**A dynamic maneuvering model for the Joubert BB2 submarine in calm water and waves**

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**Abstract**

Extensive computational fluid dynamics and experimental results for the Joubert BB2 notional submarine are used to create a reduce order model capable of reproducing several types of maneuvers with good fidelity and low computational cost. The model extends available kinematic models for underwater crafts to include model depth dependence and wave effects. A detailed description of the hydrodynamic modelling and the procedures to calculate its coefficients is included. Validation of the model against experimental and CFD results for canonical maneuvers, such as vertical and horizontal zigzags and turning circles, are also presented.

1. **Introduction**

Modeling of submarine maneuvers under environmental disturbances such as ocean currents and waves can be a very challenging problem (Fang et al. 2006, Fischer et al. 2014, Jin and Er 2020, Rober et al. 2021). When at periscope depth, the propulsion speed may be slowed down to the reverse speed (or dive plane reversal point, the speed point where the vertical force when actuating the stern planes changes sign, Papoulias and Riedel 1994), as the vehicle controllability is compromised by reduced control plane authority and inability to use the hull pitch to control depth (Dawson 2014). Littoral operations or maneuvers in restricted waters also force the vehicle to move slow (Newman 1977, Broglia et al. 2006, Nematollahi et al. 2015). Development of controllers and autopilots for underwater vehicles is typically done using reduced order models (ROM) for the dynamics of the craft which can provide a testbed to run simulations very fast at the cost of reduced accuracy. Free running experiments (Overpelt et al. 2015) or sophisticated computational fluid dynamics (CFD) simulations (Carrica et al. 2020) may also predict motions incorporating controllers and autopilots, but they are considerably more expensive and time consuming. Early development of control strategies and algorithms and subsequent initial tuning are typically performed using ROM, leaving experiments and CFD for fine tuning or to study controller performance under more complex effects not captured by simpler ROM approaches. In this paper we present a ROM model of the generic Joubert BB2 submarine (Overpelt et al. 2015), a publicly distributable geometry. A set of Simulink models including the ROM and controllers performing controlled vertical zigzag (VZZ), horizontal zigzag (HZZ), and turning circle (TC) maneuvers in calm water and waves, including tutorials, are released as accompanying material through GitHub to ease use of the ROM by the community of underwater control developers.

The ROM solves the rigid body equations of motion of the vehicle under inertial and external forces. The external forces in a submarine include the hydrostatic and hydrodynamic forces. Hydrostatic forces lump together the forces exerted by the hydrostatic pressure due to gravity and the time-varying pressure field created by external ocean waves. While the wave pressure force is dynamic, it is considered independent from the state of the vehicle and thus only a function of time and space, allowing grouping with the hydrostatic force. The hydrodynamic forces occur due to the state of motion of the vessel, in the form of virtual mass, pressure drag, and skin friction. More accurate prediction of the hydrodynamic loadings requires forces under wider motion conditions, requiring large number of coefficients to calibrate. In order to optimize calibration of the model, the order of the forces is reduced using mathematical methods such as least square techniques (Go and Ahn 2019). The most frequently used form of hydrodynamic model (HDM) for cruciform stern plane configuration was proposed by Gertler and Hagen (1967). Feldman (1987) suggested an update to the model with cross-flow effects, but the original model is typically preferred by the community due to its simplicity. In this HDM only forces and moments due to certain motions are considered and the history of motions is neglected. The coefficients or derivatives required by the model are evaluated from experiments, semi-empirical approaches, or computational methods.

Experimental methods are the most conventional technique to obtain the coefficients by performing captive model tests using scaled models. Towing with or without Planar Motion Mechanisms (PMM) and Rotating Arms (RA) are used to isolate the desired coefficients. Good examples of captive model tests are presented by Feldman (1987, 1995). Wind tunnel tests may replace towing tank experiments if the free surface is ignored, with different model scales for water and air (Park et al. 2017). The validation of HDM can be done experimentally by performing free running controlled maneuvers in model scale in a wave basin (Overpelt et al. 2015). Experimental techniques provide reliable data but require expensive facilities and construction of a model. In addition, experiments are limited to model scale and extrapolation to full scale can be difficult (ITTC 2008).

The semi empirical method assumes that the vehicle is composed of several sub-bodies and uses empirical correlations to obtain forces and moments. The method is only valid for small drift angles, but predictions are reasonably good when the maneuvering conditions are mild (Philips et al. 2010).

Computational techniques may use potential flow or CFD solvers. Potential flow solvers are cost-effective tools to estimate the pressure effects (including virtual mass) with reasonable accuracy (Watt 2007). However, the method does not have viscous terms, therefore predictions at large angles of attack is poor (Evans 2004). Early attempts to use CFD to compute coefficients used relatively simple geometries or very coarse grids to make the problem affordable (Cura-Hochbaum et al. 2006, Tyagi and Sen 2006). In many cases unsteady techniques such as PMM are replaced by static conditions to alleviate demanding computational resources (Wang et al. 2014). As massive computing power became accessible, virtual unsteady model simulations have been conducted (Zhang et al. 2010, Pan et al. 2012 & 2019). Model scale simulations of VZZ and TC maneuvers of the Joubert BB2 submarine using a dynamic overset approach including the rotating propellers and moving planes were performed by Carrica et al. (2020), showing excellent agreement with experiments. Full and model scale simulations of the same geometry for VZZ maneuvers also show good agreement with model scale experiments and support the general assumption that, at least at moderate and high speed, model scale experiments can be used to predict performance of full-scale maneuvers (Carrica et al. 2021). CFD studies of turning circle maneuvers in calm water and in waves have also been performed (Carrica et al. 2019). The success in predicting maneuvers with CFD lends credibility to the use of CFD to obtain the coefficients of ROM, but development of accurate ROM simulation models is a significant challenge as the operational conditions deviate from those used to obtain the coefficients, as shown by the blind workshops on maneuvering simulation of surface ships where ROM techniques were compared against experiments for various maneuvers (SIMMAN 2008, SIMMAN 2014).

In most studies using ROMs the model formulations were limited to deep conditions, were effects of depth or waves can be neglected (Wang et al. 2020, Cho et al. 2020). In this study the coefficients are evaluated by steady and unsteady CFD simulations as a function of depth and speed, including values below the reverse speed. The wave induced virtual mass and pressure forces are modeled for regular waves of amplitude and wavelength equivalent to significant wave heights and most probable periods of sea states 2 to 7, enabling performance of HDM simulations under environmental disturbances. The free running 6-Degree-of-Freedom (6-DoF) simulations are performed using MatlabTM SimulinkTM and the results are validated against self-propulsion in waves, and VZZ, HZZ, and TC maneuvers in calm water and waves from experiments performed at MARIN (Overpelt et al. 2015) and CFD simulations. The Simulink model along with tutorials and inputs for the validation cases presented in this paper can be found in https://github.com/caslabuiowa/IowaBB2model.

1. **Geometry, controller and CFD details**
   1. **Geometry**

The Joubert BB2 is a redesign of the generic design submarine BB1, originally proposed by P. N. Joubert (2006 and 2008) and updated by MARIN in the Netherlands (Overpelt et al. 2015). The main particulars and geometry are summarized in Table 1 and Fig. 1, and the sign convention is shown in Fig. 2. Overpelt et al. (2015) redesigned the sail and the sail and stern planes and performed free running maneuvers in MARIN’s wave basin.

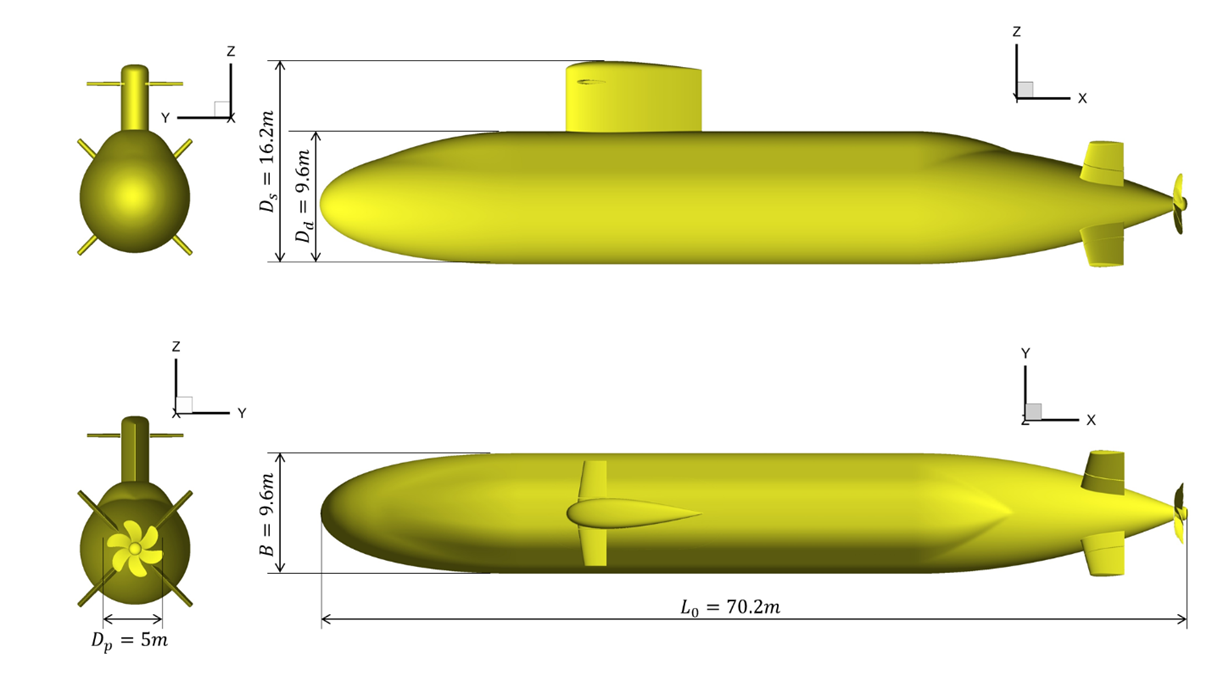


Figure 1. Geometry of the generic submarine Joubert BB2.

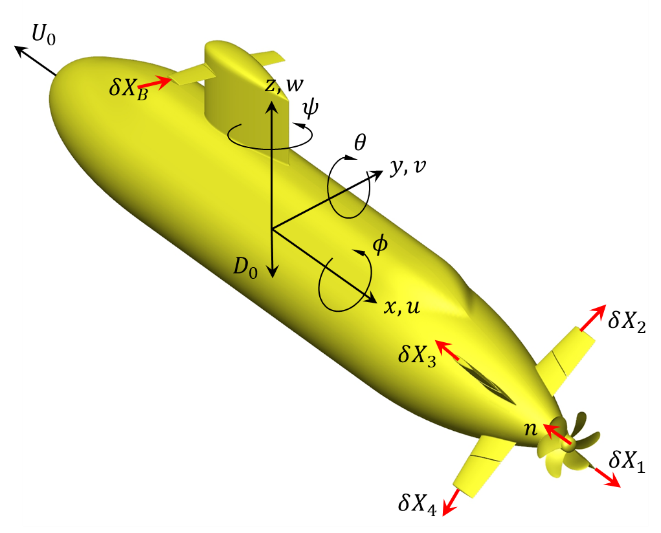


Figure 2. Local coordinate system and appendage axes of rotation.

