

Article

Not peer-reviewed version

Large Eddy Simulation of Flow Around a Generic Submarine at Straight Ahead and 10° Yaw Conditions

[Mo Chen](#)^{*}, Nan Zhang, Hailang Sun, Xuan Zhang

Posted Date: 13 November 2023

doi: 10.20944/preprints202311.0843.v1

Keywords: Submarine; LES; Flow field; Yaw; Straight ahead



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Article

Large Eddy Simulation of Flow Around a Generic Submarine at Straight Ahead and 10° Yaw Conditions

Mo Chen ^{a,b,*}, Nan Zhang ^{a,b}, Hailang Sun ^{a,b} and Xuan Zhang ^{a,b}

^a Scientific Research Department of Hydrodynamics, China Ship Scientific Research Centre, Wuxi 214082, China

^b National Key Laboratory of Hydrodynamics, China Ship Scientific Research Centre, Wuxi 214082, China

* Correspondence: heu_chenmo@163.com

Abstract: Aim at a better understanding of the flow field around a fully appended Joubert BB2 submarine model and complementing the experimental investigations of the wake of the hydroplanes and sail, the Large eddy simulation (LES) with the dynamic Smagorinsky model is conducted. Three sets of grids with a maximum grid number of up to 228 million are designed, to perform the LES simulation for the Joubert BB2 at 10° yaw conditions, with a freestream Reynolds (Re) number based on the local freestream velocity and the hull length of $Re_L = 2.2 \times 10^7$. And comparison of the wake of the cruciform appendage is made with experiments, to verify the computational accuracy and examine the influence of the spatial resolution. A satisfactory result shows more favorable agreement with experimental measurements as the improvement of spatial resolution, with the relative error of the vortice centers well within 7.2% in the most refined grid arrangement. And under this grid arrangement, the evolution characteristics of three co-rotating vortices originating from the cruciform appendage are further described in detail at straight ahead and 10° yaw conditions.

Keywords: submarine; LES; flow field; yaw; straight ahead

1. Introduction

The submarine will generate vortex structures with various scales and forms that develop downstream during navigation. Generalized appendages such as a sail, hydroplane, rudder, deck, and floodhole create coherent vortex structures, like the horseshoe vortex, tip vortex, Karman vortex, discrete vortex, et al., leading to intense flow vibration. The development of these vortex structures also influences the maneuverability and deteriorates the wake of the platform. The vortex oscillation and its induced pressure fluctuation excite the hull, resulting in flow-induced noise, which seriously influences the stealth. The investigation of the flow physics of a submarine can help to better understand maneuverability limitations and flow-induced noise sources.

A certain amount of available literature has described the flow around a submarine, among which experiment plays an important role, especially in early studies. Fu utilized a PIV (Particle image velocimetry) system to characterize the flow field around a sting-mounted captive ONR Body-1 submarine model in a steady turn (Fu et al., 2002). Jimenez and Ashok utilized a hot-wire system and a SPIV (Stereo particle image velocimetry) system to measure the flow field around an axisymmetric DARPA SUBOFF model, respectively, and the flow field experimental databases with different Reynolds numbers, pitch, and yaw angles were obtained (Jimenez et al., 2010; Ashok et al., 2012; 2013; 2014; 2015a; 2015b).

Another DSTO generic submarine model with a large deck, sail, and an X-form rudder arrangement (Joubert, 2004; 2006), which can provide a useful representation of a conventional submarine, has been widely discussed in the open literature. The flow field measurements of the fully appended model at both straight ahead conditions and during a 10° side-slip, were conducted by Defence Science and Technology (DST) Group, with data collected using pressure probes, PIV, and flow visualization of wool-tuft streamers (Kumar et al., 2012; Anderson et al., 2012; Jones et al., 2013; Lee et al., 2014; Manovski et al., 2014; Fureby et al., 2016). And it provided a benchmark prototype to validate and improve numerical simulations of submarine wakes.

Since a new vertical sail and two horizontal hydroplanes were designed to improve its stability and control characteristics (Bettle, 2014; Overpelt et al., 2015), which is known as “Joubert BB2” recently, the wind-tunnel experiment of the model at 10° yaw was conducted again, with China-clay visualization and a high-resolution SPIV system (Lee et al., 2018; 2019; 2020). And the wake of this cruciform appendage can be available to assist validation studies.

With the development of Computational Fluid Dynamic (CFD) methods, the numerical simulation of the flow field around a fully appended submarine model can complement the experimental investigations and create opportunities to advance the understanding of the flows, as the experiments only obtain limited flow field information. Careful verification and validation studies should be conducted with experimental data.

Three main CFD methods have been developed for predicting the flow field, and direct numerical simulation (DNS) is not practical in engineering prediction because of its enormous demand for computing resources, Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulation (LES) are gradually becoming dominant in computing the flow field around underwater vehicles. But for the fully appended hull, the RANS seems to slightly lack prediction accuracy, particularly for the second-order statistical moments and the local flow topology. The development of LES can provide very useful insights into the complicated transient nature of the flow, including unsteady wake flow, flow-induced noise, and vibrations (Bensow et al., 2006; Fureby et al., 2008; 2016; Toxopeus et al., 2012; Anderson et al., 2012; Zhang et al., 2016a).

The LES method was first proposed by Smagorinsky (Smagorinsky, 1963), and the applicability of predicting the flow field around submarines has been verified by many researchers. Alin and Bensow evaluated the predictive capabilities of LES by comparing it with experimental data from DTMB (Huang, 1992), and some generic features of the flow past DARPA SUBOFF configuration were discussed, both the fully appended model and the bare hull model. (Alin et al., 2003; 2010a; 2010b; Bensow, et al., 2004a; 2004b; 2006; 2008).

Anderson and Fureby performed LES computations of the fully appended DSTO generic submarine model at 10° yaw, and good qualitative agreement was found between the LES results and the experimental data, with respect to the velocity distributions and the locations of the main vortex structures (Anderson et al., 2012; Fureby et al., 2016). Norrison extends the computational studies by using a near-wall-modelled LES approach to simulate the flow around a full-scale, fully-appended Joubert generic submarine equipped with either a 5-bladed or 7-bladed propeller under straight-ahead (Norrison et al., 2016; 2017). The computational ability of LES for the surrounding flow of submarines under maneuvering conditions has been verified.

Zhang studied the numerical prediction approach for hydrodynamic force and noise of SUBOFF submarine appended by AU5-65 propeller by LES and Powell vortex theory (Powell, 1964), and expand LES to the field of submarine noise prediction and more complex maneuvering conditions, such as submarine propeller interaction and crashback (Zhang et al., 2010; 2014; 2016b; 2021; Wang and Zhang, 2022). The results further validated the numerical prediction ability of LES. Kroll performed LES of the flow over SUBOFF submarine appended by DTMB-4381 propeller in forward mode and crashback, mean flow fields and propeller load statistics show good agreement with experiments and previous simulations (Kroll et al., 2020).

In the paper, three sets of grids with a maximum grid number of up to 228 million are designed, to perform the LES simulation for the fully appended Joubert BB2 submarine model at 10° yaw. And a comparison of the wake of the sail and hydroplanes is made with Lee’s work (Lee et al., 2019), to verify the grid convergence and computational accuracy of LES in terms of predicting the flow field around the submarine. Simulations are conducted at a freestream Reynolds (Re) number based on the local freestream velocity and the hull length of $Re=2.2\times10^7$, which is higher than those in previous work and more representative of a full-scale submarine. Then the characteristics of the flow around the submarine are described in detail at straight ahead and 10° yaw conditions. These computations further elucidate the structure of the flow around the fully appended Joubert BB2 submarine model, and provide an effective complement to the experimental investigations.

2. The Joubert BB2 Submarine Model

Figure 1 shows the Joubert BB2 submarine model with a length $L=3.826$ m and a model scale of 1:18.348. The hull is designed as an axisymmetric body of revolution with a length-to-diameter ratio $L/2r_m = 7.3$, and the bow profile is derived from a NACA0018 curve (Loid and Bystrom, 1983), splined to allow the rise in pressure to occur further aft (Fureby et al., 2016). The cross-section of the sail is based on a NACA0022 with a height of $0.080L$ and a chord length of $0.157L$. Two horizontal NACA0015 hydroplanes are assembled on the sail, and the combined span and the root chord are designed as $0.117L$ and $0.033L$ respectively. The stern control plane consists of four rudders in an X configuration, and the trailing edge is $0.075L$ away from the end of the hull. A further detailed description can be found in Joubert (Joubert, 2006), Bettel (Bettel, 2014), and Overpelt (Overpelt et al., 2015).

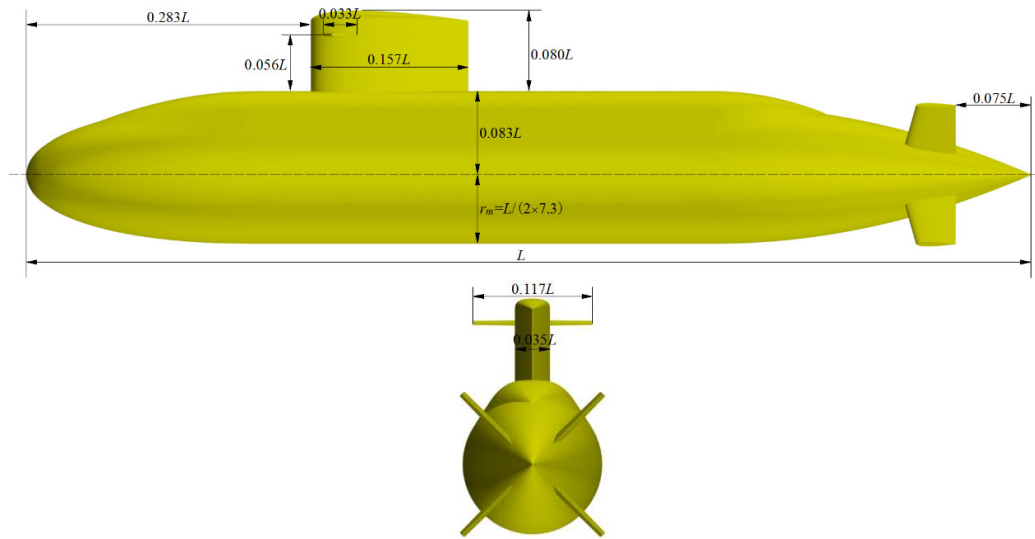


Figure 1. The Joubert BB2 geometry.

In Lee's work (Lee et al., 2019), the experimental results are discussed in a wind axis coordinate system, with the x -axis direction defined as the direction of freestream as shown in Figure 2, which is also adopted in the paper for more direct comparison. The velocity field is obtained with a SPIV measurement system at three selected model-length locations $x/L=0.511$, $x/L=0.650$, and $x/L=0.815$, and the normal direction of these experimental planes is parallel to the free-stream direction. For further details on SPIV setup and measurements, see Lee (Lee et al., 2019). It should be noted that the model-length Reynolds numbers are chosen as $Re_L=4 \times 10^6$ and $Re_L=8 \times 10^6$ in the experiments, which are lower than those of this paper. The conclusion has been drawn that it shows similar experimental results of the velocity field, turbulence kinetic energy (TKE), cross-stream Reynolds stress, and et al. under different Re_L , and according to previous research results on the wake field of submarines models, when the Re_L increases from 1×10^7 to 3.5×10^7 , the dimensionless mean velocity changes between 3% and 10%, the reciprocal validation of computations and experiments is still reliable.

