On estimating the hydrodynamic coefficients and environmental loads for a free-running vessel in waves

Lucas J. Yiew, Yuting Jin, Allan R. Magee
Technology Centre for Offshore and Marine, Singapore (TCOMS),
12 Prince George’s Park, Singapore 118411
E-mail: lucas_yiew@tcoms.sg

Abstract. This paper is a first attempt to develop real-time methods to accurately and reliably simulate vessel manoeuvring in waves. In this paper, hydrodynamic coefficients for the benchmark KCS hull are estimated using URANS-CFD generated manoeuvres in regular waves. Added resistances are derived from a potential-flow based solver over a range of incidence angles, wavelengths, and Froude numbers. These estimated wave loads, together with rudder and propeller forces are prescribed in a mathematical manoeuvring model. A state-augmented extended Kalman filter is applied to estimate the remaining hull coefficients, with empirically derived coefficients used as initial state estimates. Calm water cases are also investigated for comparison. Estimated coefficients using manoeuvres in waves show reasonable agreement with reference values. The methods discussed in this paper will eventually lead to robust control strategies for remotely-controlled and autonomous navigation under realistic environmental conditions.

1. Introduction
The characterisation and prediction of a vessel’s manoeuvrability is an important part of the engineering design process. This is especially relevant with recent paradigm shifts towards the development of digital twins (i.e. virtual replicas of a physical entity which captures, to a sufficient degree, dominant physical responses of a system), which can be used for remotely-controlled or autonomous navigation. There are three main strategies to predict the manoeuvrability of a vessel [7]. The first is a simulation-free method, whereby manoeuvring parameters are derived from either full-scale trials, free-running model scale tests, or vessel performances of similar types of craft. The second involves simulations using computational fluid dynamics (CFD) to parameterise various hydrodynamic derivatives/coefficients with respect to a vessel’s 6 degree-of-freedom (6-DOF) motions and control responses (i.e. rudder and propeller action). This can be done via virtual captive tests. Hydrodynamic derivatives are then compiled within equation of motions to describe a vessel’s response via a mathematical manoeuvring model. The last method, which is the focus of this study, involves the estimation of hydrodynamic derivatives using system identification (SI) methods and manoeuvring models.

Herrero and González [5] provides a concise summary of relevant works related to SI of ship manoeuvring models. One of the more classical and widely used SI methods is through the use of Kalman filters. Abkowitz [1] and Huang [6], for example, employed a state-augmented extended Kalman filter (SAEKF), whereby the original state vector is augmented to include a vector of hydrodynamic coefficients. For complex systems with a large number coefficients, augmentation
increases the size of the state error covariance matrix such that it becomes detrimental to the performance of the filter. The Jacobian matrix of the state equation may also become increasingly complex due to the introduction of instabilities through ill-conditioned or singular matrices. To resolve these issues, strategies such as estimation-before-modelling and parallel processing have been implemented to improve the performance of the filter [6, 20].

It is important to note that the bulk of existing SI methodologies focus on parameter identification using data from tests (e.g. sea trials) conducted in relatively calm waters. In this paper, we revisit the use of the SAEKF to estimate the hydrodynamic coefficients for the benchmark KRISO Container Ship (KCS) hull in calm water and in regular waves. Section 2 gives a description of the numerical models used to generate training datasets. Sections 3.1 and 3.2 describe the manoeuvring model and the implementation of the SAEKF algorithm. Section 3.3 presents the results and validations with data from published literature. Section 4 summarises the main findings and discusses areas for further research.

2. Numerical Simulations

2.1. Vessel Manoeuvres

Dynamic manoeuvres are simulated using the commercial unsteady Reynolds-averaged Navier-Stokes (URANS) solver STAR-CCM+. The solver uses a finite volume discretisation on structured or unstructured grids consisting of arbitrary convex polyhedrals. The pressure-velocity coupling is solved using the PIMPLE algorithm. Ship motions are simulated by the Dynamic Fluid Body Interaction module integrated in the 6-DOF motion solver. Two reference frames are involved in solving the motion equations, which are denoted as the ship-local and earth-fixed reference frames. A hierarchy of overset regions is included in the computation of 6-DOF dynamic manoeuvres. The background domain is superimposed with velocities of the ship’s surge and sway motion, which enables a relative static position between the overset and overlapping region of the background domain. The rudder overset region is defined within the ship local reference frame and act as children objects to the ship overset body and move together with it. The strategy to compute the angular motion of rudder depends on the type of manoeuvres required.