Table 1. Main Particulars of Joubert BB2.

|  |  |  |  |
| --- | --- | --- | --- |
| **Description** | **Symbol** | **Magnitude** | |
| **Full** | **Model** |
| Length |  | 70.2 | 3.8260 |
| Beam |  | 9.6 | 0.5232 |
| Depth to deck |  | 10.6 | 0.5777 |
| Depth to top of sail |  | 16.2 | 0.8829 |
| Propeller diameter |  | 5 | 0.273 |
| Displacement |  | 4440 | 0.7012 |
| Longitudinal Center of Gravity (from nose) |  | 32.31 | 1.761 |
| Vertical Center of Gravity (from shaft) |  | 0.0443 | 0.0024 |
| Roll radius of gyration |  | 3.433 | 0.1871 |
| Pitch radius of gyration |  | 17.6 | 0.9592 |
| Yaw radius of gyration |  | 17.522 | 0.955 |

* 1. **Computational Grid and Conditions**

A coarse structured computational grid of approximately 4.45M points (see Table 2) is used the simulations performed to obtain the ROM coefficients as discussed in §5. The propeller thrust and torque are incorporated using an actuator disc model (Hough and Ordway 1965). For the grid system used for free running CFD simulations discussed in §6 and the corresponding convergence study see Carrica et al. (2019) and Kim et al (2020). Coarse grids provide good estimations of forces and moments, with differences limited to less than 5% compared to a very fine grid in the case of self-propulsion of Joubert BB2 near the surface (Carrica et al. 2019), and within the same differences for a VZZ maneuver at depth on the same geometry (Carrica et al. 2021). Though desirable, use of fine grids would make the computation of the model coefficients very expensive, but will not necessarily improve the final model significantly since most errors in the performance of the ROM model are caused by approximations used in the development of the model.

Table 2. Grid system for captive model simulations.

|  |  |  |
| --- | --- | --- |
| **Grid** | | **Points (M)** |
| Hull, Sail, Plane Roots | | 1.47 |
| Sail Planes | | 0.33 |
| Stern Planes | | 0.46 |
| Refinements | Hull | 0.49 |
| Propeller | 0.49 |
| Free Surface | 0.49 |
| Background | | 0.73 |
| **Total** | | 4.45 |

* 1. **Numerical Approach**

The simulations are performed using the general-purpose naval hydrodynamics solver REX. REX is a hybrid RANS/LES solver based on the SST turbulence model (Menter 1994) with overset capabilities. A single phase level set approach is used to model free surface (Carrica et al. 2007a), and a dynamic overset technique is used for large amplitude motions (Carrica et al. 2007b). The overset domain connectivity information is computed using Suggar++ (Noack et al. 2009). A hierarchy of moving bodies enables computation of 6 Degree of Freedom (6DoF) rigid body motions with moving appendages and/or discretized propulsors. Other capabilities include environmental forces like regular and irregular waves, and a variety of controllers. For more details on the numerical techniques used in REX readers are referred to Carrica et al. (2020) are references therein.

* 1. **Controller**

A set of Proportional-Integral-Derivative (PID) controllers are implemented to control speed, vertical and horizontal motions, ballast and trim tanks. The propeller rotational speed is controlled as

|  |  |
| --- | --- |
|  | (1) |

where are the proportional, integral and derivative gains of the linear speed controller, respectively. The vertical and horizontal commands for the control surfaces are defined as

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |

The vertical and horizontal command angles determine the deflection angle of the sail planes ( and stern planes ( the lower starboard plane, upper starboard, upper port, lower port),

|  |  |
| --- | --- |
|  | (4) |

While there are no limitations in the values of and , the deflection of the sail and stern planes have saturation angles at , with the maximum deflection rate limited at . The depth of the vehicle can also be controlled using a ballast tank PID controller as

|  |  |
| --- | --- |
|  | (5) |

and the pitch angle can additionally be controlled using trim tanks that change the longitudinal location of the center of gravity LCG,

|  |  |
| --- | --- |
|  | (6) |

The ballast tanks and change in LCG saturate at and , respectively. The ballast tanks can pump water in and out with a maximum rate of , and the trim tanks can move the at a maximum speed of .

1. **Rigid body model**

The rigid body motions are obtained from Newton’s second law as

|  |  |
| --- | --- |
|  | (7) |

where the mass matrix and the velocity state vector are

|  |  |
| --- | --- |
|  | (8) |
|  | (9) |

The external load vector in the right-hand side of Eq. (7) contains the hydrodynamic and hydrostatic loadings,

|  |  |
| --- | --- |
|  | (10) |

The gravity and hydrostatic forces provide restoring moments that arise with angular displacement of the submerged body. The hydrodynamic loadings include hull drift forces, control surface forces, and propulsor thrust and side forces as discussed in §5.1. The inertial coupling vector in Eq. (7) is computed as

|  |  |
| --- | --- |
|  | (11) |

1. **Hydrostatic forces**

The hydrostatic loading is computed integrating the hydrostatic pressure over a surface grid of the submarine consisting of triangular elements as shown in Fig. 3, including motions of the appendages. The hydrostatic force is computed with second order accuracy from

|  |  |
| --- | --- |
|  | (12) |

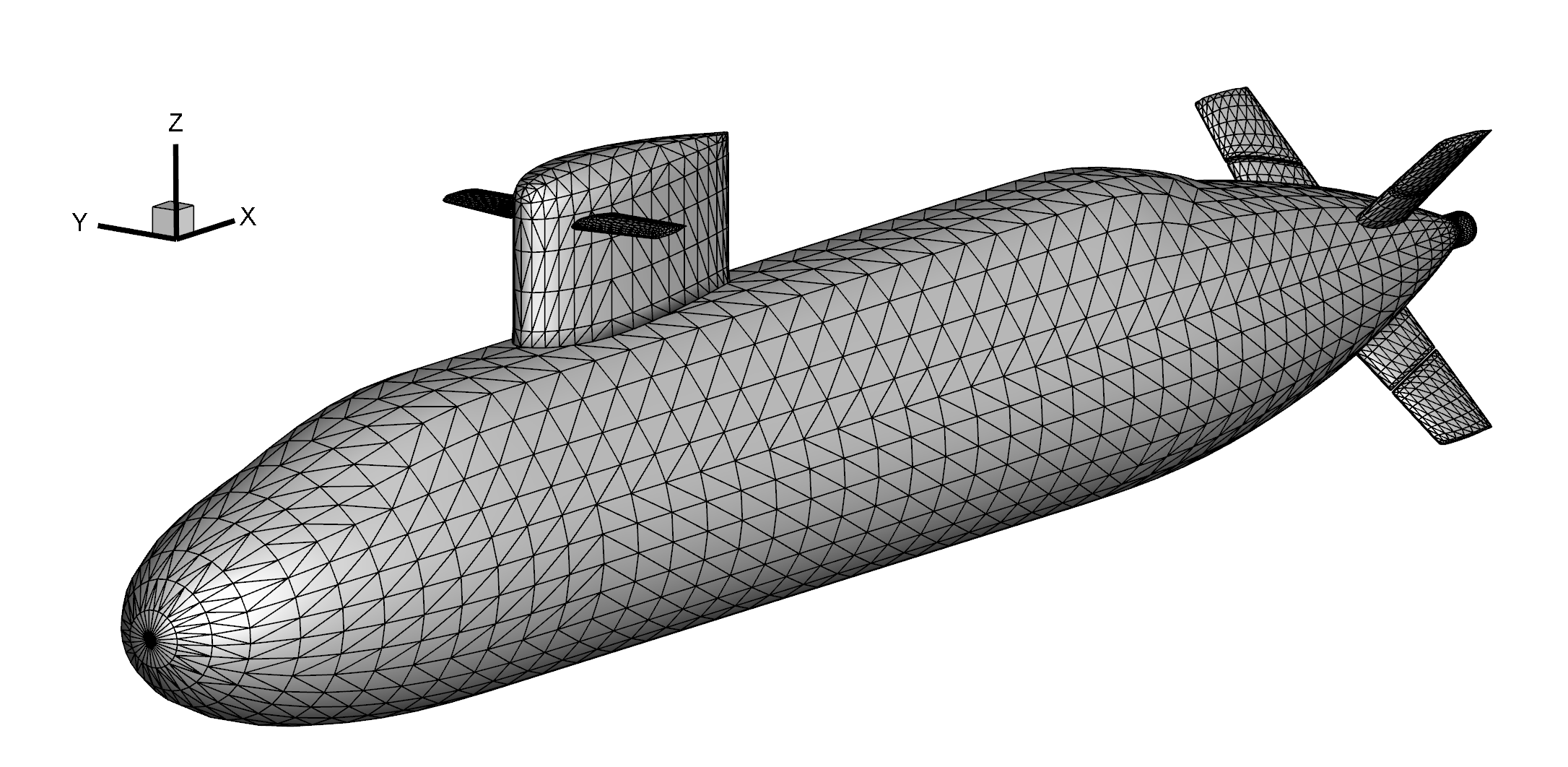


Figure 3. Triangulated surface grid used for hydrostatic load computations.

The buoyancy of a neutrally buoyant submerged body is equal to its weight. Therefore, the resultant force in -direction from the integration in the Eq. (12) must be identical to the initial weight of the submarine. The forces and moments due to the buoyancy are included in the external load vector in the Eq. (10). The hydrostatic forces in the earth system do not change as long as the submarine remains incompressible and fully submerged. The weight can change by operation of the ballast tanks. The moment due to buoyancy is computed as.

|  |  |
| --- | --- |
|  | (13) |

In this model surface waves are considered as a one-way coupled mechanism that produces forces in the submarine due to the wave-induced pressure field and by virtual mass. The wave-induced pressure can thus be integrated over the submarine surface in the same way as the hydrostatic pressure to yield the wave-induced load. The total pressure field under a progressive regular wave in deep water is

|  |  |
| --- | --- |
|  | (14) |

where is the wave number, is the wave frequency in , is the amplitude and is the vertical distance to the calm water level.

1. **Hydrodynamic forces**
   1. **Reduced order model of Submarine with X-shape stern plane arrangement**

The hydrodynamic loadings and in Eq. (10) can be approximated as functions of current states of motion, neglecting time-history effects. The hydrodynamic term in each degree of freedom has in principle an infinite number of terms when expanded using power series, so the series is truncated to remove high order terms with small contribution. The most widely used is the model proposed by Gertler and Hagen 1967. Gertler and Hagen’s model is modified for BB2 since, unlike the cruciform stern plane configuration, each stern plane in an X-shape arrangement has significantly different vertical and horizontal load contribution. The hydrodynamic loads are

|  |  |
| --- | --- |
|  | (15) |
|  | (16) |
|  | (17) |
|  | (18) |
|  | (19) |
|  | (20) |

Each term in the hydrodynamic model represents the contribution from certain motion. For simplicity, most models have constant coefficients or derivatives. In this study the coefficients are interpolated from tabulated values determined as functions of depth and speed to account for effects of the free surface and Reynolds number.

* 1. **Hydrodynamic Coefficients**

In order to obtain coefficients for the hydrodynamic model, sets of simple CFD simulations were performed. For each simulation, the submarine motions were imposed and run until a pseudo-steady state was achieved.

* + 1. **Hull Drift Coefficients**

The forces and moments during submarine maneuvers depend heavily on the hull drift. The forces and moments on the hull and sail allow maneuvering in the desired direction, while forces and moments on the control surfaces produce the change and attitude and may help or oppose the intended motion.

The hull drift forces and moments are obtained from constant speed simulations by changing static pitch and yaw at sail top depths and and towing speeds and . The coefficients are expressed as functions of the vertical and horizontal drift angles and , and the total velocity . The coefficients are computed for with interval of . For horizontal drift the coefficients are calculated for , due to symmetry. The forces and moments are evaluated integrating contributions from the hull, sail, and the sail and stern plane roots.

The coefficients , , and as a function of and speed for and are shown in Fig. 4. While vertical force and pitch moment change linearly with the drift angle, the resistance decreases for both positive and negative drift until , increasing for possibly due to the increased proximity of the nose to the free surface. The presence of the sail structure makes the geometry significantly asymmetric, but no significant vertical drift angle effects were observed for vertical force and pitch moment. The coefficients , , , and are shown in Fig. 5 for with . the results show that the resistance decreases, and the magnitude of the lateral force and roll and yaw moments increase linearly with the horizontal drift angle.