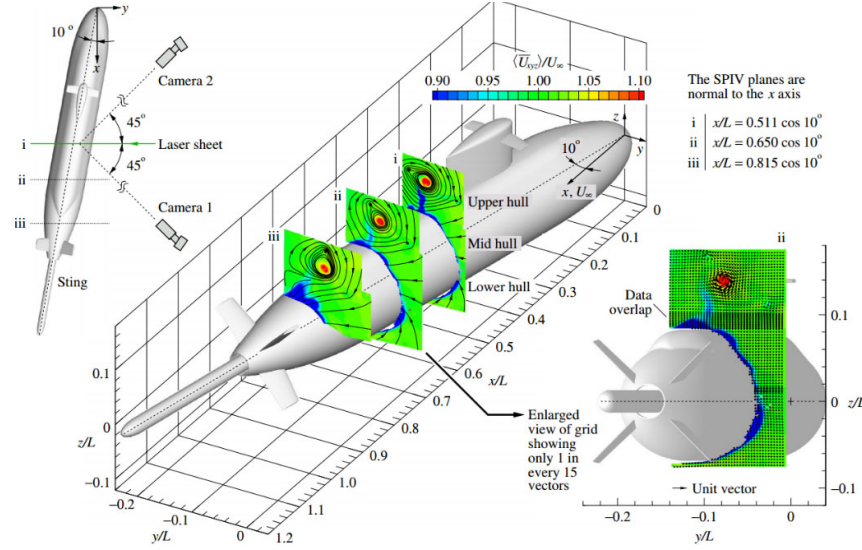


Figure 2. The schematic diagram of SPIV measurement and wind axis coordinate system (Lee et al., 2019).

3. Numerical Methodology

3.1. Large Eddy Simulation

The commercial CFD code StarCCM+ by Siemens PLM based on the finite volume method is utilized to conduct the LES simulations presented in the paper. For LES, large scales by which transport is largely governed are directly computationally resolved by the spatially filtered Navier-Stokes equations, and small scales are modeled by appropriate subgrid-scale turbulence models. The vortex flow is separated into small and large eddies, achieved by means of a low-pass filter. The filtered Navier-Stokes equations are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \tilde{\mathbf{v}}) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \tilde{\mathbf{v}}) + \nabla \cdot (\rho \tilde{\mathbf{v}} \otimes \tilde{\mathbf{v}}) = -\nabla \cdot \tilde{\mathbf{p}} \mathbf{I} + \nabla \cdot (\tilde{\mathbf{T}} + \mathbf{T}_{SGS}) + \mathbf{f}_b \quad (2)$$

Where ρ is the density, $\tilde{\mathbf{v}}$ is the filtered velocity, $\tilde{p}$ is the filtered pressure, $\mathbf{I}$ is the identity tensor, and $\mathbf{f}_b$ is the resultant of the body forces. $\tilde{\mathbf{T}}$ is the filtered stress tensor due to molecular viscosity and $\mathbf{T}_{SGS} = 2\mu_t \mathbf{S} - \frac{2}{3}(\mu_t \nabla \cdot \tilde{\mathbf{v}}) \mathbf{I}$ is the subgrid-scale stress, where $\mathbf{S}$ is the strain rate tensor

and computed from the resolved velocity field $\tilde{\mathbf{v}}$. To model the sub-grid-scale stress terms, the dynamic Smagorinsky model proposed by Germano (Germano et al., 1991) and modified by Lilly (Lilly et al., 1992) is used here. This approach has shown good performance for a variety of complex marine flows of full appended submarines (Zhang et al., 2010; 2016b; 2021; Mahesh et al., 2017; Kumar et al., 2018; Kroll et al., 2020; Wang and Zhang, 2022).

As for the discretization of the governing equations, a bounded central difference scheme is applied. The coupling between the velocity and pressure is achieved by means of the classic PISO algorithm, and the algebraic multigrid method is employed to accelerate the solution convergence.

3.2. Computational Domain and Boundary Condition

Figure 3 shows the cylindrical computational domain, the domain has a length of $4L$ and a radius of L , and extends from L upstream of the front of the hull to $2L$ downstream of the stern of the hull, for modeling a fully developed wake. Free-stream boundary conditions are imposed at the inflow and radial boundaries, and a pressure-outlet boundary condition is imposed at the outflow boundary. The no-slip wall treatment is used for shear stress specification.

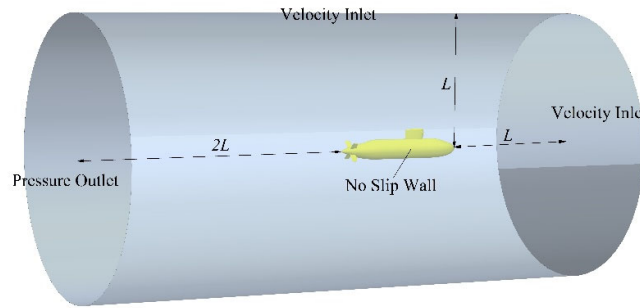
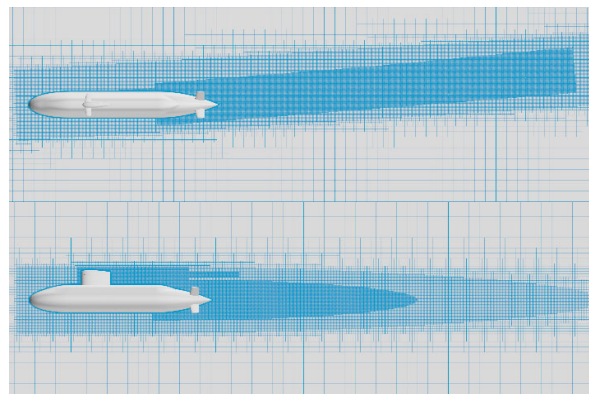


Figure 3. The computational domain.

3.3. Computation Mesh

In this subsection, three sets of grids are designed for convergence study. The simulation domain is discretized using the unstructured hex-dominant grid (trimmer mesher, Octree grid), and a prism layer mesher is used for the generation of boundary layer mesh with $y^+ \approx 1$ for all grid sets. The refinement ratio of grids in three directions is $\sqrt{2}$, as recommended by the International Towing Tank Conference (ITTC, 2014). The corresponding grid numbers are 3.30×10^7 , 8.62×10^7 , and 2.28×10^8 respectively and the three grid codes are G1 to G3 respectively. All numerical simulations are carried out by parallel processing in CSSRC (China Ship Scientific Research Centre) with 50 nodes (2400 processors). The time needed to finish a simulation with 228 million cells is about 30 days.

For capturing the flow field more accurately, a local volumetric control block is established around the submarine to control the surrounding grid size. Care is taken to resolve initial vortex formation and roll up of the free shear layer, and avoid rapid dissipation of vortex structure in the wake of the sail, hydroplanes, and X-rudder, local volumetric control blocks are also established around these appendages for more refined volume mesh control. There is an angle of approximately 5.5 degrees between the blocks and the longitudinal axis of the hull in calculation at 10° yaw conditions.



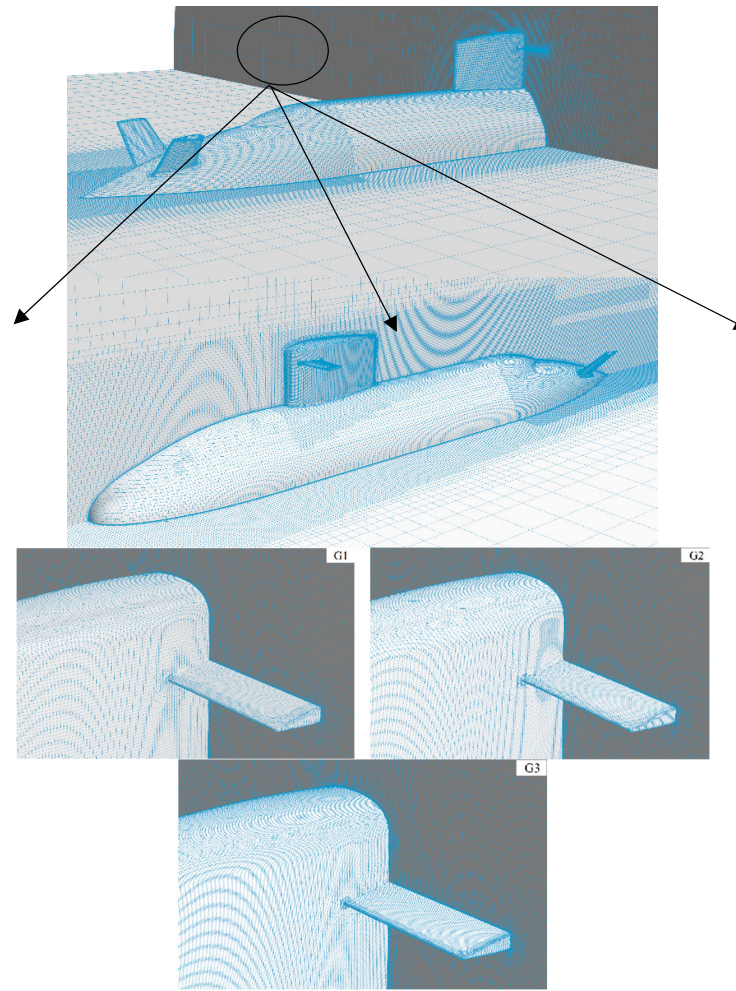


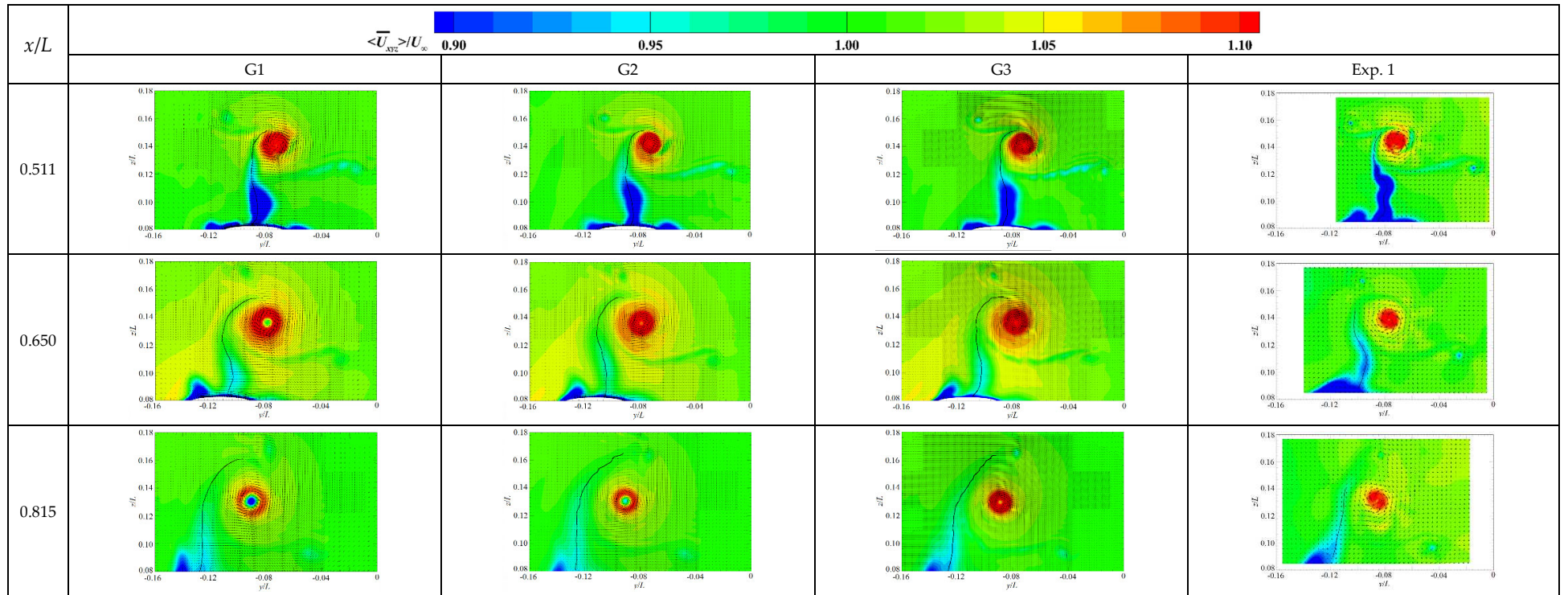
Figure 4. Grids for computation.