Table 1 provides the principal particulars of the KCS. The KCS is self-propelled at model scale (1:31.6) by a momentum disk/body-force propeller model. The angular velocity of this virtual propeller is initially adjusted manually to match the vessel’s advancing speed, and then maintained throughout individual manoeuvres. The approach applies the actuator disk concept to account for the presence of the propellers. Fifth-order Stokes waves are used for manoeuvring simulations – this theory is based on [3] and resembles a real wave more closely than one generated by the method using the first-order wave theory. Figure 1 shows the agreement between different techniques for predicting KCS manoeuvrability in calm water. Results from

| Table 1. KCS principal particulars. |
|-----------------------------------|
| **Scale** | 1 | 31.6 |
| **Length between perpendiculars L [m]** | 230 | 7.28 |
| **Breadth at waterline B [m]** | 32.2 | 1.02 |
| **Draft T [m]** | 19 | 0.6 |
| **Mass m [kg]** | 53,330,750 | 1,690 |
| **Block coefficient C_b** | 0.651 | 0.651 |
| **Radius of gyration R_{zz}/L** | 0.25 | 0.25 |
free-running and captive planar motion mechanism model tests [15, 11], and data from a mathematical model based on the MMG manoeuvring model of [21] are shown for comparison. This mathematical model is described in more detail in Section 3.1. Figure 1 shows that our URANS simulations correlate well with the mathematical model. When comparing with free-running model test manoeuvres, the two approaches slightly under-predict the manoeuvrability of the KCS model within approximately 90% accuracy.

In this study, URANS-CFD simulations are generated for (i) $\delta = -35^\circ$ (portside rudder) turning-circle, (ii) $\delta = 35^\circ$ (starboard rudder) turning-circle, (iii) $20^\circ$ starboard rudder/$20^\circ$ yaw angle zig-zag manoeuvres, in calm water and in regular waves. Two wavelength to ship length ratios are considered: $\lambda/L = 0.5$ and 1.1. In both wave cases the initial angle of incidence is $\chi_0 = 180^\circ$ (initial head seas), and the incident wave amplitude is $a = 0.035$ m. The initial forward speed in all simulations is $u_0 = 2.2$ m s$^{-1}$, with a corresponding Froude number $Fr = 0.26$.

2.2. Added Resistance in Waves

The time domain potential-flow based Rankine source solver, WASIM, is used to calculate the mean added resistance of the KCS hull in regular waves. The solver applies the principle of conservation of momentum on a near-field fluid volume bounded by a vessel’s wetted hull, the free surface and a virtual control surface near the hull. Wave added resistance is calculated by integrating fluid velocities and free surface elevations over the virtual control surface to obtain the second-order forces and moments [12]. The virtual control surface is set at 1.2 times the ship length $L$ and 1.4 times the ship breadth $B$ in the $x$- and $y$-axes, and 1.2 times the draft $T$ in the $z$-axis. The computational domain is set at 10 times $L$. A double body linearisation of the basis flow is also applied (see [12] for details) to derive the added resistance. Following [12], a time step of 0.025 s and an artificial restoring force and moment equivalent to eigenperiods of 200 s in surge, sway and yaw is applied to the model to ensure positional stability.

Figure 2 shows the mean added resistance derived from WASIM for head seas and $Fr = 0.26$, in comparison to a range of URANS (CFDSHIP-IOWA, STAR-CCM+) and potential-flow (AEGIR) solvers, and experimental data [16, 15]. Our results generally correlate well with most of these data, except for some discrepancies at $\lambda/L = 1.2$ where data from other sources are largely scattered. Our results however are within the range of these data points.

To account for added resistance in the turning-circle and zig-zag test cases described in Section
2.1 WASIM simulations are generated for a KCS hull moving at forward speeds with fixed headings, in regular waves over $\chi = 0^\circ - 360^\circ$ at every 10° interval. Simulations are generated for two incident wavelengths $\lambda/L = 0.5$ and 1.1, and two Froude numbers $Fr = 0.104$ and 0.178 to account for the mean steady-state speeds in the turning-circle and zig-zag tests. Figure 2 shows the service speeds $U$ (expressed in terms of $Fr$) generated from STAR-CCM+ for turning-circle and zig-zag manoeuvres in waves. Dashed lines indicate the mean steady-state Froude numbers used. Figure 4 shows the added resistances obtained from WASIM.

