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Numerical study of the flow noise generated by an underwater vehicle with appendages

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Abstract: The appendages of underwater vehicles, such as the stern, are a primary source of flow noise. In the present study, we investigate an underwater vehicle model and analyze the effects of cross-shaped and X-shaped sterns on flow noise using numerical simulation methods. The results indicate that the underwater vehicle with an X-shaped stern exhibits lower resistance and sound pressure levels compared to one with a cross-shaped stern.

1. Introduction

The flow noise generated by underwater vehicles is crucial for their survivability and represents a significant concern in the marine field. Appendages on underwater vehicles can induce flow separation and interact with the boundary layer turbulence, which substantially affects resistance and acoustic characteristics. The David Taylor Research Center has contributed extensively to this field, proposing the DARPA SUBOFF model and conducting comprehensive experiments that provided valuable experimental data [1].

The DARPA SUBOFF model is widely utilized for validating numerical methods. Özden et al. [2] used the RANS method to examine the flow noise generated by underwater vehicle models. Qu et al. [3] employed the LES approach to explore the flow field surrounding the model, identifying three distinct flow patterns. Delen and Kinaci [4] performed direct numerical simulations of the model and revealed the high turning capability of this model. Wu et al. [5] compared the flow noise of that model simulated by three numerical methods with the experimental results and revealed that the DDES method closely matched the experimental data. Apart from the traditional approaches, Xie et al. [6] introduced a Bayesian deep learning method that predicted the underwater vehicle model with remarkable speed. Additionally, the DARPA SUBOFF model was also adopted to study flow noise resulting from the interaction between underwater vehicles and propellers [7-10].

Despite these advancements, research on the impact of X-shaped sterns on flow noise remains limited. This study aims to numerically investigate the DARPA SUBOFF underwater vehicle models with the bare hull, the cross-shaped stern, and the X-shaped stern, aiming to provide a detailed comparison of their hydrodynamic and acoustic performances. By shedding light on these less explored aspects, this research intends to provide significant understanding that can inform the design and operation of underwater vehicles with enhanced acoustic performance.

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2. Numerical setup

2.1. Numerical method

In the present study, we employ the DDES approach and the FW-H equation to simulate the DARPA SUBOFF model. The DDES approach is a hybrid RANS and LES method, utilizing RANS near solid boundaries and transitioning to LES in regions of flow separation. This method offers a balance between computational expense and accuracy in capturing complex fluid dynamics. In our previous study [5], the DDES method and the FW-H equation have been effectively used to analyze flow noise characteristics, proving their predictive capability for these problems.

2.2. Numerical grid

The cylindrical simulation domain's radius extends fivefold beyond the hull's radius. The inlet is positioned at a distance equal to the model's length from the bow of the model, and the outlet extends four times the length of the model from the aft. The structured grid for the model with the cross-shaped stern is shown in Figure 1, ensuring a dimensionless wall distance (y+) of 50.

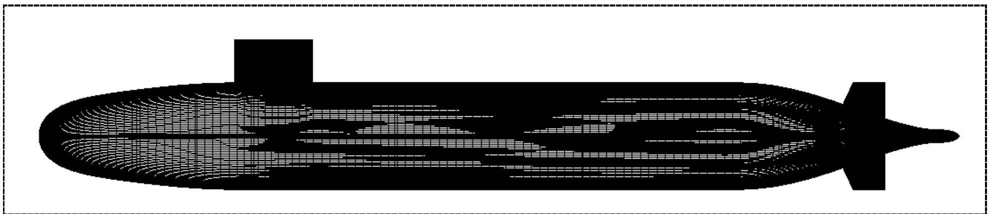

Figure 1. Structured grid for the model with the cross-shaped stern.

2.3. Boundary conditions

The inlet of the simulation domain is configured as a velocity inlet, where the water enters the computational domain at a uniform speed of 3.05039 meters per second. Such a specification is crucial for establishing a controlled and consistent flow scenario that builds real-world conditions where the underwater vehicle operates.

At the opposite end of the simulation domain, the outlet boundary is configured as a pressure outlet. Unlike a velocity inlet that prescribes the flow rate entering the system, a pressure outlet boundary condition sets the static pressure at the exit of the domain.

