar to the model 1 shown in Figure 13, in which case the reflection coefficient of the scattering surface can be regarded as 1 [10-13]. However, the actual sail is generally a steel plate soaked in water, which is more similar to the model 2. In this case, most of the incident waves will pass through the sail and only a few will be reflected. In this case, the TS of the sail will be more dependent on its internal non-permeable structures, especially when the incident wave frequency is low. A detailed discussion of such issues can be found in some relative studies [14].

Model 3 in Figure 13 shows a common solution for reducing the intensity of the TS. A layer of material having a very high sound absorption coefficient is applied to the surface of the sail. In this case, the sound waves incident on the sail will be mostly absorbed and dissipated so that both the reflected wave and the transmitted wave are attenuated. Thereby, the TS of the sail can be effectively reduced.

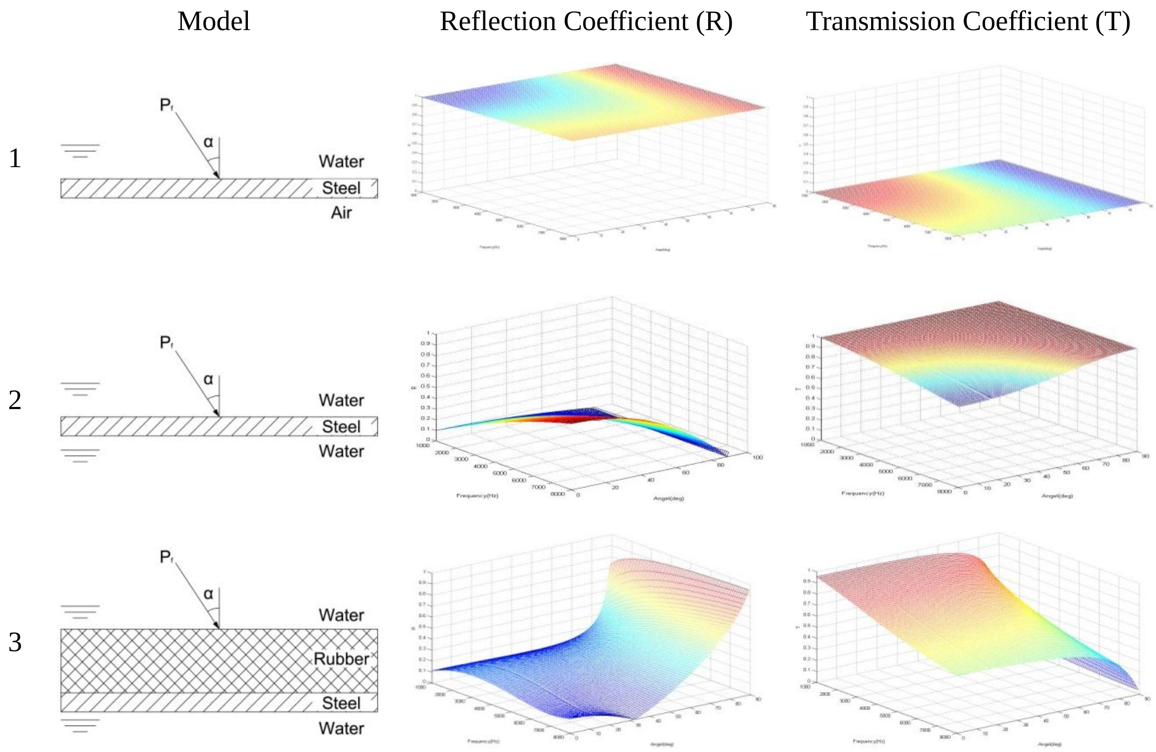

Figure 13: Acoustic properties of several materials in the enclosure

Another possible solution to reduce the TS through the material is to make the sail with a material with a high reflection coefficient. In this case, since the incident wave is difficult to penetrate the sail, the contribution of the inner structures to the TS can be reduced significantly. Then the acoustic target strength of the enclosure will depend primarily on its exterior design as discussed above.

5. CONCLUSIONS

In this paper, the planar element method is used to numerically study the omnidirectional sound target strength of the Benchmark Simple model. Moreover, the influence of design parameters on the target strength of the sail is analysed. The main conclusions are as follows:

1.Sail is the structure that contributes the most to the omnidirectional target strength of the submarine. This is mainly because there is a large area on the sail that is easy to be vertically incident by sound waves.

2.Theoretical derivation and numerical calculations show that the omnidirectional target strength will increase by $20 \log i$ (dB) when the height of the sail increases by a factor of i.

3. Increasing the tilt angle of the sidewall of the sail can effectively reduce the omnidirectional acoustic target strength, and the most significant effect can be obtained in the range of $\theta < 10°$.

4. Designing round corners at the edge of the sail is effective and easy to implement for reducing the omnidirectional target strength.

5. When the material of the sail has a high transmission coefficient, the target strength of the sail will depend primarily on its internal non-permeable structures, especially at low frequencies. Making a shell with a material with a high sound absorption coefficient or a high reflection coefficient can play a role in controlling the target strength.

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