3. Estimating Hydrodynamic Coefficients in Regular Waves

3.1 Mathematical Formulation: Manoeuvring Model

A 3-DOF manoeuvring model is implemented to simulate the surge, sway and yaw motions of the KCS. The model applied here is based on Yoshimura and Masumoto’s [21] formulation of the MMG model. The equation of motions for surge, sway and yaw are

\[
\begin{align*}
(m + m_s)\ddot{u} &= X_H + X_R + X_P + X_W \\
(m + m_y)\ddot{v} &= Y_H + Y_R + Y_P + Y_W \\
(I_{zz} + J_{zz})\ddot{r} &= N_H + N_R + N_P + N_W
\end{align*}
\]

(1)
Figure 4. Added resistance in waves as a function of wave incidence angle $\chi$, wavelength and Froude number. Surge and sway forces are normalised with respect to $\rho g a^2 B^2 / L$, and yaw moment with respect to $\rho g a^2 B^2$.

where $m$ is the mass of the vessel, $m_x$, $m_y$ are the added masses in the $x$- and $y$-axes, $I_{zz}$, $J_{zz}$ are the moment and added moment of inertia of the vessel, and $\dot{u}$, $\dot{v}$, $\dot{r}$ are the surge, sway and yaw accelerations. The right-hand side of (1) represents body forces acting on the vessel due to the hull, rudder, propeller and wave forces (as indicated by the terms with subscripts $H$, $R$, $P$ and $W$ respectively).

Hull forces can be expanded into the following terms:

$$X_H = \frac{\rho}{2} L T U^2 \left[ X'_0 + X'_{\beta\beta} + X'_{\beta r} + X'_{rr} + X'_{\beta\beta\beta\beta} \right] - m_y v r$$

$$Y_H = \frac{\rho}{2} L T U^2 \left[ Y'_{\beta} + Y'_r + Y'_{\beta\beta\beta} + Y'_{\beta\beta r} + Y'_{\beta r r} + Y'_r r^2 \right] + m_x u r$$

$$N_H = \frac{\rho}{2} L^2 T U^2 \left[ N'_\beta + N'_r r + N'_{\beta\beta\beta} + N'_{\beta\beta r} + N'_{\beta r r} + N'_{rr r} r^2 \right]$$

where $L$ is the ship length between perpendiculars, $T$ the draft, $U = \sqrt{\dot{u}^2 + \dot{v}^2}$ the service speed, and $\beta = \arctan(-v/u)$ the drift angle. Terms with the prime symbol (') indicate non-dimensionalised quantities. In this paper, we adopt the Prime-II normalisation system (see [4], Table 5.1), hence linear and angular velocities are normalised by $U$ and $U/L$, and lengths and masses by $L$ and $\rho L^2 T / 2$, respectively.

The following sections will focus on the identification of the 16 hull coefficients in (2), namely: $X'_{\beta\beta}, X'_{\beta r}, X'_{rr}, X'_{\beta\beta\beta\beta}, Y'_\beta, Y'_r, Y'_{\beta\beta\beta}, Y'_{\beta\beta r}, Y'_{\beta r r}, Y'_r r^2, Y'_{rr r}, N'_\beta, N'_r, N'_{\beta\beta\beta}, N'_{\beta\beta r}, N'_{\beta r r}, N'_{rr r}$. The coefficient $X'_0$ represents calm water hull resistance, and is evaluated as $X'_0 = -37.2 u^2 / \rho L T U^2$.
by running a CFD resistance simulation within STAR-CCM+. In the following analyses, added masses and added moment of inertias are prescribed using values from \cite{9}. Rudder and propeller forces and moments in (1) are prescribed based on published data for the KCS propeller and rudder models. Details of these models are given in the Appendix. Wave forces and moments $X_W$, $Y_W$, $N_W$, are prescribed using the mean wave added resistances obtained from WASIM.