4. Results and Discussion

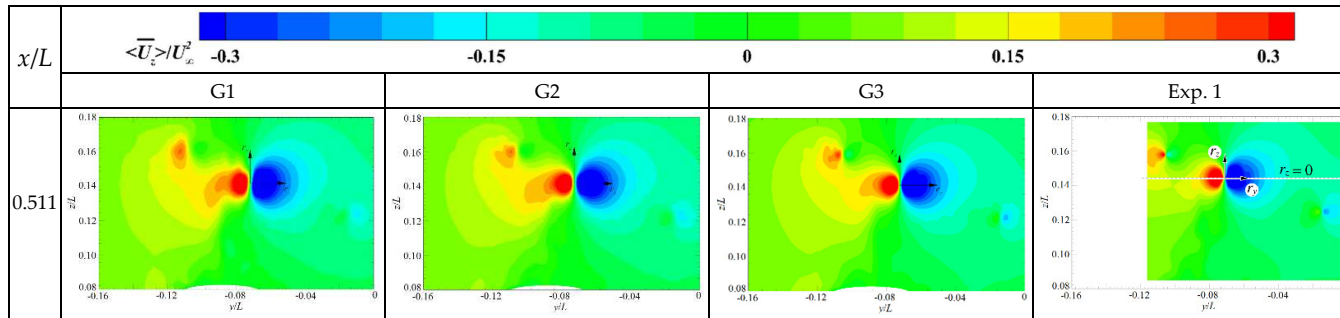
In this section, we present results initially for the qualitative and quantitative comparison between the numerical results and experimental results at 10° yaw, and then the detailed numerical investigation of the flow around the submarine is conducted at straight ahead and 10° yaw conditions.

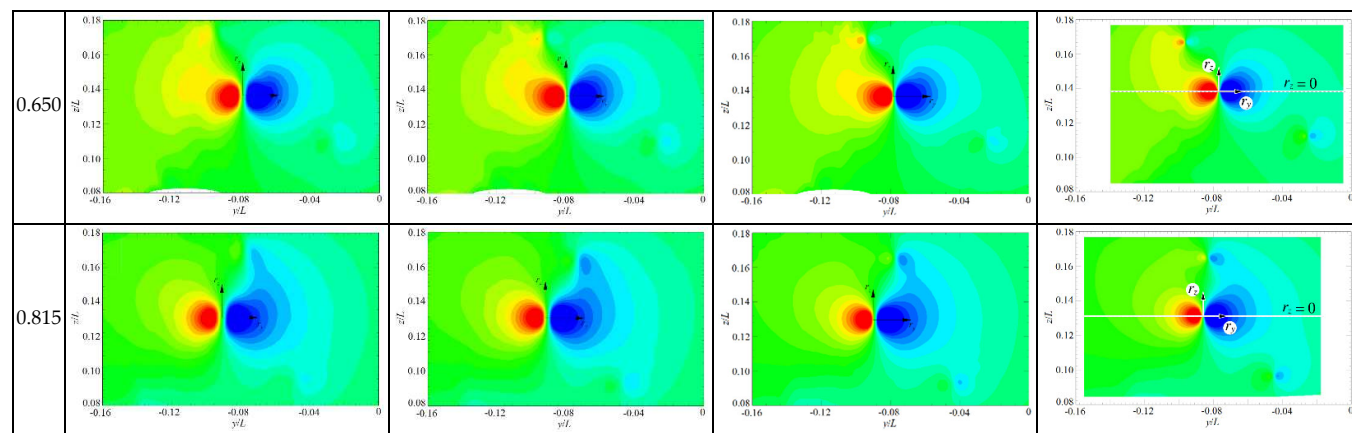
4.1. Validation of the Numerical Approach

Figure 5 provides a direct comparison of the wake of the cruciform appendage, including the mean resultant velocity $\langle \bar{U}_{xyz} \rangle / U_\infty$, the vertical component of velocity $\langle \bar{U}_z \rangle / U_\infty$, and the cross-stream Reynolds stress $\langle u_y u_z \rangle / U_\infty^2$, where U_∞ denotes the freestream velocity. The experimental results with $Re_L = 4 \times 10^6$ and $Re_L = 8 \times 10^6$ are denoted by Exp. 1 and Exp. 2 respectively. It can be observed that the sail-tip vortex formed by the rolling up of the wake can be presented by the numerical calculations under all sets of grids. The region of the core flow, defined as a region of vortex flow from its center to its radial location of maximum swirl, is quite similar to the experimental results. While the range of the core flow and low-velocity region presents minor differences under different sets of grids. Especially for the vertical component of velocity, as the number of grids increases, the distribution of high/low-velocity regions becomes more concentrated and obvious, and the numerical results are closer to the experiments. In addition, the numerical dissipation decreases as the grid number increases, and the capture of the cross-stream Reynolds stress seems to be more refined.

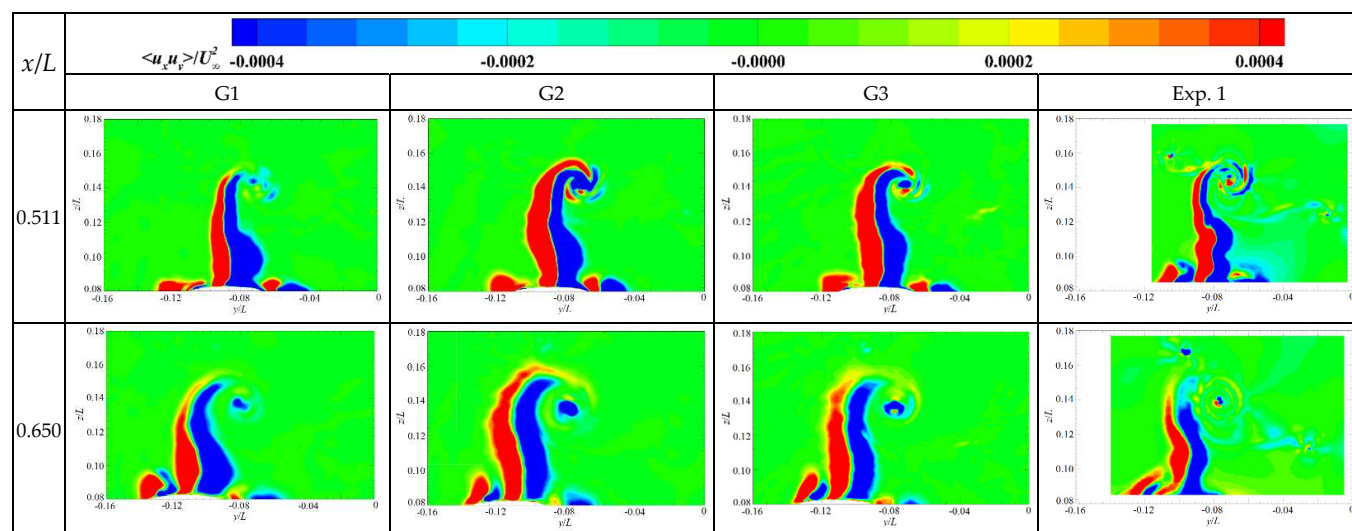


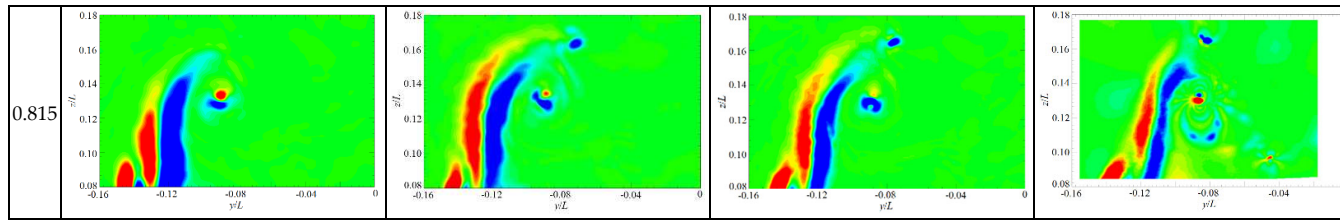
(a) The mean resultant velocity





(b) The vertical component of velocity





(c) The velocity cross-stream Reynolds stress

Figure 5. Comparison of the wake of the cruciform appendage under different sets of grid.

Figure 6 shows a comparison of the mean resultant velocity $\langle \bar{U}_{xyz} \rangle / U_\infty$ as functions of radial distance r_y/L from the vortex center, in the horizontal profiles through the sail-tip vortex. The mean resultant velocity under different grid sets exhibits a considerable difference, especially for the region of the core flow, which presents a corresponding increase with the grid number's continuous growth. The core-flow velocity obtained from numerical calculations exhibits a significant difference at different axial distances from the bow, but is quite close for the experiments. The core flow obtained in the first set of grids (G1) has a mean velocity $\langle \bar{U}_{xyz} \rangle / U_\infty \approx 1.12$ and $\langle \bar{U}_{xyz} \rangle / U_\infty \approx 0.91$ at $x/L=0.511$ and $x/L=0.815$ respectively, with an axial descent rate of 18.8%. It corresponds to $\langle \bar{U}_{xyz} \rangle / U_\infty \approx 1.26$ and $\langle \bar{U}_{xyz} \rangle / U_\infty \approx 1.11$ respectively in G3, with an axial descent rate of 11.9%. It indicates that the numerical attenuation inevitably exists in the LES simulations with the dynamic Smagorinsky model of the core flow, which is not advantageous compared to experiments, and can be partly eliminated by improvement of the spatial resolution of the grid.