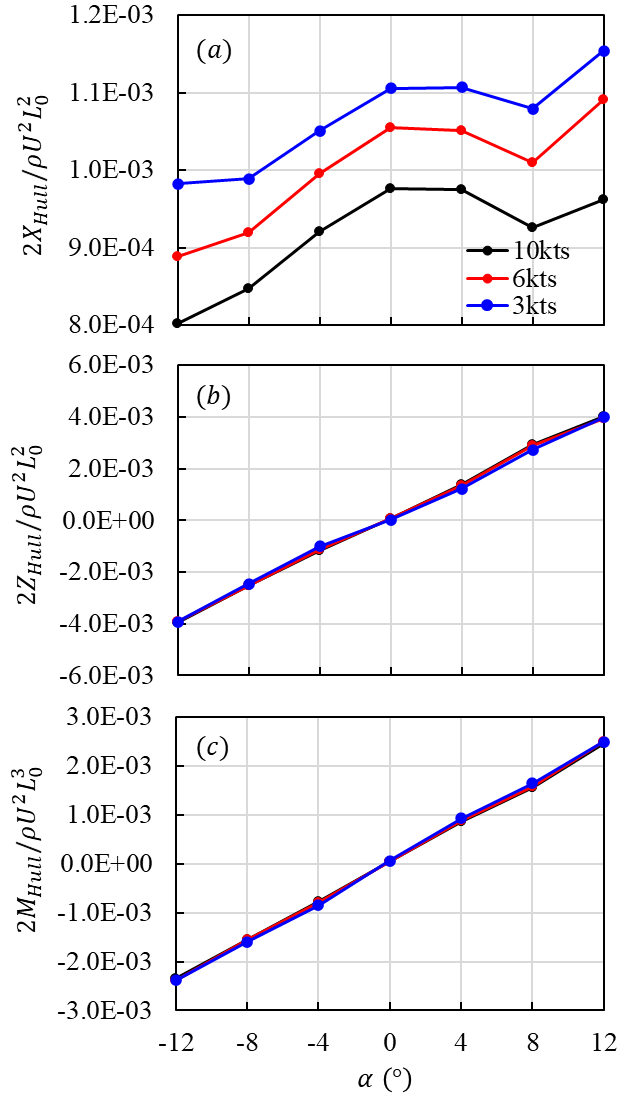


Figure 4. Coefficients for (a) resistance , (b) vertical force , and (c) pitch moment at as a function of the vertical drift angle.

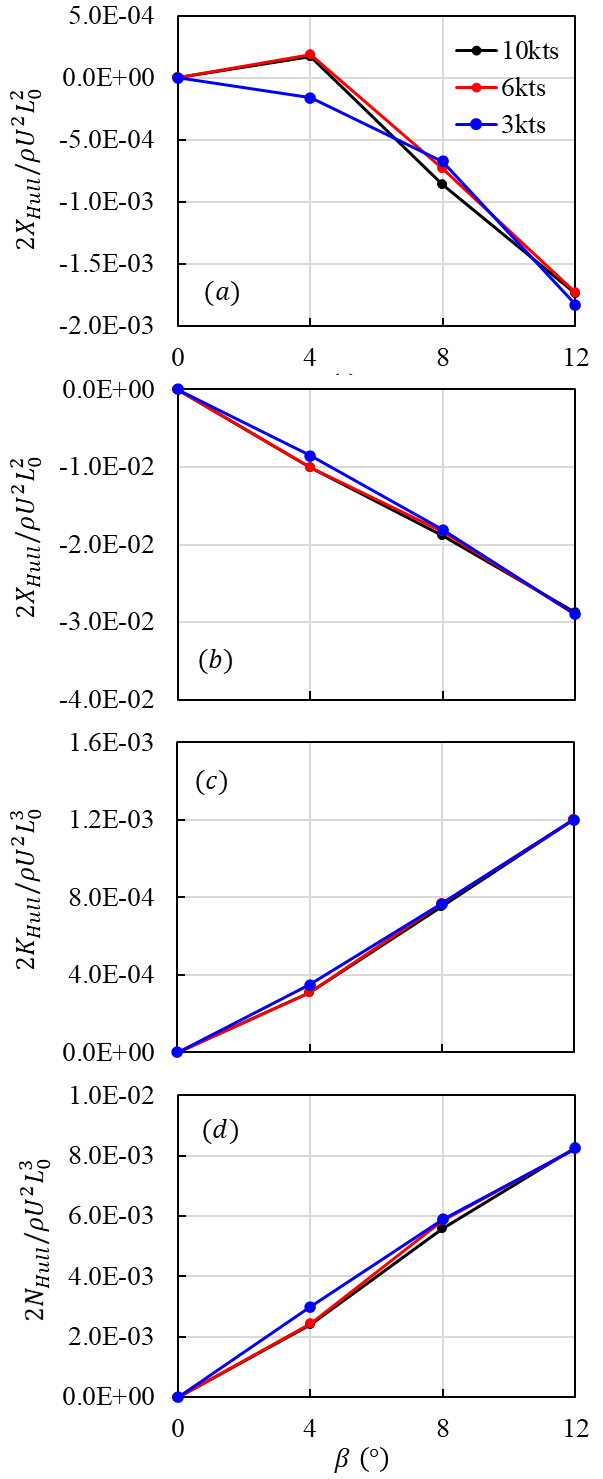


Figure 5. Coefficients for (a) resistance , (b) lateral force , (c) roll moment , and (d) yaw moment at as a function of the horizontal drift angle.

* + 1. **Propeller Thrust and Thrust Deduction**

The thrust and torque coefficients and and corresponding thrust and torque are obtained from the open water performance curves for MARIN propeller 7371R and shown in Fig. 6 as function of the advance coefficient . and are approximated as second order polynomials. Since the propeller rotates clockwise and the axis is toward stern in the local coordinate system, the propeller produces positive roll moment.

A thrust deduction factor was computed and shown in Fig. 7, evaluated from even-keel self-propulsion CFD simulations at and at approach speeds and . increases with approach speed for , but decreases near the surface particularly at , as the free surface suctions reduces the relative importance of the suction effect of the propeller.

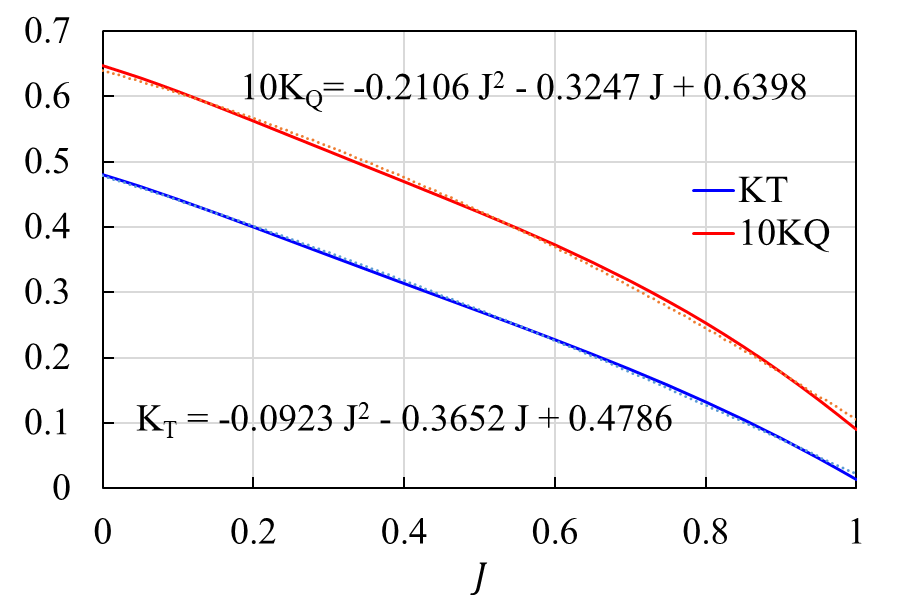


Figure 6. Open water thrust and torque coefficients and for MARIN propeller 7371R.

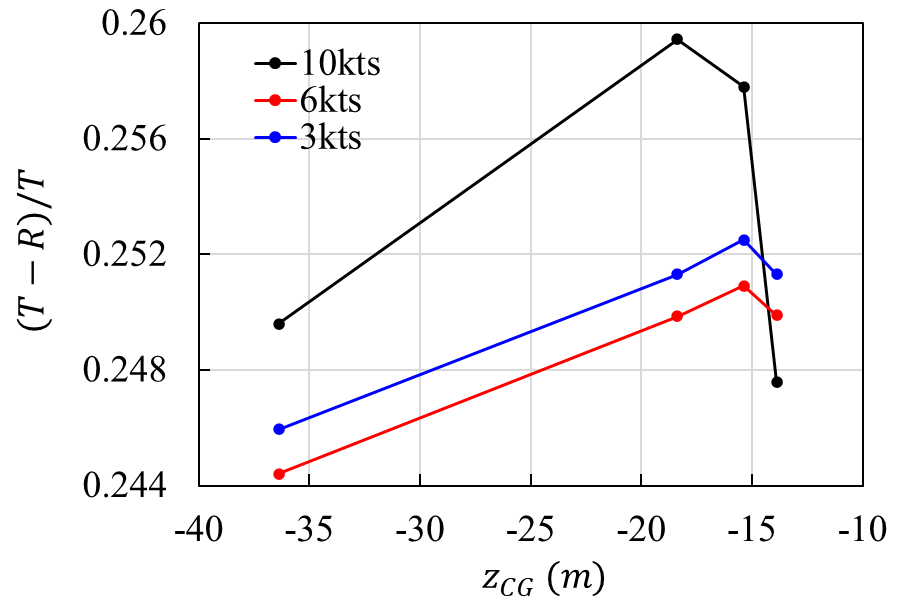


Figure 7. Thrust deduction at and and and .

* + 1. **Virtual Mass**

The virtual mass occurs as the acceleration of a submerged object accelerates the fluid around it, yielding the virtual mass force that can be considered additional inertia. The forces and moments due to virtual mass always oppose the direction of acceleration and provide significant damping. The virtual mass coefficients are evaluated from forces on 15 different surface sub-sections as shown in Fig. 8.

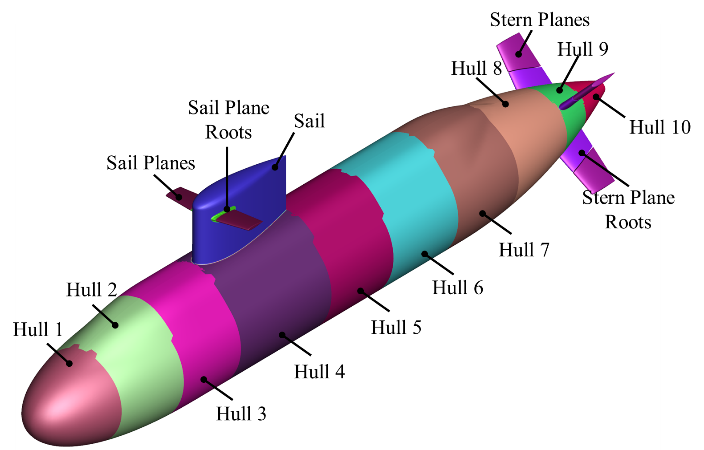


Figure 8. Hull surface sections for computation of virtual mass coefficients.

The overall virtual mass force is computed from the sectional coefficients as follows.

|  |  |  |
| --- | --- | --- |
|  |  | (21) |

The moment due to virtual mass can be computed without introducing additional sets of coefficients for angular acceleration, using the position vector to the volumetric center of each section as

|  |  |
| --- | --- |
|  | (22) |

In order to obtain the virtual mass coefficients, motions with constant accelerations of in direction, and in and directions are imposed. The virtual mass coefficients obtained for each section in Fig. 8 are listed in Table 4.

* + 1. **Control Surface Forces and Moments**

The control surface performance was evaluated from even-keel constant speed CFD simulations, by imposing static deflection angles within in intervals of The ranges for speed and the sail top depth are the same as for the hull drift coefficients in §5.2.1.

Figures 9 and 10 show control surface forces and moments at for the sail plane and the lower starboard stern plane, respectively. The sail and stern planes resistance increase non-linearly with the appendage deflection, while vertical and side forces and moments saturate as the fins stall at large angles of attack (). The asymmetry of the sailplane location in the sail results in higher resistance when producing negative lift, as well as higher positive pitch moment.