3.2. Mathematical Formulation: Extended Kalman Filter
A discrete-time state-augmented extended Kalman filter (SAEKF) is implemented to identify vessel manoeuvring coefficients in the MMG model. The system state, which includes the surge, sway and yaw velocities ($u, v, r$), is appended with the hull coefficients from \cite{1} such that $x = [u, v, r, \alpha]^\top$ where $\alpha \in \mathbb{R}^{1 \times 16}$.

The state transition and observation equations are, respectively,

$$
\dot{x} = f(x(n), u(n)) + Ew, \quad \text{(3)}
$$

$$
y = Hx + v. \quad \text{(4)}
$$

For a system with time-invariant hydrodynamic derivatives, $\dot{\alpha} = 0$ where $0$ is a $(1 \times 16)$ zero matrix. In \cite{3}, the vector $u = [n_P, \delta]^\top$ contains the system input variables, where $n_P$ is the propeller speed (rps) and $\delta$ the rudder angle. The states $w$ and $v$ represent process and measurement noise, respectively. The measured state $y = (u_m, v_m, r_m)$, hence by definition, $H = [I | 0]$, with $I$ and $0$ representing the identity and zero matrices.

The EKF algorithm is as follows:

1. Define the initial state estimate $\hat{x}(0)$, initial error covariance $\hat{P}(0)$, and the so-called design matrices $Q, E, R$ which represent process and measurement noise covariances.
2. Compute the Kalman gain $K$ at $n$-th time step:

$$
K(n) = \hat{P}(n)H^\top(n)[H(n)\hat{P}(n)H^\top(n) + R(n)]^{-1} \quad \text{(5)}
$$

3. Update the state estimate and error covariance:

$$
\hat{x}(n) = \hat{x}(n) + K(n)[y(n) - H(n)\hat{x}(n)] \quad \text{(6)}
$$

$$
\hat{P}(n) = [I - K(n)H(n)][\hat{P}(n)H(n) - K(n) \hat{P}(n)H(n)]^\top + K(n)R(n)K^\top(n) \quad \text{(7)}
$$

4. Predict the state and error covariance at the next time step $n + 1$:

$$
\hat{x}(n + 1) \approx \hat{x}(n) + h[f(\hat{x}(n), u(n))] \quad \text{(8)}
$$

$$
\hat{P}(n + 1) = \Phi(n)\hat{P}(n)\Phi^\top(n) + \Gamma(n)Q(n)\Gamma^\top(n) \quad \text{(9)}
$$

where

$$
\Phi(n) \approx I + h \frac{\partial f(x(n), u(n))}{\partial x(n)} \bigg|_{x(n) = \hat{x}(n)} \quad \text{(10)}
$$

$$
\Gamma(n) \approx hE \quad \text{(11)}
$$

5. Repeat from Step 2 at time step $n + 1$.

The accuracy of state estimates and the performance of the filter is dependant on time step $h$, due to the Euler integration in \cite{8} and \cite{10}. A time step of $h = 0.01$ s was used in the model.

The convergence of estimated states is also known to be sensitive to the initial state estimate, initial error covariance, and design matrices \cite{13}. The initial state estimate is set as

$$
\hat{x}(0) = [u_m(0), v_m(0), r_m(0), \alpha_E]^\top, \quad \text{(12)}
$$
where $\alpha_E$ is the initial estimated hull coefficients. Empirical formulas from [8, 21] are used to obtain these initial estimates. Empirical formulas were obtained by deriving linear relationships between hull coefficients and vessel properties (e.g. $C_b$, $L$, $B$) for a range of fishing/training vessels, container ships, cargo and car carriers.

The initial error covariance $\bar{P}(0)$ provides information on the uncertainty of the initial state estimate, and is defined as

$$\bar{P}(0) = [(\bar{x}(0) - \hat{x}(0))(\bar{x}(0) - \hat{x}(0))]^\top,$$

where $\hat{x}(0) = [u_m(0), v_m(0), r_m(0), \alpha_R]^\top$, with $\alpha_R$ a set of reference values. In this study, we use the KCS coefficients from [21] as reference values for $\alpha_R$.