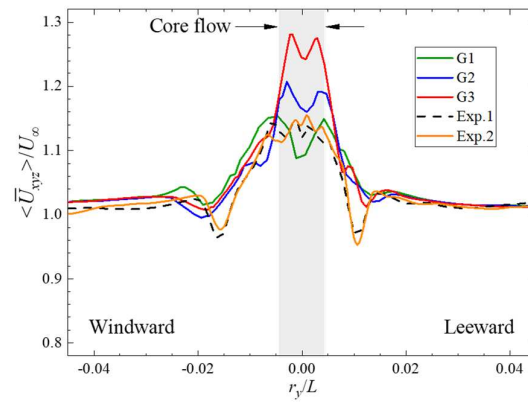
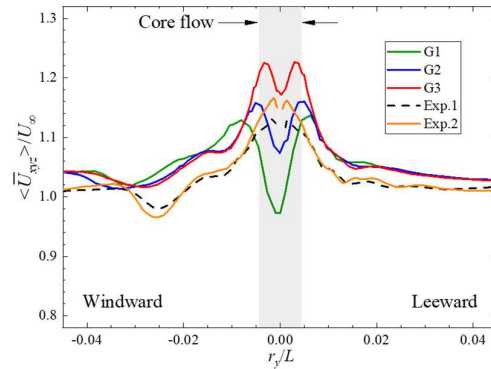
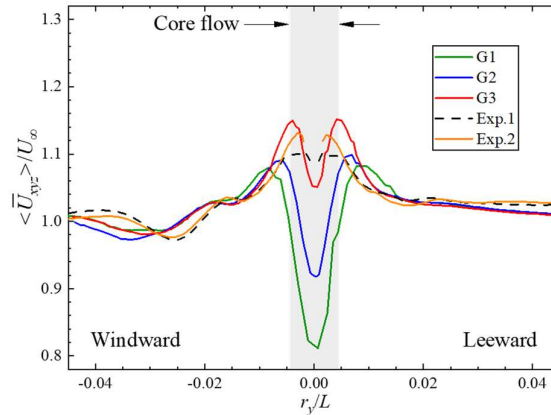
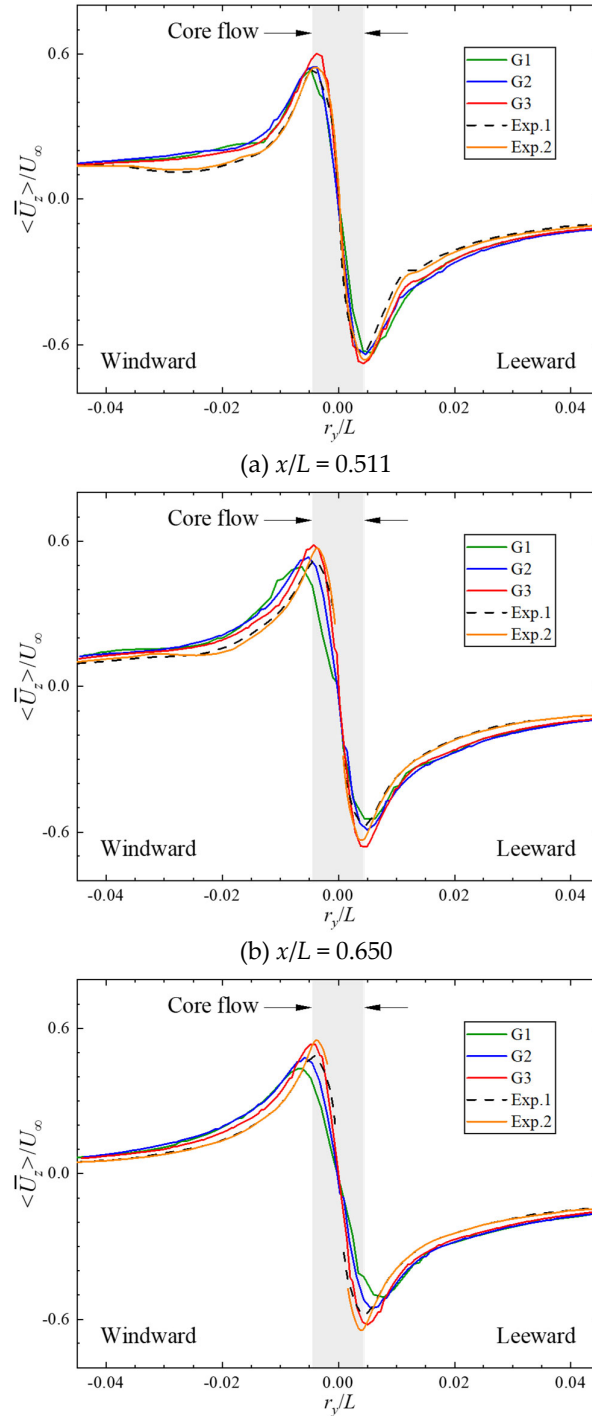
(a) $x/L = 0.511$ (b) $x/L = 0.650$ (c) $x/L = 0.815$

Figure 6. Comparison of the mean resultant velocity under different sets of grid.

Figure 7 shows a comparison of the vertical component of velocity $\langle \bar{U}_z \rangle / U_\infty$. It can be seen that the numerical results become gradually closer to the experimental values as the grid number increases. Especially for the prediction of the peak and valley values, the results obtained in G3 are quite close to that of Exp. 2 with a relatively higher Reynolds number. Overall, the relative errors of the peak and valley values in G3 are 10.6% and 4.3% respectively, which turns to 13.2% and 14.0% in G2, and 21.6% and 21.1% in G1. It can be concluded that with the refinement of the grids, the extreme values can be more accurately captured in numerical simulations, due to the improvement of spatial resolution.



(c) $x/L=0.815$ **Figure 7.** Comparison of the vertical component of velocity under different sets of grid.

Figure 8 provides a plot of the comparison of the turbulence kinetic energy (TKE) k/U_∞^2 for the sail-tip vortex. The distribution of TKE along the radial distance r_y/L for all grid sets is consistent with the experimental results, and the simulations of G3 are more representative of the experiments, with the relative error of the peak value in the region of core flow being relatively smaller.

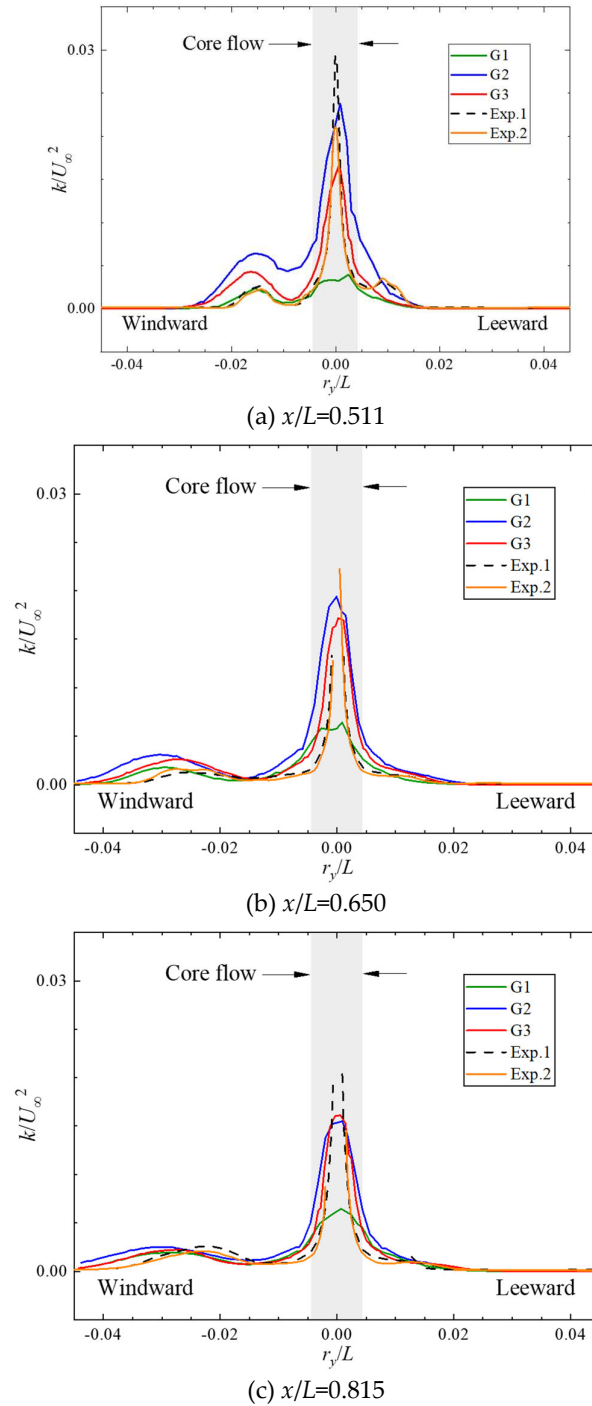
**Figure 8.** Comparison of the turbulence kinetic energy under different sets of grid.

Figure 9 summarizes the comparison of the centerline of the sail wake, which is defined by tracing the boundary $\langle u_x u_y \rangle = 0$ between the positive and the negative Reynolds stresses. Overall, the sail-wake centerline shifts very slightly windward by no more than $0.01L$, and by refining the grids from $G1$ to $G3$, it shifts leeward and closer to the experiments. The centers of the vortices on the upper hull are listed in Table 1, and their relative errors to Exp. 2 are listed in Table 2. In the near sail-wake region ($x/L=0.511$), the numerical simulations for all grid sets can well define the centers of the vortices, but as they evolve downstream, the advantages of refining the grids are gradually being reflected. For the case of $G3$, the maximum horizontal and vertical relative errors of the vortex centers at $x/L=0.815$ are 7.2% and 1.5%, which is quite satisfied with actual engineering predicting needs.

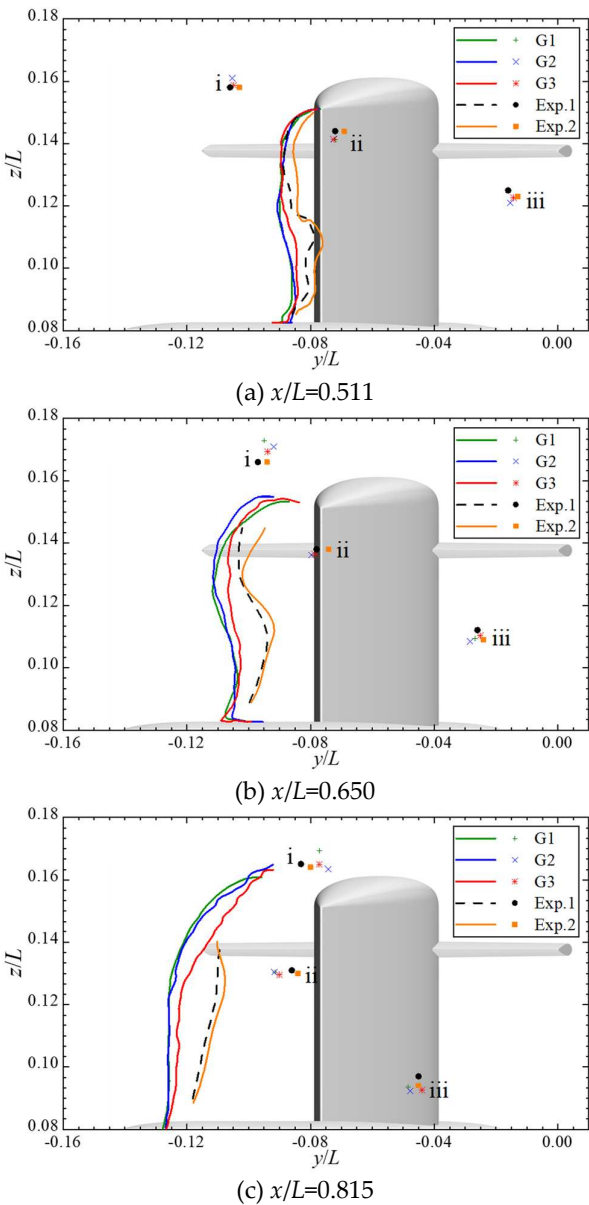


Figure 9. Comparison of the centerline of the sail wake under different sets of grid.

Table 1. Summary of the centers of the vortices on the upper hull.

Measurement Plane	Grid Scheme	Sail tip		Hydroplanes			
				Windward		Leeward	
		y/L	z/L	y/L	z/L	y/L	z/L

$x/L=0.511$	G1	-0.072	0.141	-0.108	0.161	-0.013	0.123
	G2	-0.073	0.141	-0.105	0.161	-0.015	0.121
	G3	-0.072	0.141	-0.105	0.159	-0.014	0.123
$x/L=0.650$	G1	-0.079	0.136	-0.095	0.173	-0.027	0.109
	G2	-0.080	0.136	-0.092	0.171	-0.028	0.109
	G3	-0.079	0.136	-0.094	0.169	-0.025	0.110
$x/L=0.815$	G1	-0.092	0.130	-0.077	0.169	-0.048	0.094
	G2	-0.092	0.130	-0.074	0.163	-0.048	0.092
	G3	-0.090	0.130	-0.077	0.165	-0.044	0.093

Table 2. Summary of the relative errors to Exp. 2 of the centers of the vortices.