Table 4. Virtual mass coefficients different sections.

|  |  |  |  |
| --- | --- | --- | --- |
| **Section** |  |  |  |
| Hull 1 | 8.47E+04 | 1.72E+05 | 1.65E+05 |
| Hull 2 | 2.36E+04 | 4.34E+05 | 3.62E+05 |
| Hull 3 | 1.16E+03 | 5.98E+05 | 4.30E+05 |
| Hull 4 | 1.41E+02 | 1.14E+06 | 6.56E+05 |
| Hull 5 | 9.15E+01 | 6.97E+05 | 5.17E+05 |
| Hull 6 | 9.61E+01 | 6.72E+05 | 5.19E+05 |
| Hull 7 | 1.22E+04 | 5.78E+05 | 4.75E+05 |
| Hull 8 | 3.72E+04 | 3.47E+05 | 3.35E+05 |
| Hull 9 | 1.93E+04 | 7.73E+04 | 7.66E+04 |
| Hull 10 | 1.54E+04 | 2.64E+04 | 2.63E+04 |
| Sail | 1.83E+04 | 4.59E+05 | 5.11E+04 |
| Sail Plane Roots | 3.19E+02 | 1.26E+04 | 3.49E+02 |
| Stern Plane Roots | 3.03E+03 | 4.49E+04 | 4.45E+04 |
| Sail Planes | 7.92E+02 | 8.90E+02 | 1.33E+04 |
| Stern Planes | 1.21E+03 | 3.95E+04 | 3.92E+04 |
|  | 0.05 | 1.15 | 0.81 |

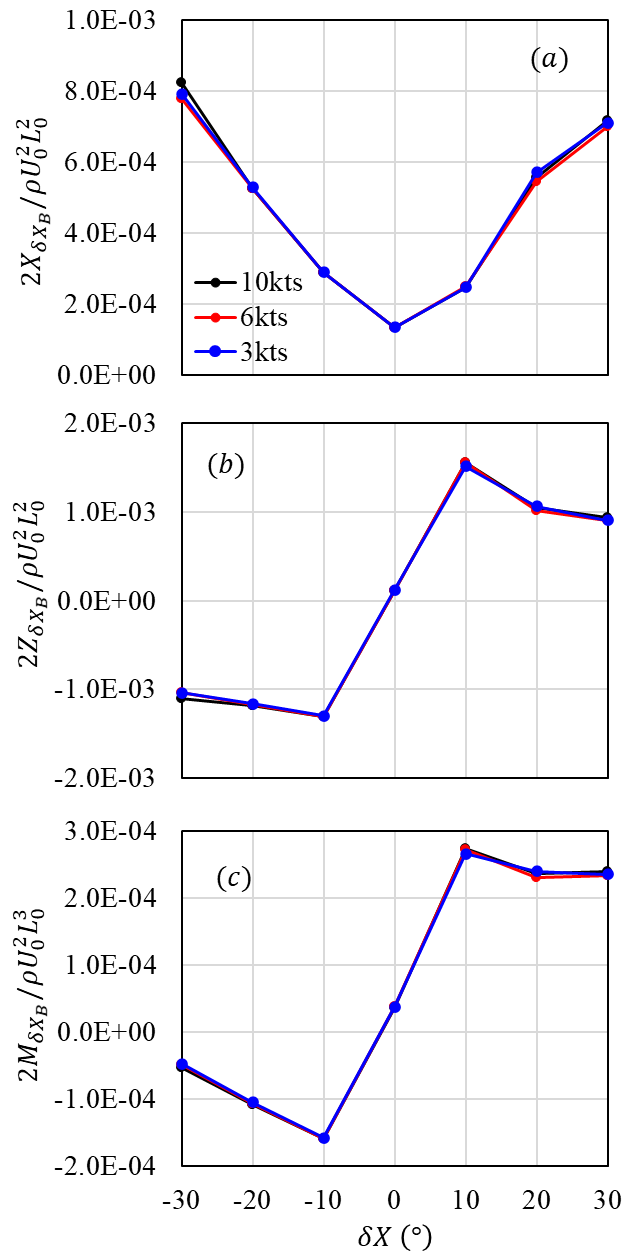


Figure 9. Sail plane coefficients of (a) resistance, (b) vertical force and (c) pitch moment for deflections , at and and .

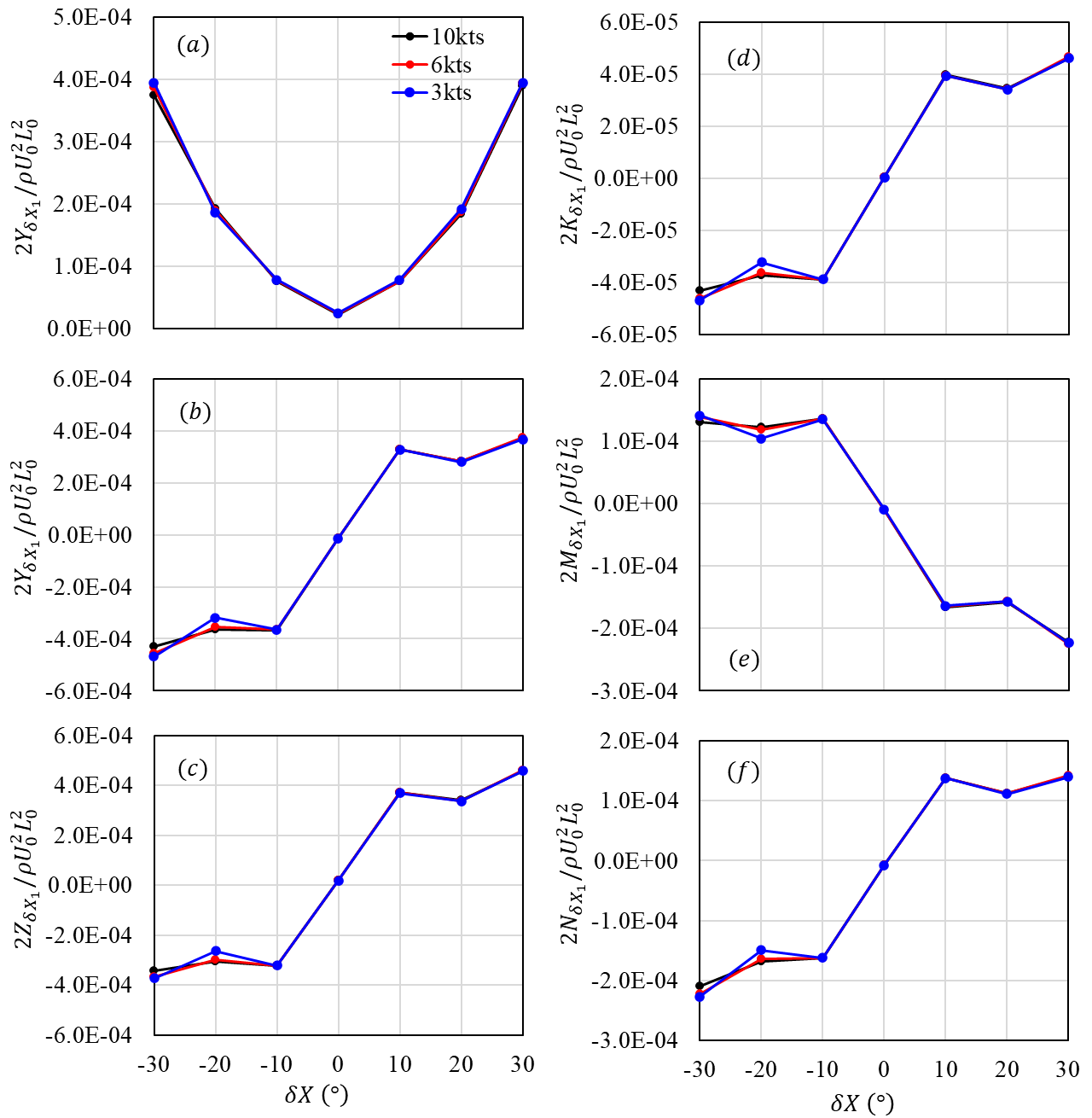


Figure 10. Lower starboard stern plane coefficients of (a) resistance, (b) lateral force, (c) vertical force, (d) roll moment, (e) pitch moment and (f) yaw moment for deflections , at and and .

* + 1. **Forces and Moments due to Angular Rates**

Pure rotation simulations were performed to evaluate the forces and moments generated due to angular velocity about the , as shown in the schematic in Fig. 11. The hydrodynamic coefficients , , …, , and can be obtained from these CFD computations. Pure yaw simulations were not performed, and the corresponding hydrodynamic coefficients were obtained from the RA simulations in the -plane presented in §5.2.6. Moments about the axis of rotation always oppose motion, providing significant damping. The off-axis moments and linear forces are also of interest.

The results of the pure roll simulations are shown in Fig. 11. Positive roll induces forces that push the submarine to starboard and up, see Fig. 11 (a). The induced force in the longitudinal direction is smaller, positive for small roll rates and changing to forward thrust for higher roll rates. Fig. 11 (b) shows that the yaw moment is negative for positive , implying that roll to port causes yaw to starboard, as expected because the sail is located forward of the The pitch moment is positive, caused by the sail-induced vertical force and its location forward of the .

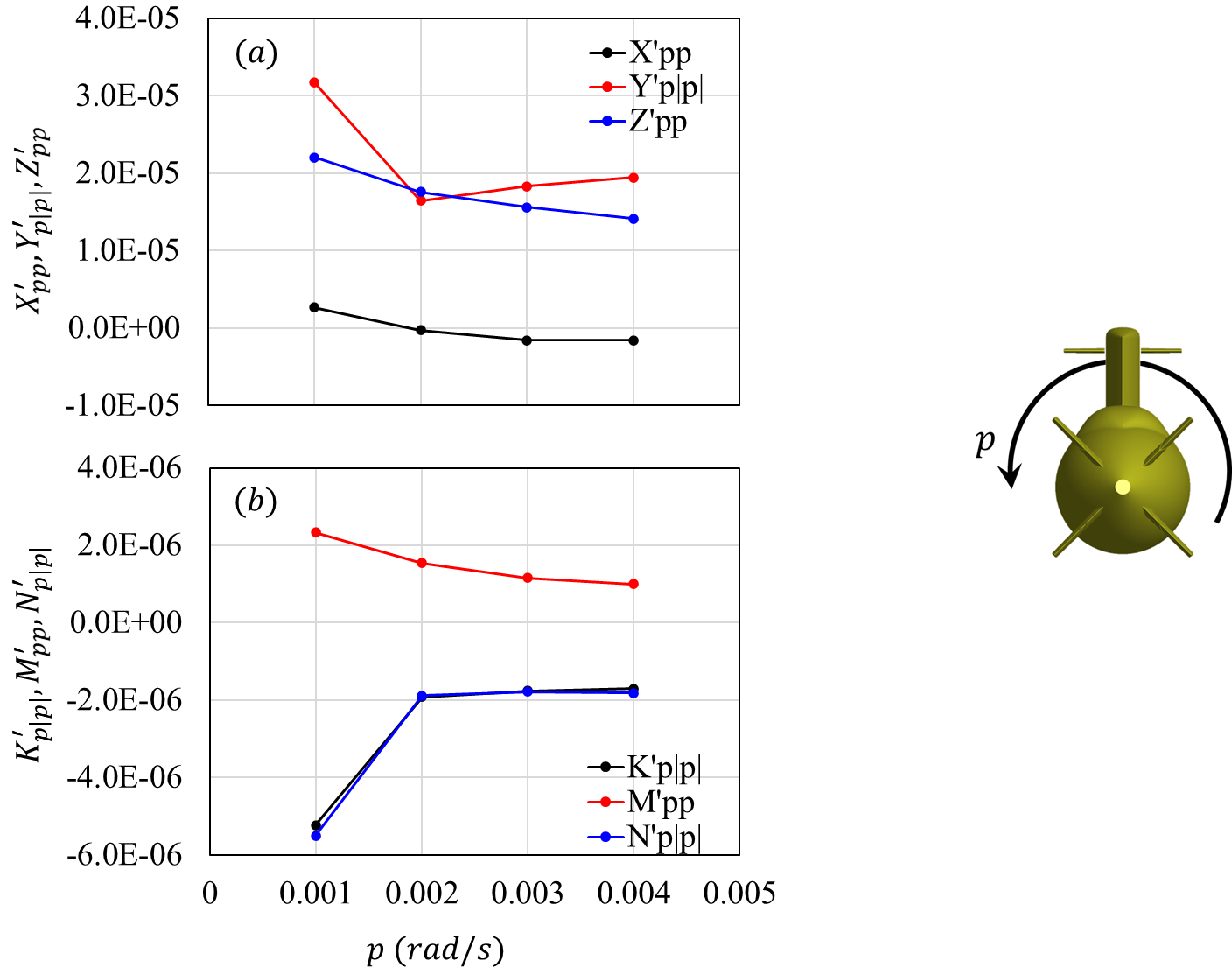


Figure 11. Pure roll induced forces (a) and moments (b).