As for the design matrices, the output from URANS simulations are essentially noise-free, therefore we use the matrix $R = 10^{-6}J_{3,3}$ to describe the measurement noise covariance, where $J_{n,m}$ denotes a matrix of ones of dimension $n \times m$. With regards to process noise, since we account for environmental disturbances (when modelling the effect of waves), covariances in $Q$ and $E$ will be small. However, these covariances also account for modelling errors, therefore we apply more conservative values of $Q = E = \text{diag}[(10^{-2}J_{1,3}, 10^{-3}J_{1,16})]$.

One improvement commonly adopted in the SAEKF is the application of parallel processing of multiple manoeuvres [1]. This strategy is implemented to increase the rate of convergence and reduce cancellation effects and parameter drift. Parallel processing is implemented by further augmenting the system state with surge, sway and yaw velocities from a second manoeuvre, such that $\bar{x} = [u_1, v_1, r_1, u_2, v_2, r_2, \alpha]^\top$. The subscripts 1 and 2 refer to the first and second manoeuvres. Figure 5 shows an example of the improvement in convergence when parallel processing is applied. In this example, the MMG model is used to obtain the state estimates. Single (10°/10° zig-zag) and two manoeuvres (10°/10° zig-zag and 35° turning-circle) are implemented, with the latter converging to the reference values within a shorter timespan.

### 3.3. Results and Discussion

Table 2 shows the coefficients predicted using data generated by: (i) the MMG model in calm water (SI-1), (ii) URANS calm water simulations (SI-2), (iii) URANS simulations in waves of $\lambda/L = 1.1$ (SI-3), and (iv) URANS simulations in waves of $\lambda/L = 0.5$ (SI-4). In each of the 4 cases, the training data includes manoeuvres from the −35° turning-circle and 20°/20° zig-zag tests. The 35° (starboard) turning-circle tests was not used as it had a similar response (e.g. less than 12% difference in turning radius) to the portside turning. We assume all asymmetries are purely due to propeller and rudder effects, i.e. there are no asymmetric effects from the hull. Predicted coefficients are compared against various reference values. These are reported

![Figure 5](image-url)

**Figure 5.** Example of convergence of state estimates with and without parallel processing (red and blue curves, respectively). Dashed lines indicate reference values from [21].
Table 2. Hull coefficients for KCS. KCS_E refers to KCS coefficients calculated using empirical formulas [8, 21]. SI-1 and SI-2 refer to coefficients identified using the outputs from the MMG model and URANS simulations in calm water. SI-3 and SI-4 refer to coefficients identified using URANS simulations in waves of \( \lambda/L = 1.1 \) and 0.5, respectively.

| KCS [21] | KCS_E (\( \Delta K \))% | SI-1 (\( \Delta K \))% | SI-2 (\( \Delta K \))% | SI-3 (\( \Delta K \))% | SI-4 (\( \Delta K \))% |
|----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( X'_{\beta} \) | -0.0549 (-0.752) (37) | -0.0552 (0.6) | -0.0577 (5.1) | -0.0660 (20.2) | -0.0598 (8.9) |
| \( X'_{\beta} \) | -0.1084 (-0.941) (-13.2) | -0.1090 (0.6) | -0.0994 (-8.3) | -0.1005 (-7.2) | -0.1049 (-3.2) |
| \( X'_{r} \) | -0.0120 (0.003) (-102.1) | -0.0136 (12.9) | -0.025 (-78.8) | -0.0185 (54.3) | -0.0149 (23.9) |
| \( X'_{rr} \) | -0.0417 (0.4912) (-1277.9) | -0.0419 (0.5) | -0.0521 (24.9) | -0.0465 (54.7) | -0.0518 (24.2) |
| \( Y'_{\beta} \) | 0.0398 (0.0416) (4.5) | 0.0402 (0.9) | -0.0065 (-116.4) | -0.0564 (-241.6) | -0.0027 (-106.8) |
| \( Y'_{r} \) | 0.0831 (0.0695) (-16.5) | 0.0833 (-0.02) | 0.0798 (-4.3) | 0.0759 (-9) | 0.0808 (-4) |
| \( Y'_{rr} \) | -0.0050 (-0.051) (920) | -0.0061 (22.7) | -0.0086 (71.3) | -0.0077 (55) | -0.0062 (24.3) |
| \( N'_{\beta} \) | 0.1111 (0.0939) (-15.5) | 0.1083 (-2.6) | 0.1056 (-5) | 0.1017 (-8.5) | 0.1069 (-3.7) |
| \( N'_{r} \) | -0.0465 (-0.0419) (-9.9) | -0.0433 (-6.9) | -0.0467 (0.4) | -0.0440 (-5.4) | -0.0454 (-2.4) |
| \( N'_{rr} \) | 0.1751 (0.2108) (20.4) | 0.1749 (-0.1) | 0.1840 (5.1) | 0.1946 (11.1) | 0.1837 (4.9) |
| \( N'_{\beta r} \) | -0.6167 (-0.4006) (-35) | -0.6172 (0.1) | -0.5622 (-8.8) | -0.4986 (-19.1) | -0.5645 (-8.5) |
| \( N'_{\beta r} \) | 0.0512 (0.0592) (215.6) | 0.0504 (-1.6) | 0.0636 (24.6) | 0.0792 (54.6) | 0.0636 (24.2) |
| \( N'_{rr} \) | -0.0087 (-0.0037) (38.8) | -0.0047 (5.1) | -0.0033 (11.8) | -0.0469 (21.2) | -0.0423 (9.4) |