Measurement Plane	Grid Scheme	Sail tip		Hydroplanes			
				Windward		Leeward	
		$y/L(\%)$	$z/L(\%)$	$y/L(\%)$	$z/L(\%)$	$y/L(\%)$	$z/L(\%)$
$x/L=0.511$	G1	4.3	-1.9	5.3	1.6	2.7	0.3
	G2	5.3	-1.8	2.2	1.9	18.2	-1.6
	G3	5.0	-1.9	1.8	0.5	10.7	-0.3
$x/L=0.650$	G1	6.5	-1.3	1.0	4.2	12.0	0.4
	G2	7.7	-1.4	-2.3	3.0	18.6	-0.4
	G3	6.1	-1.1	-0.1	2.0	4.8	1.2
$x/L=0.815$	G1	9.0	0.4	-3.7	3.3	7.5	-0.5
	G2	9.2	0.3	-7.0	-0.4	6.2	-1.8
	G3	7.2	-0.3	-3.5	0.6	-2.5	-1.5

4.2. Analysis of the Evolution of the Flow

Figure 10 presents an overall view of the flow past Joubert BB2 at straight ahead conditions in terms of the second invariant of the velocity gradient Q , colored by the mean resultant velocity $\langle \bar{U}_{xyz} \rangle / U_\infty$. In the immediate front of the junctions of the sail root and the deck, the flow rolls up into a horseshoe vortex system surrounding the sail, the legs of which develop downstream following the deck. Because of the adverse pressure gradient at the trailing edge of the sail, the flow gradually develops into turbulence, and the side vortices are formed and interact with the horseshoe vortex at the root. The side vortices over the sail cap are transported along the sail edge, then merge with the sail-tip vortices and dissipate rapidly. The flow over the outer edge of the hydroplanes induces a pair of hydroplane-tip vortices with opposite circulation, which develop downstream independently, then dissipate and disappear at a distance of approximately one submarine length from the stern. Further, horseshoe vortex, tip vortex, and wake vortex systems can be observed around the X-rudders. And between the two upper rudders, they interact with the vortices sweeping down and sideways over the end of the deck, complicating the flow into the propeller disk, which is unstable and the main source of propeller hydrodynamic noise. Downstream far away from the hull, all the tip vortices dissipate and almost only the wake vortices after complicated interaction dynamically evolve with the energy gradually weakening.

Similarly, Figure 11 presents various vortex systems past Joubert BB2 at 10° yaw conditions, from perspectives of oblique, top, and side views. It can be clearly seen that the vortex systems are more complicated. The side vortices on the leeward side of the sail occur more forward, and the sail-tip vortices are relatively strong enough to develop far downstream. The same as the hydroplane-tip vortices, but which are not clearly observed downstream because of strong interaction with the sail

wake. Figure 12 shows the development of the trajectories of the cores of tip vortices originating from the cruciform appendage, including the port and starboard hydroplanes and the vertical sail, at 10° yaw conditions. The clockwise rotating sail-tip vortices maintain an axial angle of approximately 8 degrees with the hull and develop downstream and leeward, and are almost stable vertically after experiencing a brief down-wash immediately behind the sail. The position of the port hydroplane-tip vortices fluctuates widely, the horizontal and vertical coordinates of which reach their maximum values approximately at $x/L=1.1$ and $x/L=0.7$ respectively, then experience a sharp drop. Overall, the port hydroplane-tip vortices develop and revolve around the sail-tip vortices. The development of the starboard hydroplane-tip vortices is relatively stable, whose core keeps moving towards the leeward side, with the vertical position gradually rising away from the hull after passing through a valley approximately at $x/L=1.1$, due to the repulsive interaction of the hull wake.

At 10° yaw conditions, another obvious feature that distinguishes the straight ahead conditions is the flow separation on the leeward side of the middle hull. The upper and lower vortex system can be clearly seen, and the former eventually interacts with the horseshoe vortex system originating from the sail, while the latter merges into the wake between the upper and lower rudders. The wake of the submarine becomes quite complicated, and the flow behind the stern is dominated by the mixing of various component vortex systems, including the tilted horseshoe vortex system, the upper and lower hull vortices, the tip vortices, and the wake of the sail, hydroplanes, X-rudders, and hull.

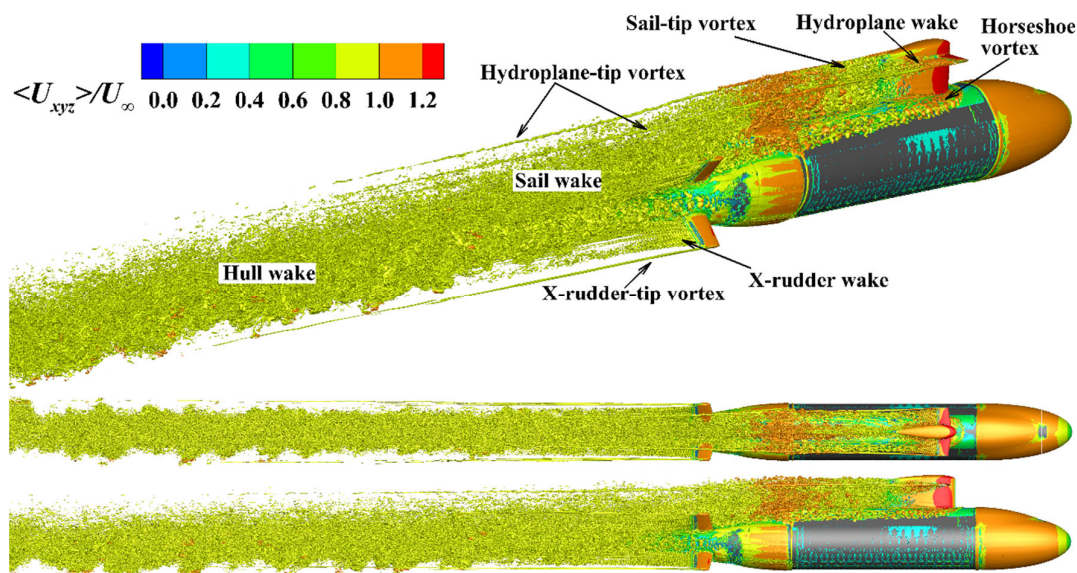


Figure 10. Development of vortex systems past Joubert BB2 at straight ahead conditions.

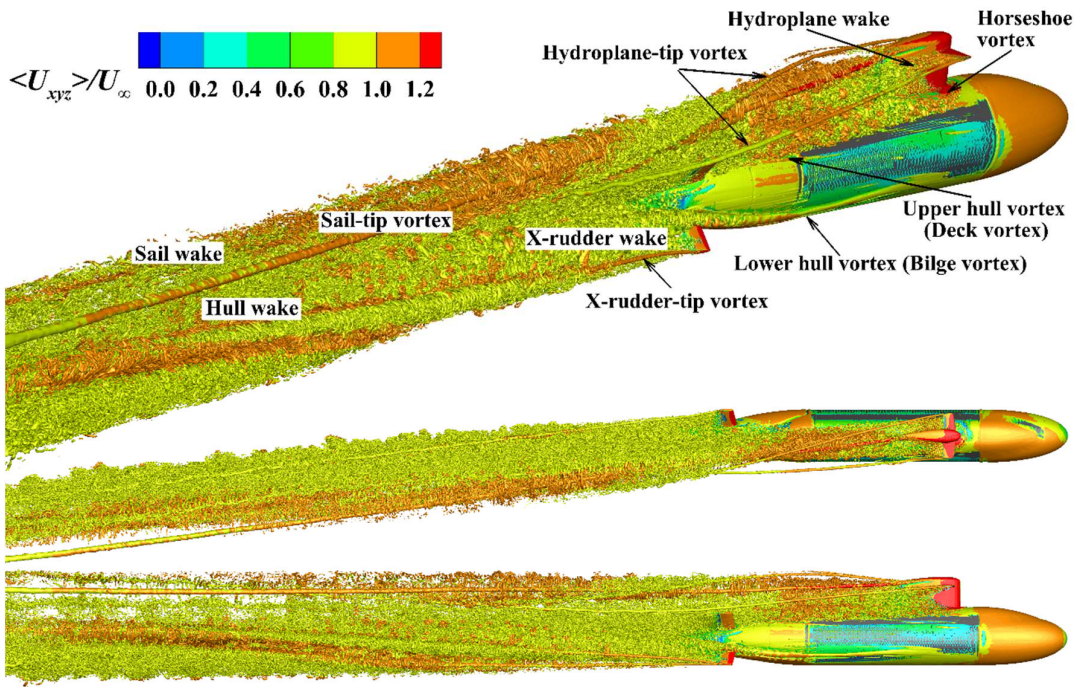
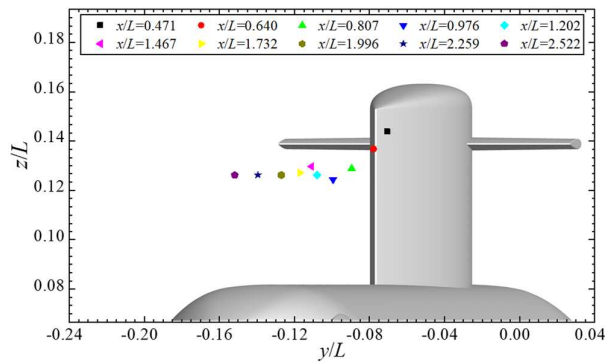
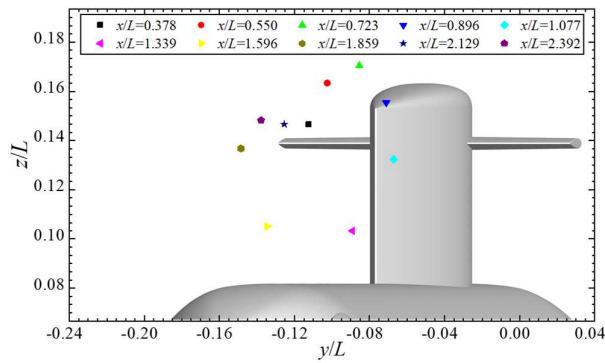


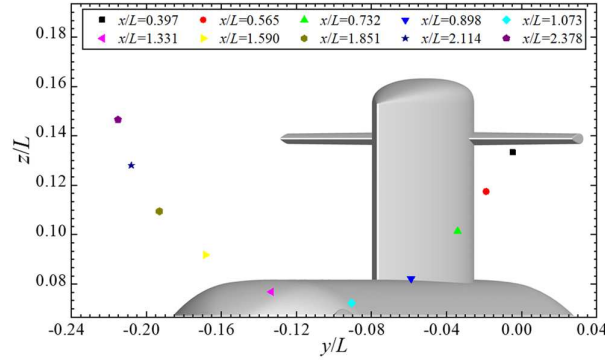
Figure 11. Development of vortex systems past Joubert BB2 at 10° yaw conditions.



(a) The sail-tip vortices



(b) The port hydroplane-tip vortices



(c) The starboard hydroplane-tip vortices

Figure 12. Trajectories of the cores of tip vortices at 10° yaw conditions.

Figure 13 shows the evolution of the mean vorticity magnitude $\langle \bar{\omega}_{xyz} \rangle r_m / U_\infty$ along the submarine axial, at straight ahead and 10° yaw conditions, where $r_m = L / (2 \times 7.3)$. The momentum and energy are transported by the development of vortex systems, where the vortex systems generated by the sail, hydroplanes, deck, hull, and X-rudder pass present an increase in vorticity, especially for the tip vortices, horseshoe vortices, wake vortices, and generated hull side vortices possibly. Noticing that the instabilities of the horseshoe-vortex system and its interaction with the hull boundary layer, cause the legs to break up and develop connected vortex loops, which results in the transport of momentum across the hull and influences the distribution of the vorticity, as mentioned by Fureby (Fureby et al., 2016). As the vortex structure gradually dissipates downstream, the vorticity gradually decreases, with the sail-tip vortices and hydroplane-tip vortices being particularly prominent. For the case straight ahead, the obvious vorticity near the sail induced by the tip vortices of the cruciform appendage quickly decays, which is quite significantly far away from the stern for the case at 10° yaw. Increased vorticity is also found around and behind the hull at 10° yaw conditions because of considerable interaction between the flow and the hull. Therefore, the flow-induced noise of submarines under maneuvering conditions has always been a research highlight in the international hydrodynamics field. As the vortex systems develop from a concentrated distribution in the near wake region to a dispersed mode in the far field in both cases, the vorticity gradually weakens while the coverage range increases, due to energy conservation.