Figure 12 shows that the axial force and pitch moment always oppose the sign of , effectively providing a small propulsion. The coefficients are considerably larger at low pitch rates. The vertical force is negative for positive pitch rate at low , but the trend reverses beyond .

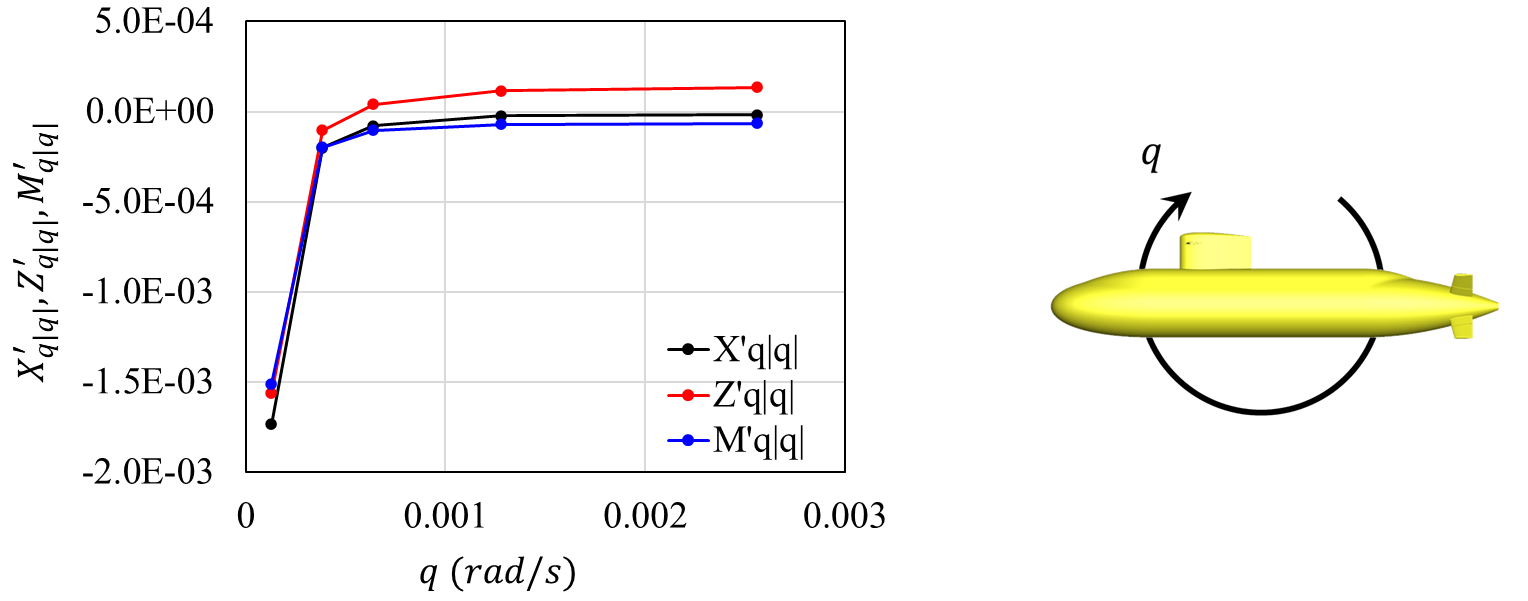


Figure 12. Pure pitch induced resistance , vertical force , and pitch moment .

* + 1. **Forces and Moments Due to Coupled Linear/Angular Velocities**

The hydrodynamic coefficients , , …, , and are obtained from RA simulations. The coefficients represent the hydrodynamic loads arising from a vehicle rotating about a pivot point away from its .

Figures 13, 14 and 15 show examples of the coefficients of forces and moments obtained from the simulations in the corresponding planes. The results from RA simulations in the plane are shown in Fig. 13, indicating that vertical force and pitch moment oppose the direction of for forward surge velocity, while an increase in resistance is observed for positive *q*. The negative vertical force coefficient shown in Fig. 13 (b) indicates that both positive or negative vertical velocity or pitch rate, resulting in positive , result in downward vertical force. The opposite occurs with the pitch moment, which is positive at moderate .

RA simulation results in plane are shown in Fig. 14. As for RA simulations of , only forward surge is considered. Since the presence of sail breaks the symmetry, vertical force, roll and pitch moment arise from are also under consideration. Positive hydrodynamic coefficients for lateral force in Fig. 14 (a) indicate that a positive lateral force develops for positive yaw rate. Resistance and vertical force induced by are always positive. The roll and yaw moments due to have negative hydrodynamic coefficients (Fig. 14 b), indicating that the roll and yaw moments to starboard when the yaw rate points to port. RA simulations in plane in Fig. 15 are only performed for . The symmetry about the center plane results in , and independent to the sign of , hence shown as , and as in Fig. 15 (a). On the other hand, the sway force and roll and yaw moments are dominated by the sail as in the pure rotation simulation results in plane discussed in §5.2.5. Therefore, the corresponding hydrodynamic coefficients , and in Fig. 15 (b) are expressed as , and .

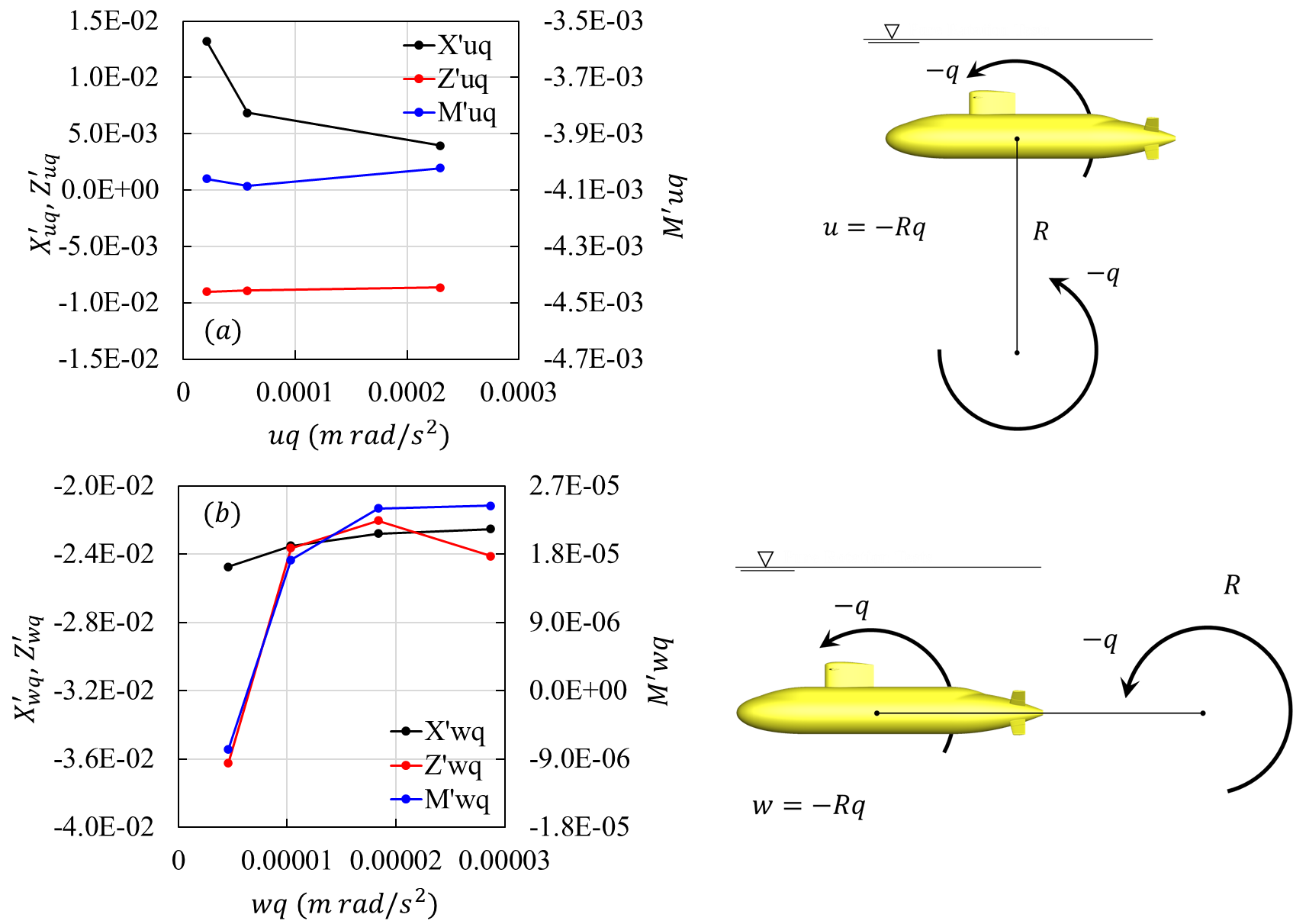


Figure 13. Hydrodynamic forces (a) and moments (b) from RA simulations in the plane.

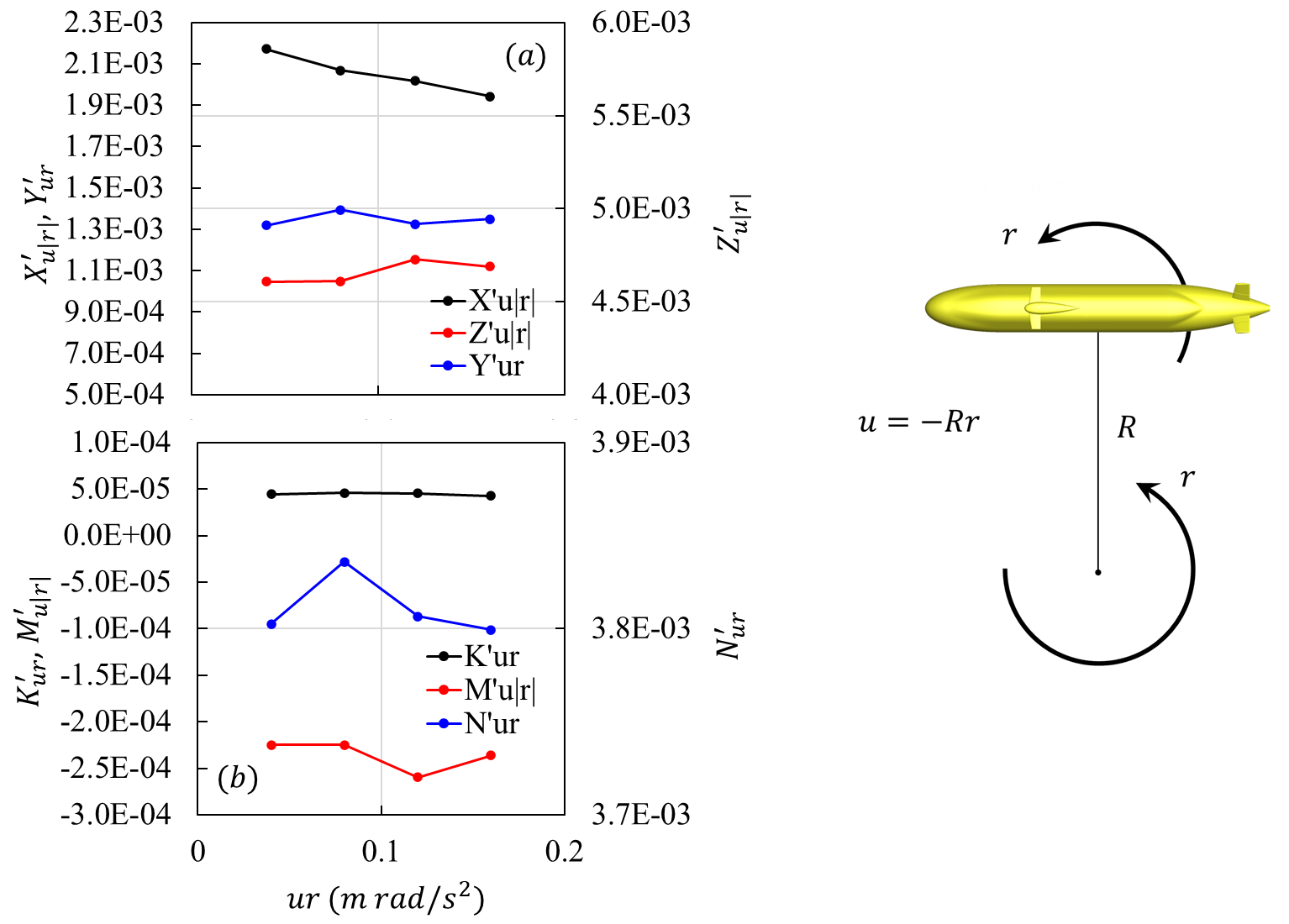


Figure 14. Hydrodynamic forces (a) and moments (b) from RA simulations in the plane.