The solid surface of the model is subjected to a no-slip boundary condition. This fundamental assumption means that the water adheres perfectly to the solid surface of the vehicle, implying that there is no relative motion between the water and the vehicle's hull at their interface.

3. Results

The pressure distribution of the models is shown in Figure 2. The simulation outcomes indicate that elevated pressure concentrations are predominantly found at the bow, the command deck, and the stern. This phenomenon arises because the water flow encounters resistance upon interacting with these specific hull areas, causing a sudden deceleration in fluid velocity. According to Bernoulli's equation, the pressure increases at these locations where the flow slows down significantly.

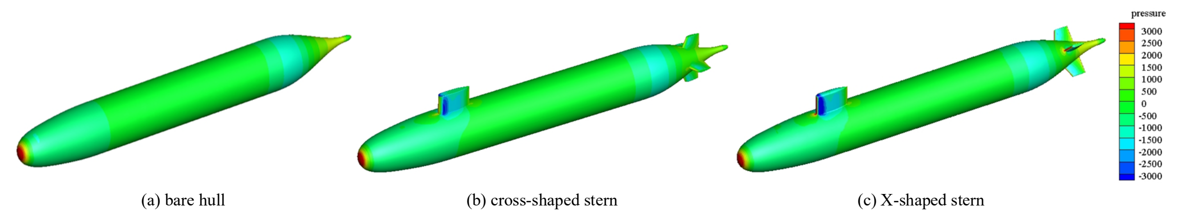

Figure 2. Distribution of surface pressure of the models.

Figure 3 illustrates the velocity magnitude across profiles. The command deck generates an extensive wake that extends its influence downstream. Comparing the results of the cross-shaped stern and the X-shaped stern, the cross-shaped stern experiences a stronger interaction with the command deck's wake compared to the X-shaped stern, which shows no significant interaction with the command deck's wake.

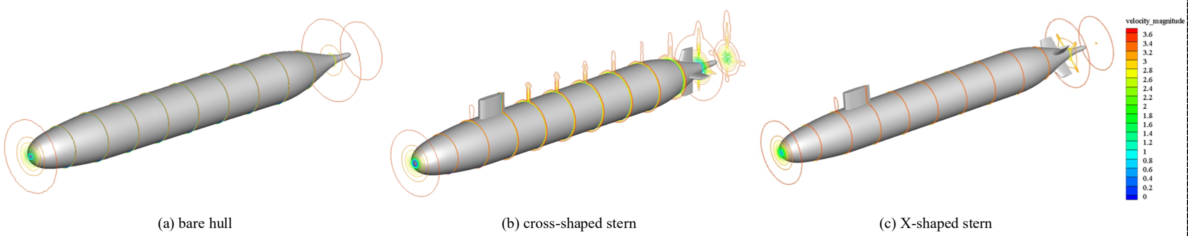

Figure 3. Distribution of velocity magnitude across profiles.

The feature point located beneath the underwater vehicle is designated with the coordinate (2.178, -2, 0). Figure 4 meticulously illustrates the sound pressure level spectra observed at this specific location. By examining this figure, we gain insight into the frequency distribution and intensity variations of the sound pressure levels generated by the underwater vehicle's operation.

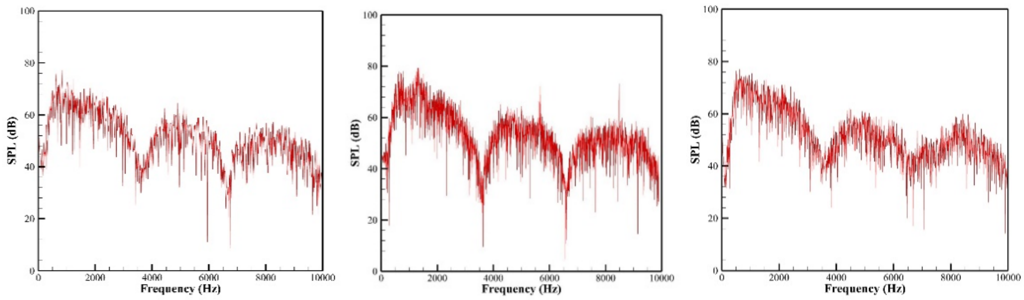

Figure 4. Spectral characteristics of sound pressure level: (a) bare hull, (b) cross-shaped stern, and (c) X-shaped stern.