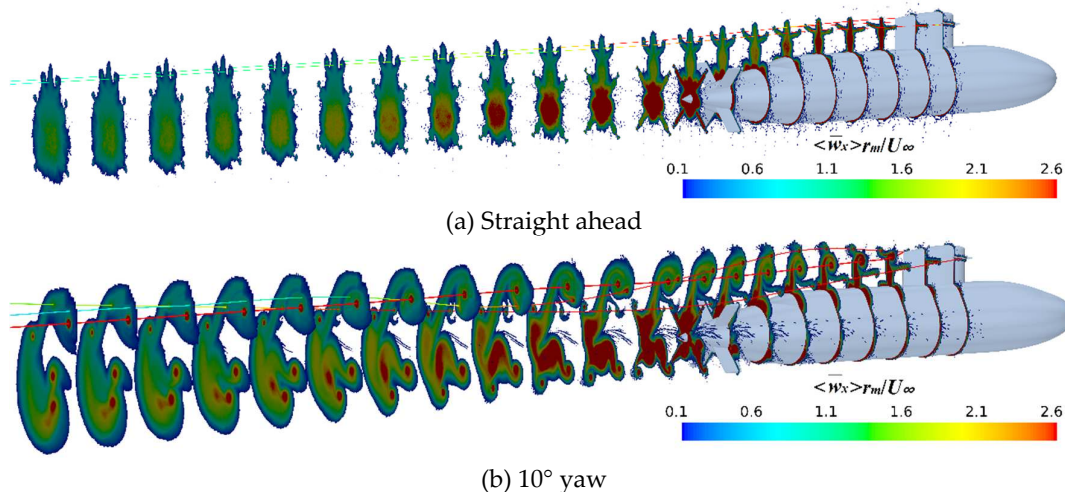
**Figure 13.** Evolution of the mean vorticity magnitude.

Figure 14 shows the evolution of the turbulence kinetic energy (TKE) k/U_∞^2 along the submarine axial, at straight ahead and 10° yaw conditions. The evolution of TKE is quite similar to that of the mean vorticity magnitude, where the vorticity is concentrated, the momentum is intense and the TKE is significant. For the case at 10° yaw, it can be obviously seen that the TKE induced by the sail-tip vortices is quite stronger than that induced by the hydroplane-tip, with the same pattern as the vorticity followed. Besides that, the TKE in the wake is strongly influenced by the X-rudder at both conditions, which exacerbates the velocity fluctuations of the flow and induces additional propeller noise, thus the hydrodynamic design of the X-rudder is also a research highlight.

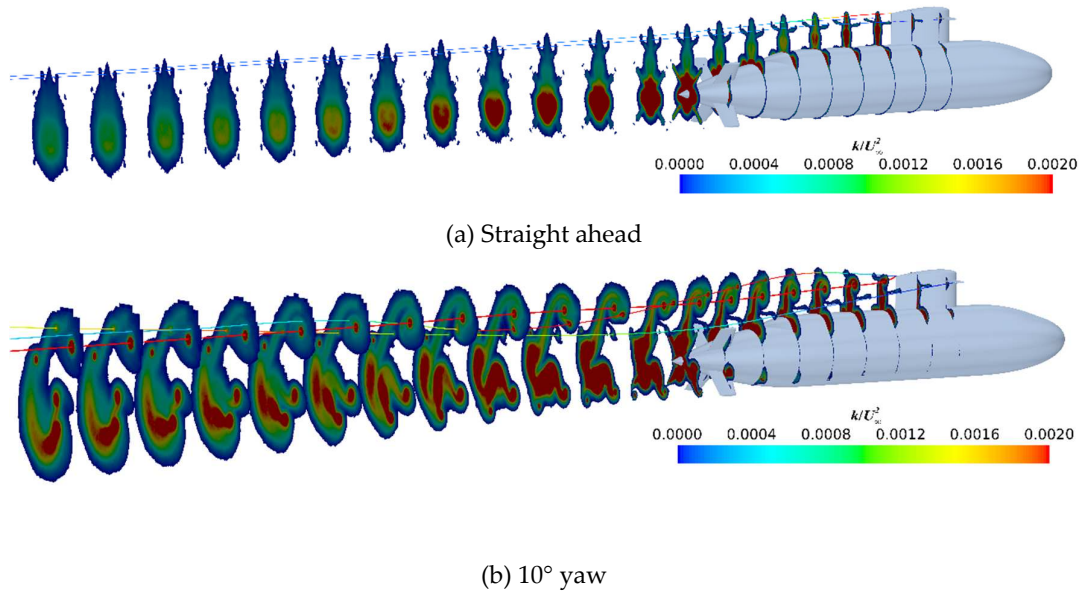
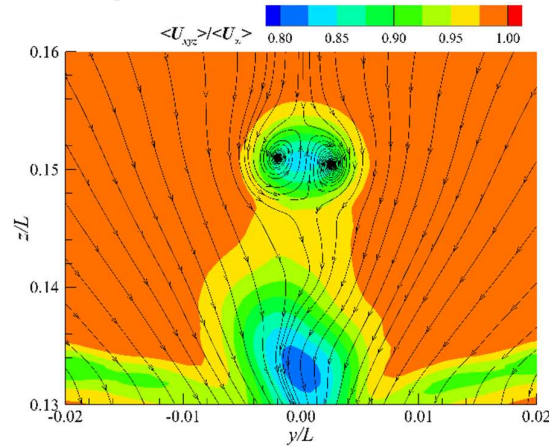


Figure 14. Evolution of the turbulence kinetic energy.

Figure 15, Figure 16, and Figure 17 show a comparison of the mean resultant velocity $\langle \bar{U}_{xyz} \rangle / U_\infty$, the mean vorticity magnitude $\langle \bar{\omega}_{xyz} \rangle r_m / U_\infty$, and the turbulence kinetic energy k/U_∞^2 respectively, for the model-length locations $x/L=0.484$, at straight ahead and 10° yaw conditions. A pair of sail-tip vortices with opposite circulation can be found at straight ahead conditions, and in the core-flow region, the mean resultant velocity, the mean vorticity magnitude, and the turbulence kinetic energy are quite smaller than those at 10° yaw conditions.



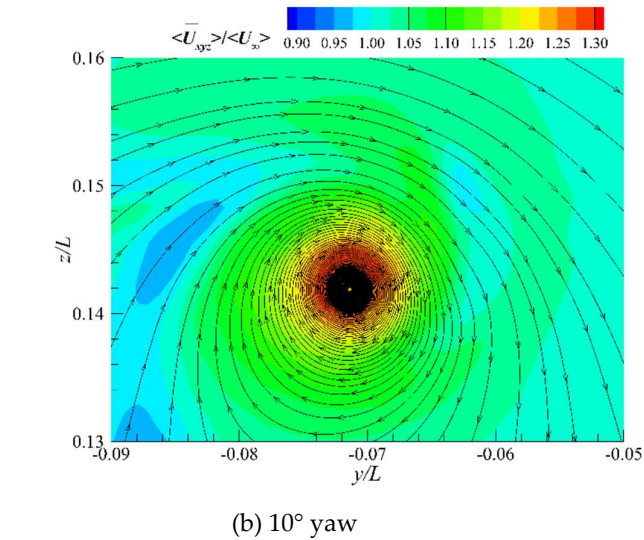


Figure 15. Comparison of the mean resultant velocity at straight ahead and 10° yaw conditions.

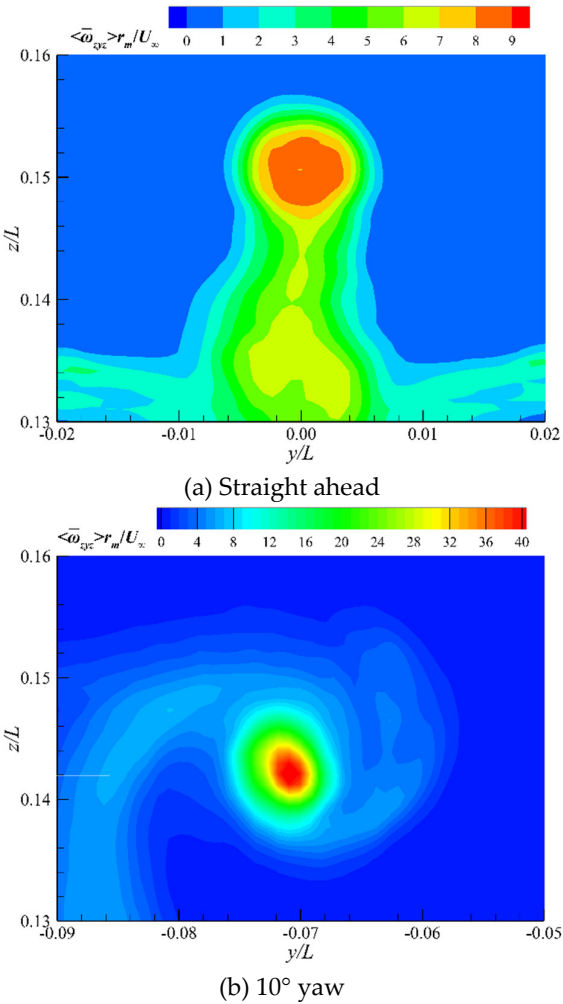


Figure 16. Comparison of the mean vorticity magnitude at straight ahead and 10° yaw conditions.

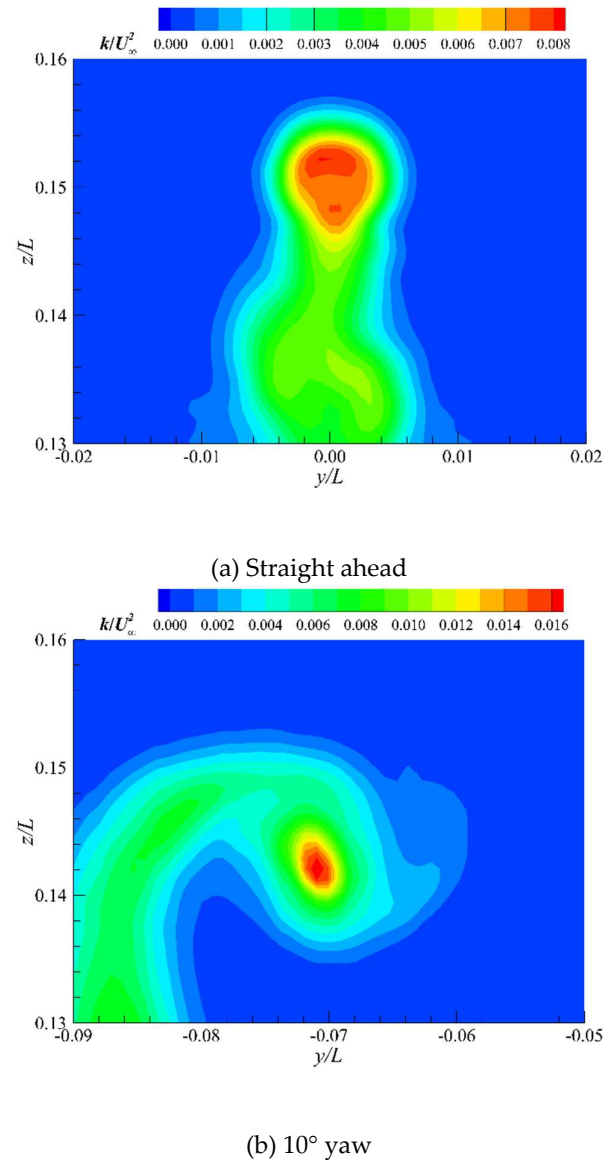
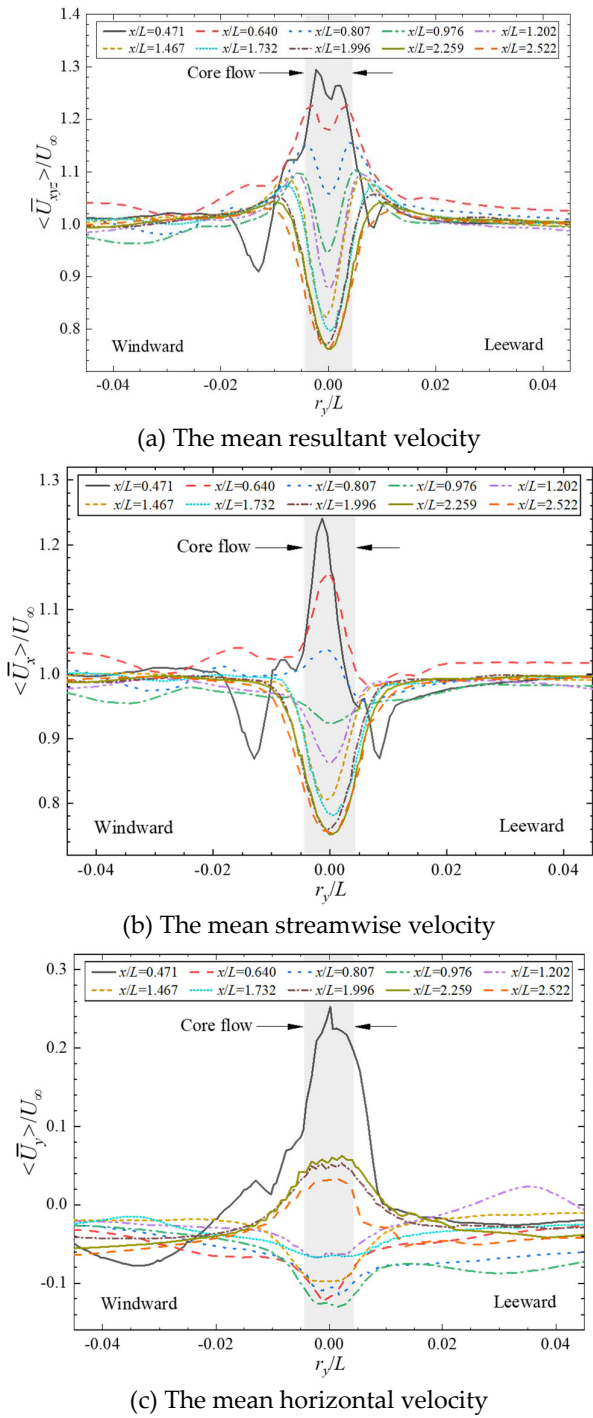
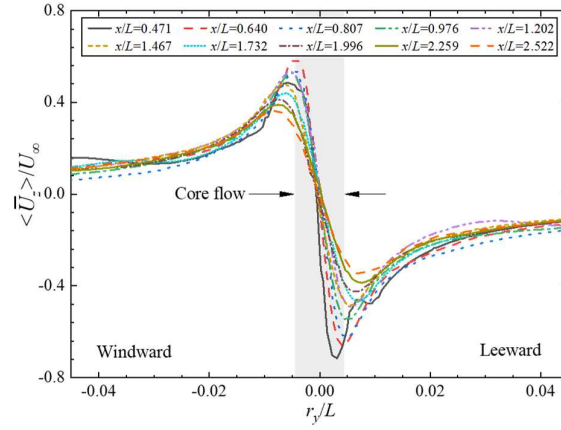