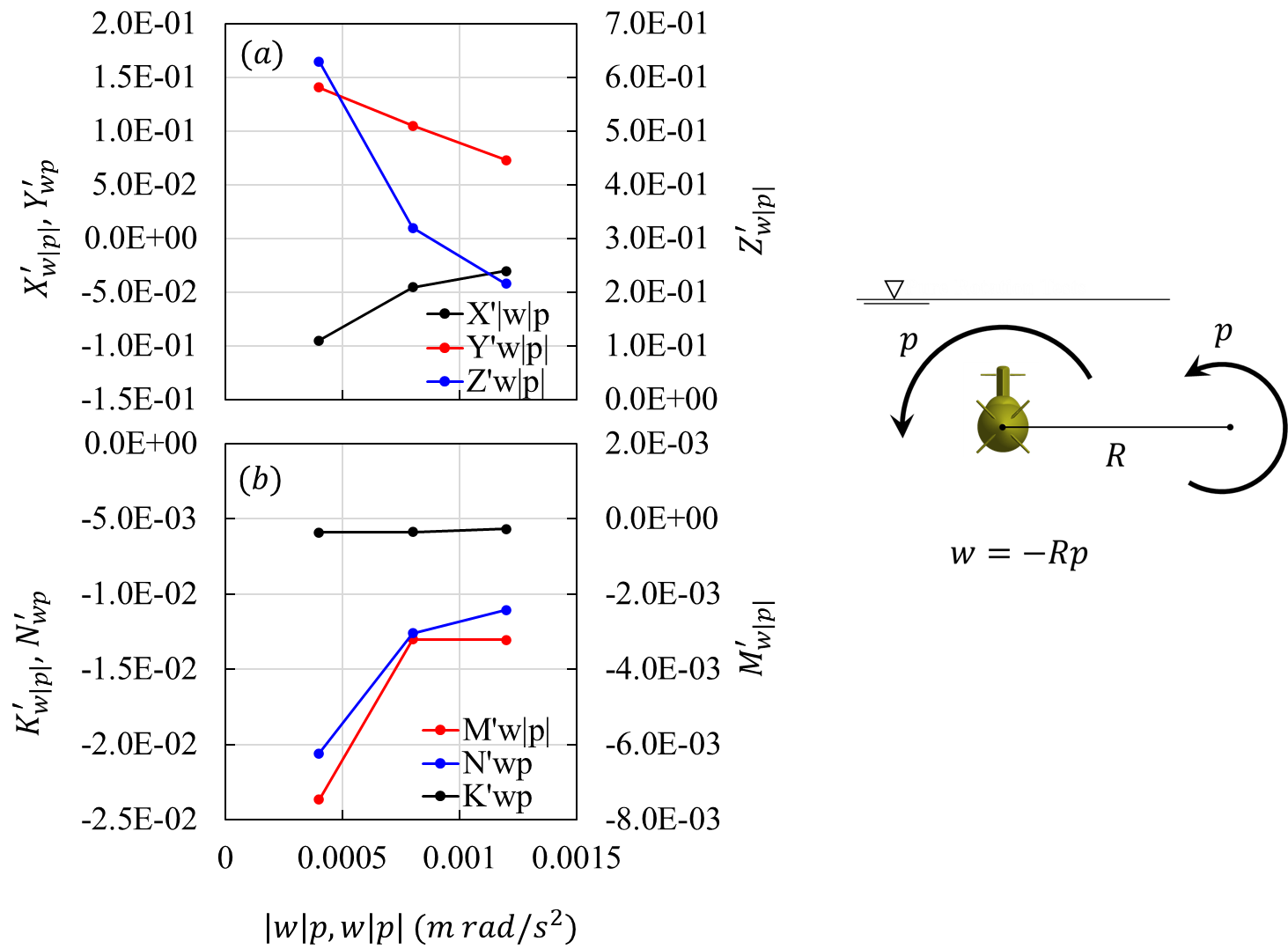


Figure 15. Hydrodynamic forces (a) and moments (b) from RA simulations in the plane.

* + 1. **Propeller Side Forces and Moments**

A screw propeller attached to the hull generates side forces and moments affected by the inflow deviation from uniformity and incidence angle. The side forces and moments are modeled as a function coupled translational/angular velocities, from zigzag CFD simulations at different boat speeds . See Carrica et al. (2020, 2021) for the details of the simulations.

The hydrodynamic coefficients , , and always oppose the motions, therefore acting as counteracting forces and moments slowing down the maneuver. The load magnitudes are in the same order as those produced by a stern plane, yielding significant damping to motions. The propeller side forces and moments including thrust are modeled as incidence parameter and . As an example, the propeller pitch moment modeled from VZZ simulations at three speeds is shown in Fig. 16. The dimensionless coefficients are proportional to , with larger slope for lower speed. Considering that the when the vessel moves forward, the pitch moment from the propeller opposes the pitching motion.

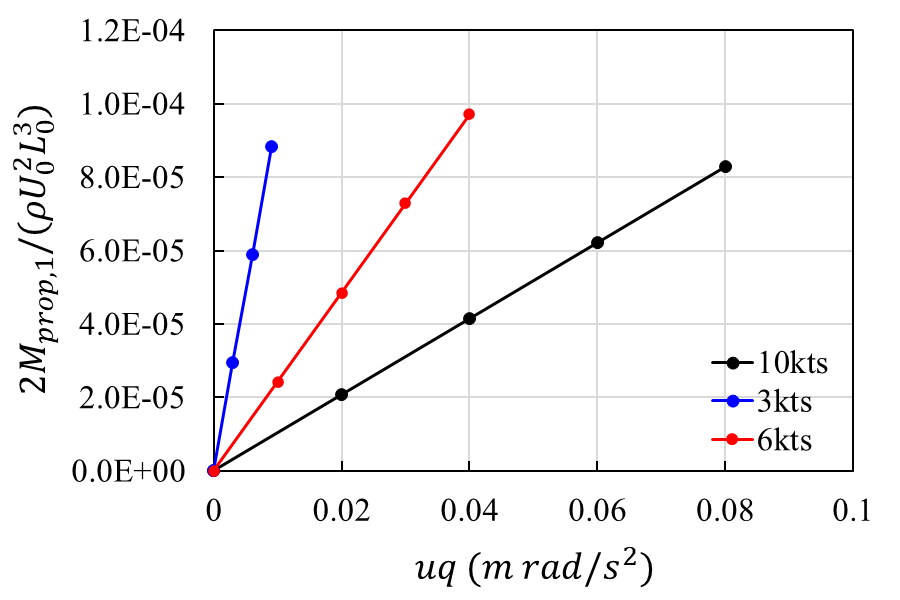


Figure 16. Propeller pitch moment as function of incidence parameter .

1. **Validation Study**
   1. **Free Roll Decay**

A submarine rotating about its longitudinal axis is subject to a restoring moment due to weight and buoyancy. The moment increases with the roll angle and the distance between the center of buoyancy and the center of gravity . A roll decay is observed when the submarine is released from a static roll angular displacement as viscous drag absorbs the initial energy.

An HDM simulation was performed with an initial roll angle of and compared against experiments (Overpelt et al. 2015). The results presented in Fig. 17 show that the predicted roll decay follows the experiment for the initial 3~4 periods and then the errors accumulate, while the period is slightly overpredicted by HDM. The errors can be attributed to the scale difference, since experiments are performed at model scale with a scale ratio of approximately , resulting in larger friction and faster decay.

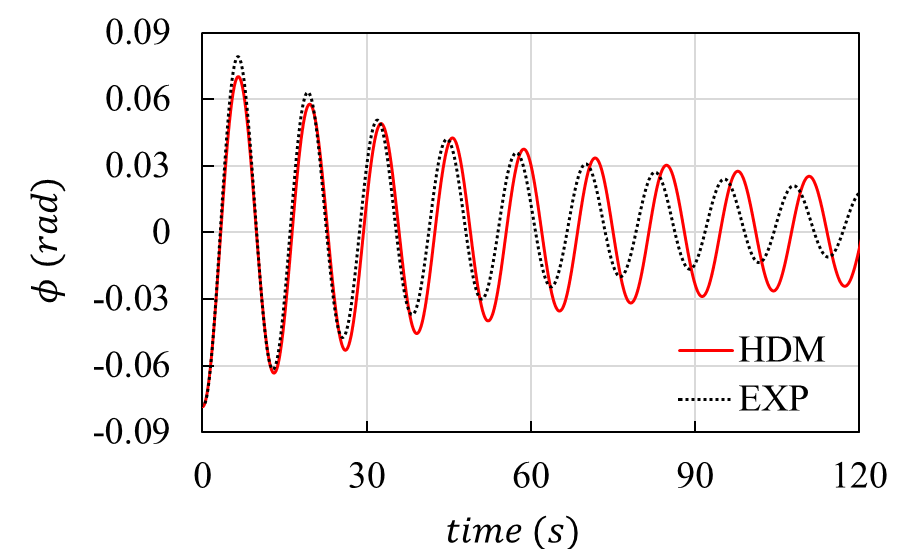


Figure 17. Free roll decay HDM simulation and model experiment.

* 1. **Self-propulsion in waves**

A case of self-propulsion in head waves at and top sail depths , and in regular waves with amplitude equal to the significant wave height and wavelength equal to the model wavelength of sea state 5 (SS5) was tested against full scale CFD simulations. The vehicle speed is controlled actuating on the propeller rotational speed, pitch and depth are controlled with sail and stern planes, while depth control is assisted by the ballast tank using the PID controllers defined in §2.4. For the details of controller gains and CFD data see Carrica et al. (2019).

The first harmonic amplitude of depth and pitch for CFD and model simulations are shown as a function of in Fig. 18. The model simulation results for depth and pitch first harmonic amplitudes are approximately 83~95% and 87~94% of the CFD simulation results, respectively, with the differences decreasing as at bigger depths. These results show that the wave hydrostatic and added mass forces and moments computation in the HDM reasonably model the effects of waves on the vehicle, but that higher-order effects could be added to improve the model.