Tables 1, 2, and 3 demonstrate the numerical results of the model with the reference value [1-2]. The tables clearly show that the total resistance and frictional resistance calculated through numerical simulations align well with the reference data, thus confirming the credibility of the numerical results utilized in this research. Compared to the bare hull, the underwater vehicle models with a stern experience higher total resistance, frictional resistance, and overall sound pressure level. It is also found that the X-shaped stern generates slightly lower resistance and noise compared to the cross-shaped stern.

Table 1. The Discrepancy Between Simulated and Experimental Total Resistance Values.

Stern Shape	Simulation	Experiment	Relative Error
Bare Hull	89.3 N	87.4 N	2.2%
Cross-shaped	106.2 N	102.3 N	3.8%
X-shaped	105.3 N	/	/

Table 2. The Discrepancy Between Simulated and Theoretical Frictional Resistance.

Stern Shape	Simulation	Theory	Relative Error
Bare Hull	79.6 N	78.2 N	1.8%
Cross-shaped	85.0 N	83.9 N	1.3%
X-shaped	84.2 N	/	/

Table 3. The Discrepancy Between Simulated and Experimental Oaspl.

Stern Shape	Bare Hull	Cross-shaped Stern	X-shaped Stern
OASPL	98.3 dB	102.3 dB	101.8 dB

4. Conclusion

The results of our study clearly demonstrate the significant impact of appendages on underwater vehicle hydrodynamics and acoustic performance. We investigate the underwater vehicle model with different appendages, including the bare hull, the cross-shaped stern, and the X-shaped stern. The numerical results indicate that the X-shaped stern exhibits reduced resistance and sound pressure levels compared to the cross-shaped stern, providing better overall hydrodynamic and acoustic performance.

This study provides a significant understanding of the design and operation of underwater vehicles with various appendages, particularly focusing on the impact of the X-shaped stern on resistance and low noise. Future research directions could build on our findings and explore other factors affecting the acoustic performance of underwater vehicles, such as propeller interactions or different environmental conditions. In addition, extending our simulation approach to more complex underwater vehicle models could further deepen our understanding of flow noise generation mechanisms.

Acknowledgments

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References

[1] Groves N C, Huang T T and Chang M S (1989) Geometric characteristics of DARPA SUBOFF models. *David Taylor Research Center.*

[2] Özden M C, Gürkan A Y, Özden Y A, Canyurt T G and Korkut E (2016) Underwater radiated noise prediction for a submarine propeller in different flow conditions. *Ocean Engineering*, 126: 488-500.

[3] Qu Y, Wu Q, Zhao X, Huang B, Fu X and Wang G (2021) Numerical investigation of flow structures around the DARPA SUBOFF model. *Ocean Engineering*, 239: 109866.

[4] Delen C and Kinaci O K (2023) Direct CFD simulations of standard maneuvering tests for DARPA SUBOFF. *Ocean Engineering*, 276: 114202.

[5] Wu J, Cao X, Liu B, Wu G and Wei W (2024) Numerical investigation of the flow noise of an underwater vehicle. *Journal of Physics: Conference Series*, 2756: 012002.

[6] Xie X, Zhao P, Bian C, Xia L, Ding J, Wang X and Liu H (2024) A novel Bayesian deep learning method for fast wake field prediction of the DARPA SUBOFF. *Applied Ocean Research*, 150: 104074.

[7] Sezen S, Dogrul A, Delen C and Bal S (2018) Investigation of self-propulsion of DARPA Suboff by rans method. *Ocean Engineering*, 150: 258-271.

[8] Sun Y, Liu W and Li T (2019) Numerical investigation on noise reduction mechanism of serrated trailing edge installed on a pump-jet duct. *Ocean Engineering*, 191: 106489.

[9] Liu L, Chen M, Yu J, Zhang Z and Wang X (2021) Full-scale simulation of self-propulsion for a free-running submarine. *Physics of Fluids*, 33(4), 047103.

[10] Su Z, Shi S, Huang X, Rao Z and Hua H (2021) Vibro-acoustic characteristics of a coupled pump-jet——shafting system——SUBOFF model under distributed unsteady hydrodynamics by a pump-jet. *Ocean Engineering*, 235: 109429.