Figure 17. Comparison of the turbulence kinetic energy at straight ahead and 10° yaw conditions.

In view that the momentum and energy transported by the sail-tip vortices at 10° yaw conditions are quite predominant, the flow characteristics of the sail-tip vortices are further studied below. Figure 18 provides a comparison of the velocity for the sail-tip vortex under different longitudinal locations, including mean resultant velocity $\langle \bar{U}_{xyz} \rangle / U_\infty$, the three-dimensional component of velocity $\langle \bar{U}_x \rangle / U_\infty$, $\langle \bar{U}_y \rangle / U_\infty$ and $\langle \bar{U}_z \rangle / U_\infty$. It can be intuitively seen that as the wake of the sail-tip vortices develops downstream, the mean resultant velocity, streamwise velocity, and horizontal velocity show a gradually decreasing trend, and the fluctuation of the vertical velocity between peak and valley values gradually weakens. In the near wake region where $x/L \leq 0.807$, the core flow exhibits a high-velocity characteristic, while in the far wake region, the velocity is smaller than the freestream velocity.

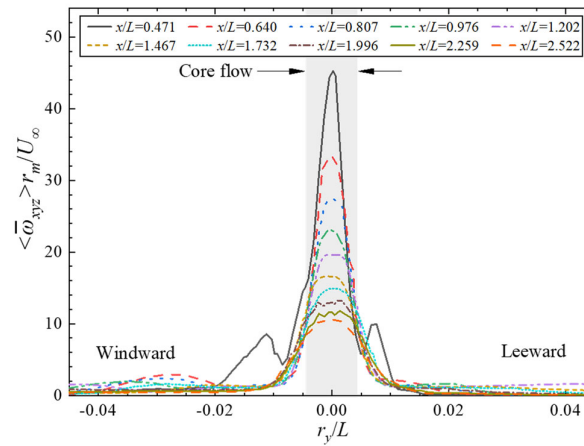




(d) The mean vertical velocity

Figure 18. Comparison of the mean velocity under different streamwise locations.

Figure 19 shows a comparison of the mean vorticity under different streamwise locations. The dominant component of the mean vorticity magnitude $\langle \bar{\omega}_{xyz} \rangle r_m / U_\infty$ is the streamwise mean vorticity $\langle \bar{\omega}_x \rangle r_m / U_\infty$, which indicates that the sail-tip vortex rotates rather faster around the x-axis compared to the other two. The core-flow vorticity weakens rapidly as the wake develops downstream, while the decay rate gradually slows down. An interesting phenomenon shows that the distribution of the peaks and valleys of the vertical mean vorticity $\langle \bar{\omega}_z \rangle r_m / U_\infty$ changes with the evolution of the flow. In the near wake region where $x/L \leq 0.807$, the peaks are located on the windward side, and the valleys are located on the leeward side, while in the far wake region, the positions of the two are exactly opposite.



(a) The mean vorticity magnitude

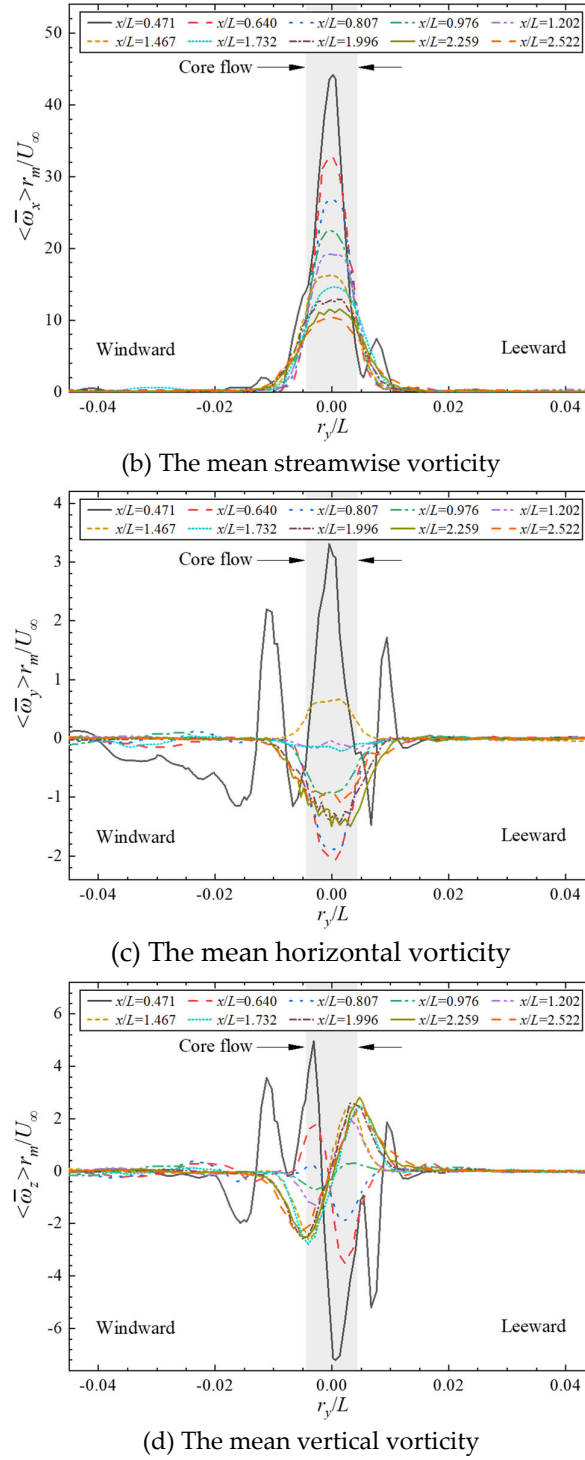
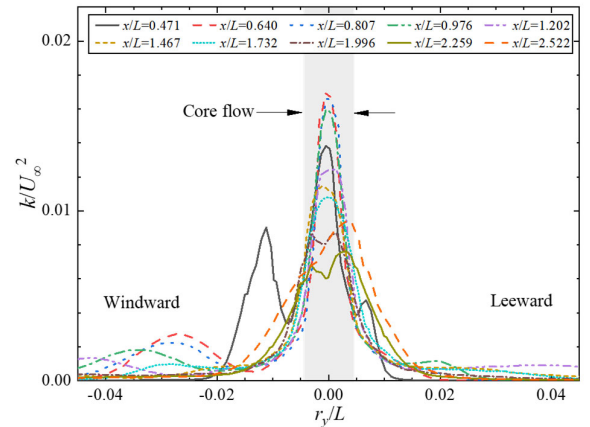


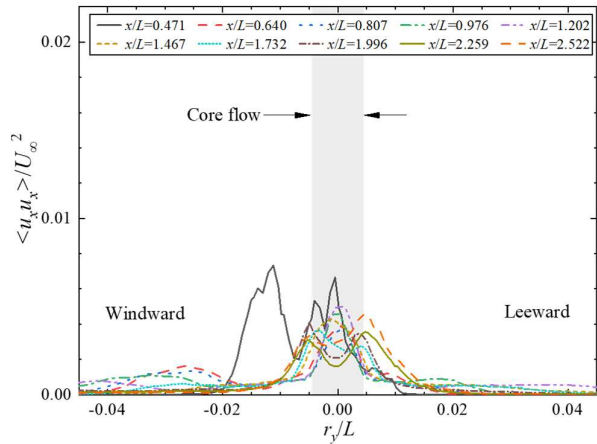
Figure 19. Comparison of the mean vorticity under different streamwise locations.

Figure 20 shows a comparison of the turbulence kinetic energy under different streamwise locations. The roll-up from the sail is accompanied by a down-wash of the sail-tip vortex (see Figure 12(a)), and the normal stress in the vertical component $\langle u_x u_x \rangle$ is the strongest contribution to the TKE, as mentioned by Lee (Lee et al., 2019). Because of the significant cross-stream, the normal stress in the horizontal component accounts for the second strongest contribution, and the normal stress in the streamwise component is the weakest. The strongest TKE does not occur immediately behind the

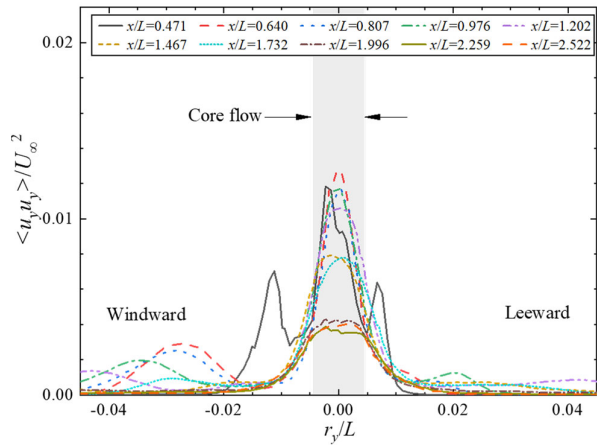
sail, but approximately in the range of x/L equal to 0.6 to 1.0, where the down-wash of the sail-tip vortex is quite intense.