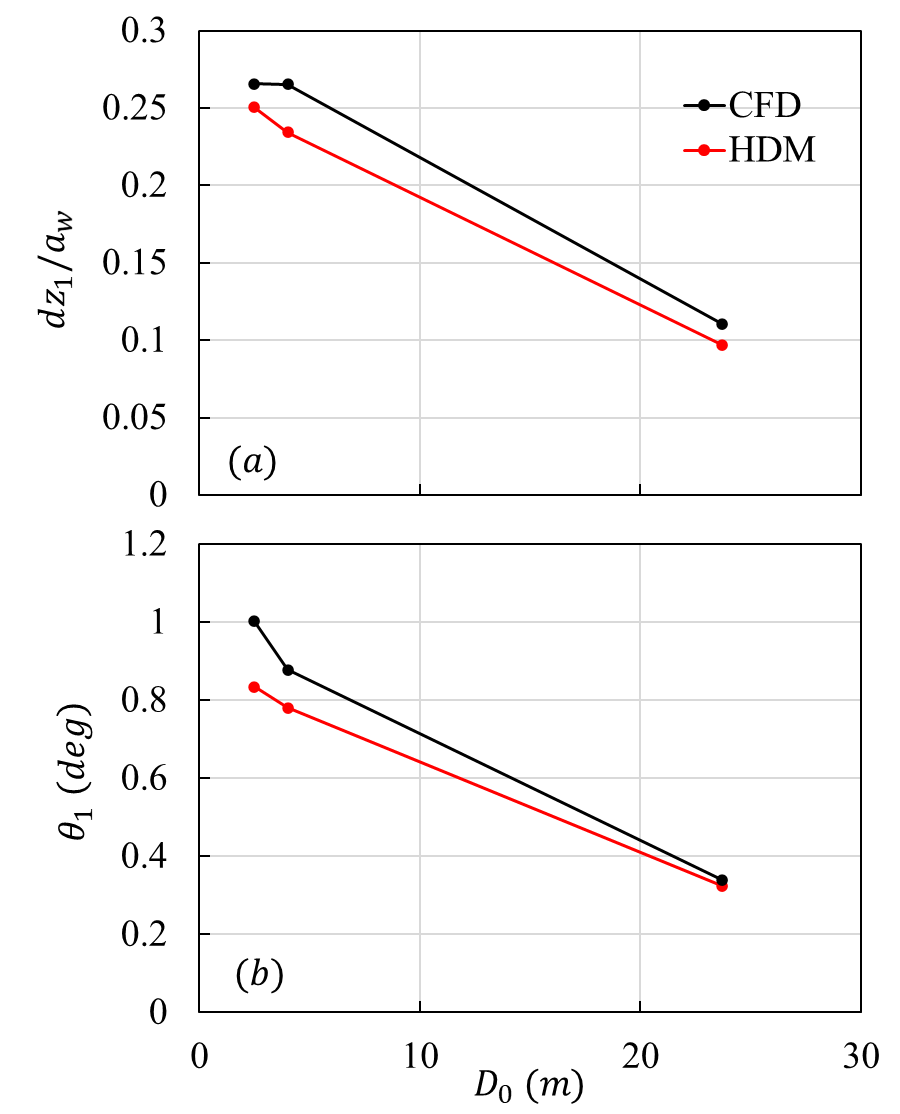


Figure 18. The first harmonic of (a) depth change and (b) the pitch angle during self-propulsion at in regular wave equivalent to SS5.

* 1. **Vertical Zigzag**

10/10 VZZ simulations are performed in the vertical plane and compared against CFD simulations for validation of the HDM under maneuvering conditions. These constant propeller rotational speed maneuvers are started from self-propulsion by initially deflecting the stern planes at maximum rate to until the pitch angle reaches , then the stern planes are reversed to until the pitch angle reaches , then reversing the stern planes again and repeating the cycle to obtain a vertical zigzag trajectory. is actuated with the horizontal control shown in Eq. (3) to maintain the boat in the vertical plane during the maneuver.

10/10 VZZ simulations at four approach speeds = , , and are performed; for the details of PID gains and CFD simulations results see Carrica et al. (2021). The histories of motions as function of time normalized by the time elapsed until the first positive peak in pitch for each speed are shown in Figs. 19 and 20. The overshoot angles and the zigzag period are in close match with the CFD simulations, with largest error occurring at lower speeds (Fig. 19 a). The pitch rate matches CFD particularly well, as shown in Fig. 19 (b), indicating that the control forces and moments are well predicted by the HDM.

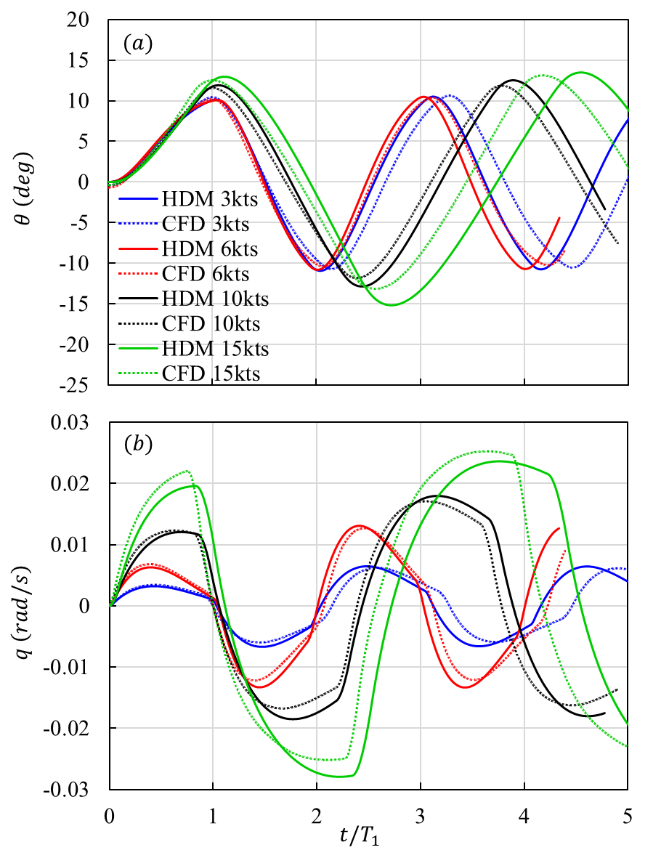


Figure 19. Time histories of pitch angle (a) and pitch rate (b) for 10/10 VZZ maneuver at , , , and as function of normalized time .

The prediction of vehicle speed loss is a key factor in the performance of the model, since all hydrodynamic forces depend on the speed. The good prediction of the speed shown in Fig. 20 (a) indicates that the resistance and propeller thrust variation modeled from free running CFD simulation results as shown in §5.2.7 successfully compensates for the inaccuracies of the very simple propeller model. The depth time histories presented in Fig. 20 (b) exhibit similar trends to the other motions, with good agreement with CFD but showing deterioration as the velocity decreases.

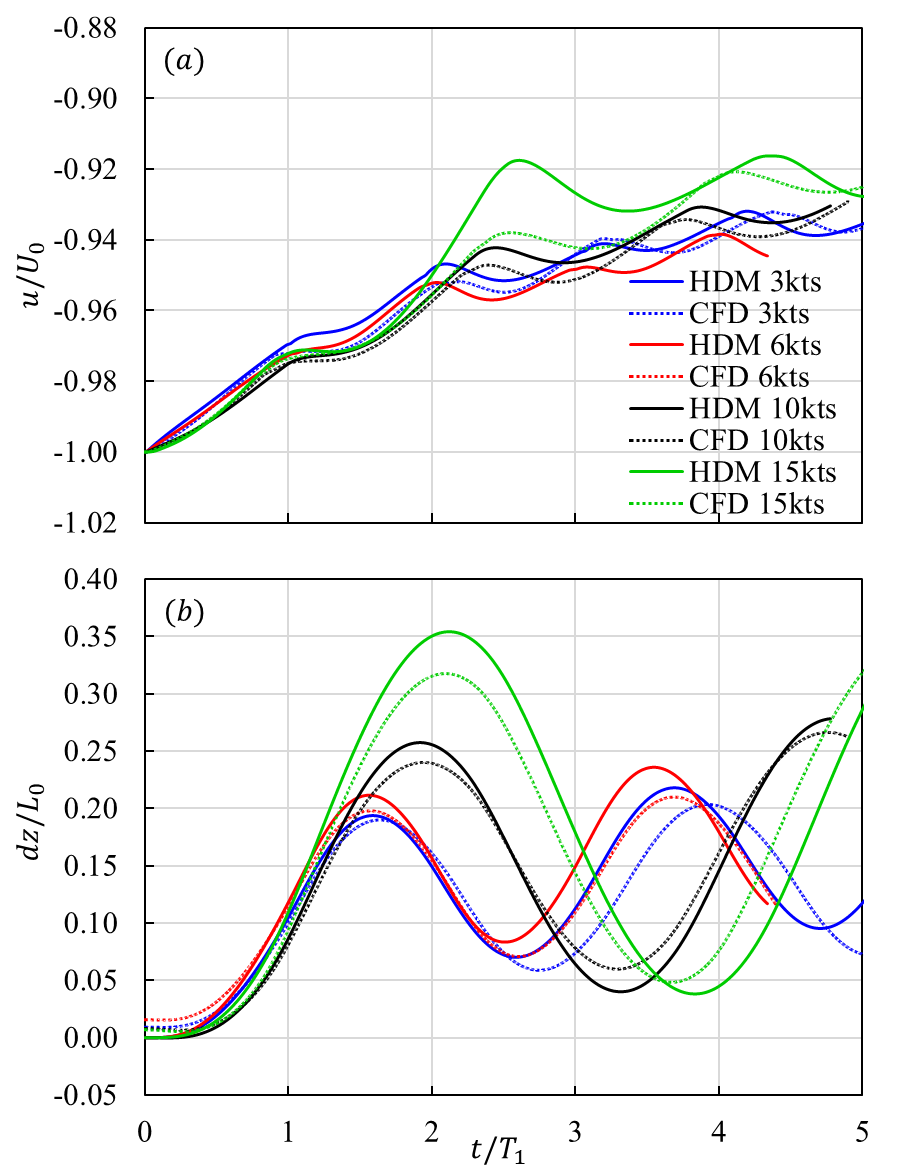


Figure 20. Time histories of (a) and (b) for 10/10 VZZ maneuver at , , , and as function of normalized time .

* 1. **Horizontal Zigzag**

A 20/20 HZZ simulation was performed for . The HDM simulation results are compared against experiment (Overpelt et al. 2015) and the CFD simulation (Carrica et al. 2020) results, both in model scale. The maneuver is executed with the same approach as VZZ, while is actuated on sail and stern planes to control the submarine in the horizontal plane. After achieving the desired speed, the propeller rotational speed is fixed and is set to until the yaw angle reach the checking yaw angle. The sign of changes upon the vehicle reaching the checking angle to each direction.

The time history of the yaw angle in Fig. 21 (a) and yaw rate in Fig. 22 (b) show good agreement against CFD and EFD, including the overshoot in the first peak. The good agreement of in the initial stage of maneuver in figure 22 (b) indicates that the lateral force and the yaw moment produced by the stern planes are accurately predicted. Predictions of speed (Fig. 22 a), sway (Fig. 21 b), roll angle (Fig. 21 c) and roll rate (Fig. 22 c) compare well with CFD and EFD, and typically differences with EFD are comparable with differences between CFD and EFD.