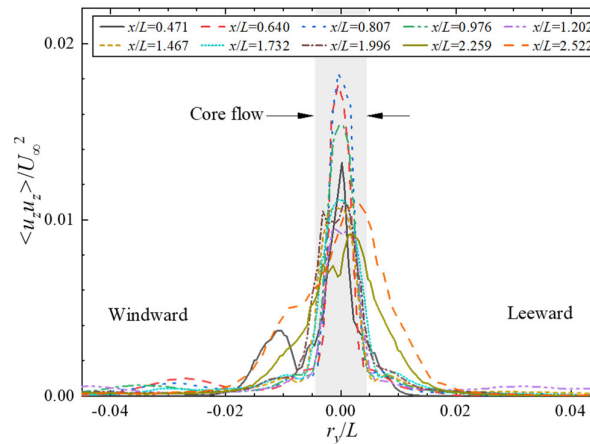
(a) The turbulence kinetic energy



(b) The normal stress in the streamwise component



(c) The normal stress in the horizontal component



(d) The normal stress in the vertical component

Figure 20. Comparison of the turbulence kinetic energy under different streamwise locations.

5. Conclusions

In the paper, the large eddy simulation with the dynamic Smagorinsky model is conducted, to investigate the flow field around a fully appended Joubert BB2 submarine model at straight ahead and 10° yaw conditions. Conclusions acquired from the analysis of computed results can be summarized as:

- 1) By qualitative and quantitative comparison with experiments at 10° yaw conditions, the computational accuracy is verified. A satisfactory result shows more favorable agreement with experimental measurements as the improvement of spatial resolution, especially for capturing the vortice centers in the far wake region, with the relative error well within 7.2% in the most refined grid arrangement.
- 2) The resultant velocity, vorticity magnitude, and TKE show a gradually decreasing trend as the wake of the cruciform appendage develops downstream. At 10° yaw conditions, the core flow velocity of the sail-tip vortices will transition from high-velocity characteristics in the near wake region, to low-velocity characteristics as the wake further evolutions.
- 3) The tip vortex tracking at 10° yaw conditions exhibits significant three-dimensional characteristics than that at straight ahead conditions. In the core-flow region, the resultant velocity, vorticity magnitude, and TKE at straight ahead conditions are quite smaller than those at 10° yaw conditions.
- 4) At 10° yaw conditions, the sail-tip vortex tracking maintains an axial angle of approximately 8 degrees with the hull, and is almost stable vertically after experiencing a down-wash immediately behind the sail. The port hydroplane-tip vortices develop and spiral around the sail-tip vortices, while the core of the starboard hydroplane-tip vortices keeps moving towards the leeward side, with the vertical position gradually rising away from the hull after passing through a valley approximately at $x/L=1.1$, due to the repulsive interaction of the hull wake.

CRedit Authorship Contribution Statement: Mo Chen: Conceptualization, Methodology, Software, Writing -original draft. Nan Zhang: Conceptualization, Methodology, Data curation, Validation, Supervision. Hailang Sun: Visualization & Investigation. Xuan Zhang: Writing-review & editing.

Funding: Support from the projects with the Grant No. 50907010101 is acknowledged.

Data Availability Statement: The data that has been used is confidential.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Alin, N., Fureby, C., 2003. LES of the flow past simplified submarine hulls. The 8th International Conference on Numerical Ship Hydrodynamics (Busan, Korea).
2. Alin, N., Bensow, R., Fureby, C., et al., 2010a. Current capabilities of RANS, DES and LES for submarine flow simulations. *J. Ship. Res.* 54, 184–196.
3. Alin, N., Chapuis, M., Fureby, C., et al., 2010b. Numerical study of submarine propeller-hull interactions. In: 28th Symposium on Naval Hydrodynamics (Pasadena, USA).
4. Anderson, B., Chapuis, M., Erm, L., et al., 2012. Experimental and computational investigation of a generic conventional submarine hull form. In: 29th Symposium on Naval Hydrodynamics (Gothenburg, Sweden).
5. Ashok, A., Smits, A.J., 2012. The turbulent wake of a submarine model at varying pitch and yaw angle. In: 65th Annual Meeting of the APS Division of Fluid Dynamics (San Diego, California).
6. Ashok, A., Smits, A.J., 2013. The turbulent wake of a submarine model in pitch and yaw. In: 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition (Grapevine, Texas).
7. Ashok, A., Buren, T.V., Smits A.J., 2014. Asymmetries in the high Reynolds number wake of a submarine model in pitch. In: 67th Annual Meeting of the APS Division of Fluid Dynamics (San Francisco, California).
8. Ashok, A., Buren, T.V., Smits A.J., 2015a. The structure of the wake generated by a submarine model in yaw. *Exp. Fluids* 56, 123.
9. Ashok, A., Buren, T.V., Smits A.J., 2015b. Asymmetries in the wake of a submarine model in pitch, *J. Fluid Mech.* 774, 416–442.
10. Bensow, R.E, Fureby, C., Liefvendahl, M., Persson, T., 2004a. A comparative study of RANS, DES and LES. In: 26th Symposium on Naval Hydrodynamics (Rome, Italy).
11. Bensow, R.E, Persson, T., Fureby, C., et al., 2004b. Large eddy simulation of the viscous flow around submarine hulls. In: 25th Symposium on Naval Hydrodynamics (Newfoundland and Labrador, Canada).
12. Bensow, R.E, Larson, M.G., 2006. Towards a novel residual based subgrid modelling based on multiscale techniques. In: 9th Numerical Towing Tank Symposium (Le Croisic, France).
13. Bensow, R.E, Liefvendahl, M., 2008. Implicit and explicit subgrid modeling in LES applied to a marine propeller. In: 38th Fluid Dynamics Conference and Exhibit (Seattle, Washington).
14. Bettel, M.C., 2014. Validating design methods for sizing submarine tailfins. In: Warship 2014: naval submarines and UAV's (Bath, UK).
15. Fu, T.C., Atsavapranee, P., Hess, D.E., 2002. PIV measurements of the cross-flow wake of a turning submarine model (ONR Body-1). In: 24th Symposium on Naval Hydrodynamics (Fukuoka, JAPAN).
16. Fureby, C., 2008. Large eddy simulation of ship hydrodynamics. In: 27th Symposium on Naval Hydrodynamics (Seoul, Korea).
17. Fureby, C., Anderson B., Clarke D., et al., 2016. Experimental and numerical study of a generic conventional submarine at 10° yaw. *Ocean Eng.* 116, 1–20.
18. Germano, M., Piomelli, U., Moin, P., Cabot, W., 1991. A dynamic subgrid-scale eddy viscosity model. *Physics of Fluids A* 3(7), 1760–1765.
19. Huang, T., Liu, H.L., Groves, N., et al., 1992. Measurements of flows over an axisymmetric body with various appendages: the DARPA SUBOFF experiments program. In: 19th Symposium on Naval Hydrodynamics (Seoul, Korea).
20. ITTC, 2014. Recommended procedures and guidelines: practical guidelines for ship CFD applications. *Int. Towing Tank Conf. Rep.* 7, 5-03-02-03.
21. Jimenez, J.M., Hultmark, M., Smits, M., 2010. The intermediate wake of a body of revolution at high Reynolds numbers. *J. Fluid Mech.* 659, 516–539.
22. Jones, M.B., Erm, L.P., Valiyf, A., Henbest, S.M., 2013. Skin-friction measurements on a model submarine. Australia Defence Science and Technology Organization, Technical Report DSTO-TR-2898.
23. Joubert, P.N., 2004. Some aspects of submarine design part 1: hydrodynamics. Australia Defence Science and Technology Organization, Technical Report DSTO-TR-1622.
24. Joubert, P.N., 2006. Some aspects of submarine design part 2: shape of a submarine 2026. Australia Defence Science and Technology Organization, Technical Report DSTO-TR-1920.
25. Kroll, T., Morse, N., Horne, W., Mahesh K., 2020. Large eddy simulation of marine flows over complex geometries using a massively parallel unstructured overset method. In: 33th Symposium on Naval Hydrodynamics (Osaka, Japan).
26. Kumar, C., Manovski, P., Giacobello, M., 2012. Particle image velocimetry measurements on a generic submarine hull form. In: 18th Australasian Fluid Mechanics Conference (Launceston, Tasmania).
27. Kumar, P., Mahesh, K., 2018. Large-eddy simulation of flow over an axisymmetric body of revolution. *J. Fluid Mechanics* 853, 537–563.

28. Lee, S.K., 2014. Topology of the flow around a conventional submarine hull. In: 19th Australasian Fluid Mechanics Conference (Melbourne, Australia).
29. Lee, S.K., 2018. Longitudinal development of flow-separation lines on slender bodies in translation. *J. Fluid Mech.* 837, 627-639.
30. Lee, S.K., Manovski, P., Kumar, C., 2019. Wake of a cruciform appendage on a generic submarine at 10° yaw. *J. Marine Science and Technology* 25(3), 787-799.
31. Lee, S.K., Jones, M.B., 2020. Surface-pressure pattern of separating flows over inclined slender bodies. *Phys. Fluids* 32, 095123.
32. Loid, H.P., Bystrom, L., 1983. Hydrodynamic aspects of the design of the forward and aft bodies of the submarine. In: RINA International Symposium on Naval Submarines, Paper no. 19.
33. Mahesh, K., Kumar, P., Gnanaskandan, A., Nitzkorski, Z., 2015. LES applied to ship research. *J. Ship Research* 59(4), 238-245.
34. Manovski, P., Giacobello, M., Jacquemin, P., 2014. Smoke flow visualization and particle image velocimetry measurements over a generic submarine model. Australia Defence Science and Technology Organization, Technical Report DSTO-TR-2944.
35. Norrison, D., Sidebottom, W., Anderson, B., et al., 2016. Numerical study of a self-propelled conventional submarine. In: 31th Symposium on Naval Hydrodynamics (Monterey, California).
36. Norrison, D., Petterson, K., Sidebottom, W., 2017. Numerical study of propeller diameter effects for a self-propelled conventional submarine. In: 5th International Symposium on Marine Propulsors (Espoo, Finland).
37. Overpelt, B., Nienhuis, B., Anderson, B., 2015. Free running maneuvering model tests on a modern generic SSK Class submarine (BB2). In: Pacific International Maritime Conference (Sydney, Australia).
38. Powell A., 1964. Theory of vortex sound. *J. Acoustical society of America* 36(1), 177-195.
39. Smagorinsky, J., 1963. General circulation experiments with the primitive equations. I. the basic experiment. *Month. Wea. Rev.*, 91.
40. Toxopeus, S., Atsavapranee, P., Wolf, E., et al., 2012. Collaborative CFD exercise for submarine in a steady turn. In: ASME 31st International Conference on Ocean, Offshore and Arctic Engineering OMAE2012 (Rio de Janeiro, Brazil).
41. Wang X.M., Zhang N., 2022. Large eddy simulation of the flow field and hydrodynamic force of submarine in crashback. *J. Ship Mech.* 26(11), 1595-1610. (in Chinese)
42. Zhang, N., Shen H.C., Yao H.Z., 2010. Numerical simulation of cavity flow induced noise by LES and FW-H acoustic analogy. *J. Hydrodynamics* 22(5), 242-247.
43. Zhang, N., Lv S.J., Xie H., Zhang S.L., 2014. Numerical simulation of unsteady flow and flow induced sound of airfoil and wing/plate junction by LES and FW-H acoustic analogy. *Applied Mechanics and Materials* 444-445, 479-485.
44. Zhang, N., Wang X., Xie H., Li Y., 2016a. Research on numerical simulation approach for flow induced noise and the influence of the acoustic integral surface. *J. Ship Mech.* 20(7), 892-908. (in Chinese).
45. Zhang, N., Xie H., Wang X., Wu B.S., 2016b. Computation of vortical flow and flow induced noise by large eddy simulation with FW-H acoustic analogy and Powell vortex sound theory. *J. Hydrodynamics* 28(2), 255-266.
46. Zhang, N., Li Y., Huang M.M., Chen M., 2021. Numerical prediction approach for hydrodynamic force and noise of propeller in submarine propeller interaction condition. *J. Ship Mech.* 25(11), 1439-1451. (in Chinese)