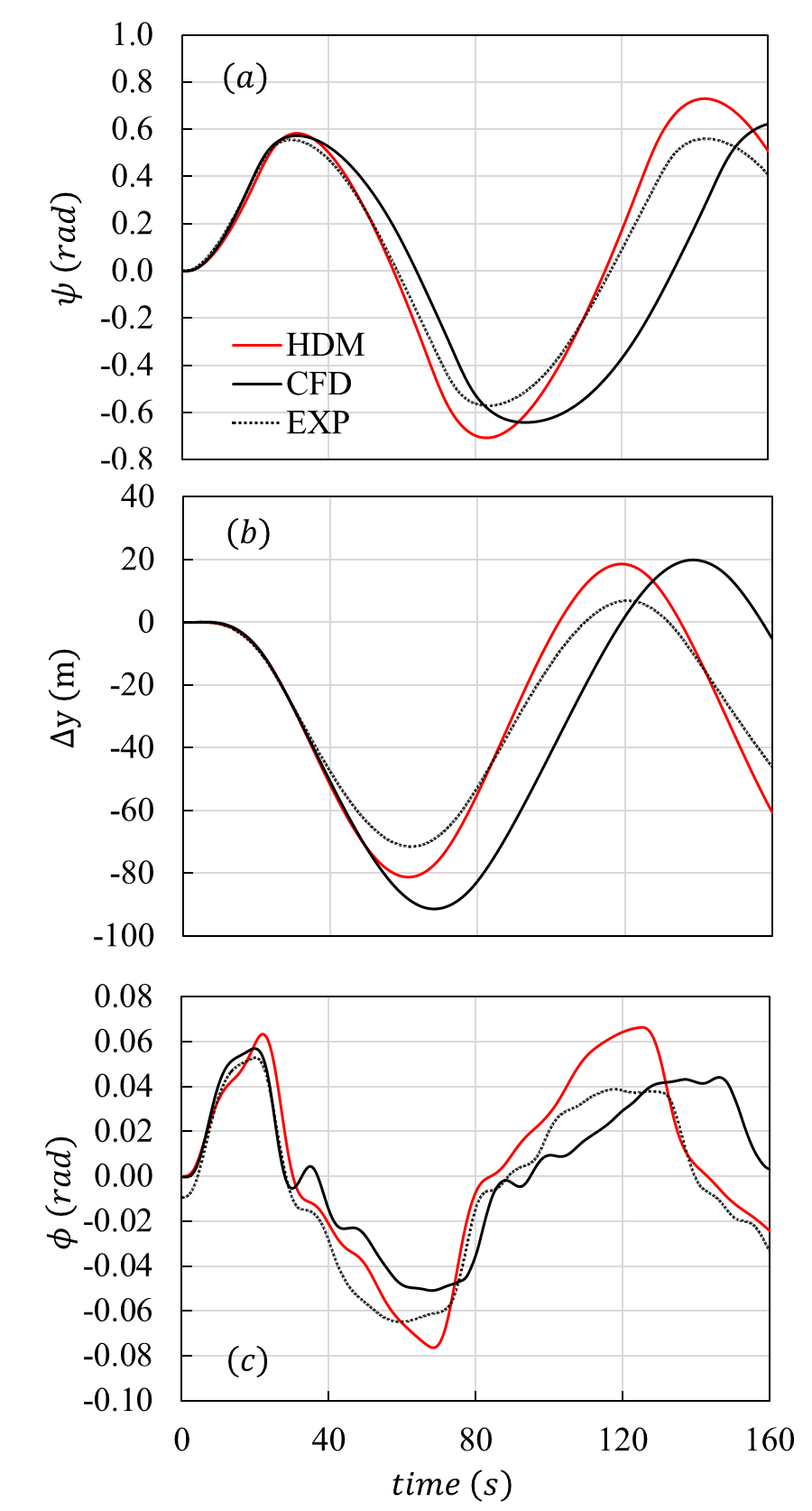


Figure 21. Time histories of (a) yaw angle (b) sway displacement and (c) roll angle during 20/20 HZZ maneuver at .

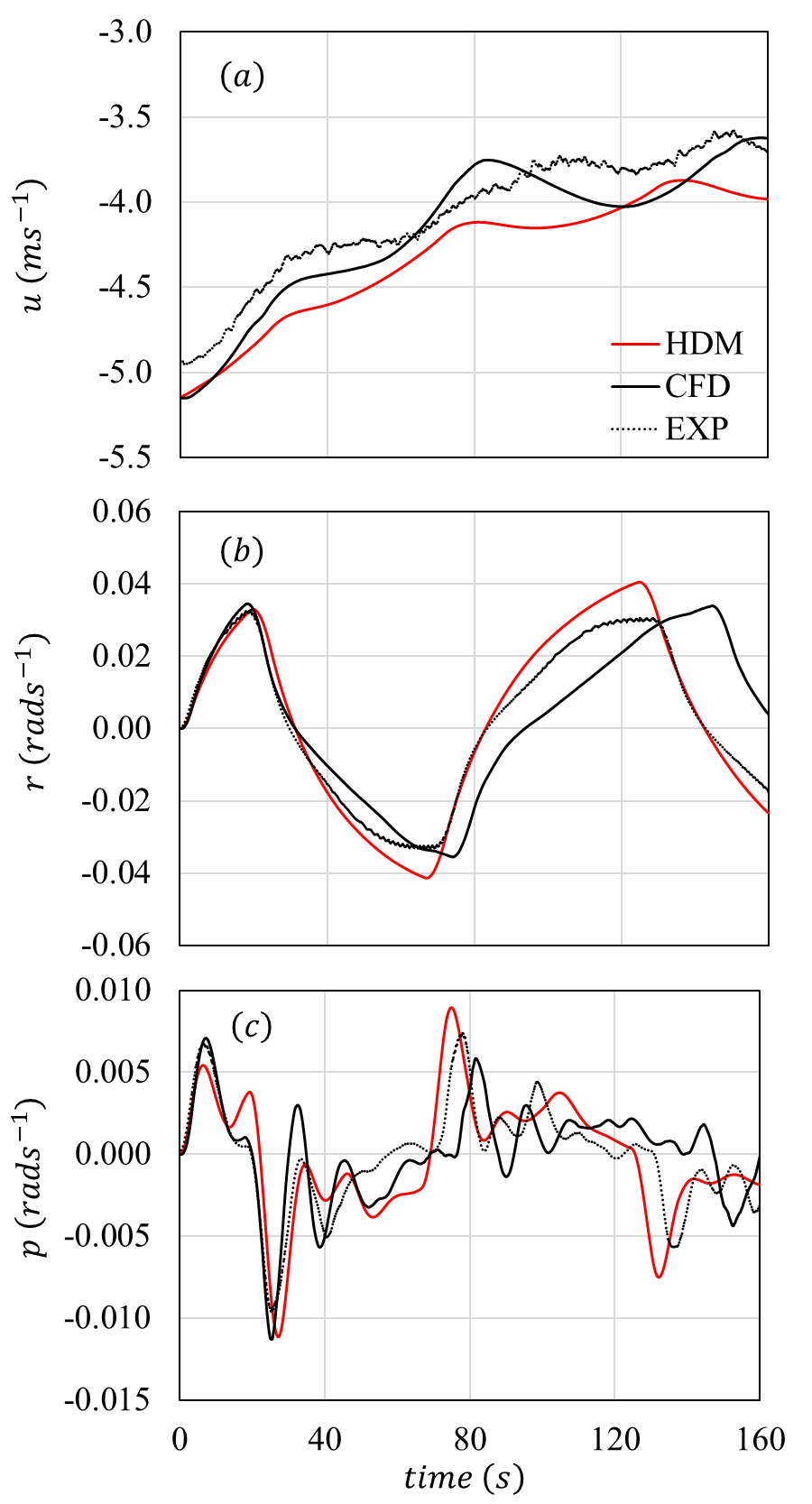


Figure 22. Time histories of (a) speed (b) yaw rate and (c) roll rate during 20/20 HZZ maneuver at .

* 1. **Turning circle maneuver**

TC maneuver simulations are performed with set to and the speed controlled to maintain . During the maneuver, the sail and stern planes are actuated by to control depth and pithch, while the depth control is assisted by the ballast tank. Simulations are performed in calm water for depths , , , and . Simulations are compared against CFD simulations, for details on the CFD setup, conditions and controller settings see Carrica et al. (2019).

The predicted trajectories in calm water shown in Fig. 23 show a tactical diameter of about for all conditions, with slightly tighter circles for shallower depth for both CFD and HDM.

On the other hand, the trajectories in regular waves shown in Fig. 23 exhibit considerable differences between CFD and EFD. The trajectories in waves are expected to drift along the wave propagating direction as repeating circles, as occurs with the CFD results. HDM is showing very little drift, as the current HDM does not considering second-order wave effects, in particular Stokes drift is neglected.

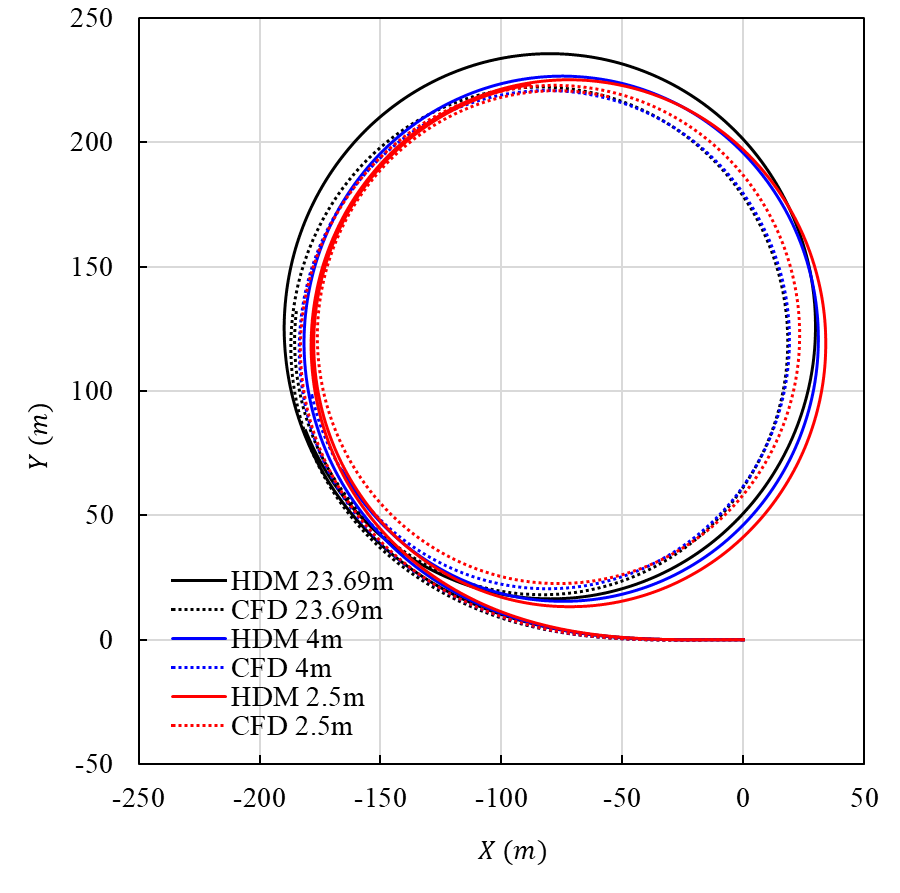


Figure 23. The trajectory of turning circle maneuver in calm water at and , at .

1. **Conclusion**

A hydrodynamic model of the generic submarine Joubert BB2 is presented. The model is based on the model of Gertler and Hagen (1967) model but modified to incorporate X-shaped stern planes, and also includes effects of the free surface. The hydrodynamic coefficients are obtained from numerical captive simulations and available free running CFD data. Free surface effects are considered by obtaining coefficients for several depth and speeds. Wave loads are implemented by geometrically incorporating the wave-induced surface pressure and the virtual mass due to wave particle acceleration. A set of validation studies are conducted against model experiments and CFD simulations.

The number of required hydrodynamic coefficients for control surface performance prediction was reduced by removing the set of coefficients for flow incidence angle, and instead computing an effective flow angle of attack. Accurate prediction of the control forces and moments is confirmed by the initial stage of vertical and horizontal zigzag maneuvers, where the appendage loads are the main contributors to the hydrodynamic loads that govern the motions. The hull drift and control surface coefficients are evaluated by towing the submarine at different flow incidence angles at several depths and speeds. The coefficients arising from angular rates are obtained from pure rotation simulations, and the coefficients for coupled linear/angular velocities with constant flow incidence are evaluated from rotating arm simulations. The propeller thrust and torque are computed using open water propeller performance curves, with supplement terms modeled from free running CFD simulations. The evolution of the submarine speed in maneuvering simulations using constant propeller rotational speed indicate that the propeller forces and moments are appropriately modeled. The virtual mass is evaluated from several hull sections and obtained by constant acceleration simulations in , and directions. The sectional approach allows the computation of moments due to the virtual mass without introducing a set of coefficients for angular acceleration. Hydrostatic and wave pressure loads are computed geometrically on a coarse triangulated surface grid every simulation time step. Results from controlled self-propulsion in waves show reasonable predictions of wave loads, while the absence of second order wave effects due to Stokes drift results in gross underprediction of the drift for TC maneuvers in regular waves.

Future work will focus on the implementation of second order effects in waves.

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