RMSE \( \Delta K \): 6.9% 40.7% 67.3% 29.7%
\[ \sum |\Delta K| \]: 0.1165 0.2762 0.5688 0.2516
\[ \sum |\Delta_1| \]: 0.2743 0.5587 0.2443 0.0352

in terms of percentage differences e.g. \( \Delta K \)% and sums of absolute differences e.g. \( \sum |\Delta_1| \) and \( \sum |\Delta_2| \). The subscripts K, 1, 2 refer to references with respect to KCS coefficients from [21], SI-1 and SI-2, respectively.

The predicted coefficients in SI-1 are generally close to the reference values of [21], with absolute errors less than 23% and the overall root-mean-square error (RMSE) at 6.9%. Coefficients predicted in SI-2 are further from the reference values, with the RMSE at 40.7%. The largest error is \( \Delta K = -116.4 \% \) for \( Y'_{r} \). Figure 6 shows the trajectories (for turning-circle tests), and yaw and rudder angles (for zig-zag tests) using the predicted coefficients from SI-1 and SI-2. Despite the larger errors for some coefficients, both results show appreciable correlation to their respective training datasets.

The right-most columns of Table 2 show the predicted coefficients when URANS data for manoeuvres in waves are used. In both sets of tests, absolute differences \( \Delta K \) range from 1.2% to 241.6%, with the largest differences again associated with \( Y'_{r} \). Predicted coefficients are still in fair agreement with reference values, with the RMSE \( \Delta K \) for SI-3 and SI-4 at 67.3% and 29.7%, and \( \sum |\Delta K| = 0.5587 \) and 0.2516, respectively. Coefficients in SI-3 and SI-4 are closer to those in SI-2 (using calm water URANS data), with \( \sum |\Delta_2| = 0.3160 \) and 0.0382, respectively. Despite the minor differences in coefficients, trajectories and yaw angles for SI-3 and SI-4 are shown to be less compatible with the URANS data (see Figures 7a and b). In particular, the effect of waves on the trajectories and yaw angles are less pronounced in SI-3 and SI-4, with the URANS simulations showing a larger mean drift in the negative x-direction, and a shorter yaw-response time.

One probable cause for these discrepancies could be inaccuracies in the derived wave loads. Mean wave loads obtained from WASIM using Fr = 0.104 (for turning-circle tests) and 0.178 (for zig-zag tests) may not be an accurate representation of the added resistances for each test due
Figure 6. Simulated trajectories and yaw angles using identified coefficients from SI-1 and SI-2 in comparison to URANS-CFD simulations and outputs from the MMG model in calm water.

Figure 7. Simulated trajectories and yaw angles using (a–b) identified coefficients from SI-3 and SI-4, and (c–d) coefficients from [21], in comparison to URANS-CFD simulations in waves.
to the variation in speed during the transient and steady-state intervals. For example, during the zig-zag test at $\lambda/L = 0.5$, $Fr$ varies between 0.175 to 0.195 during each cycle after 30 s (see Figure 3b). Also, the initial $Fr$ for all manoeuvres is 0.26, therefore a larger initial wave load is expected than those at $Fr = 0.104$ and 0.178. Figures 7(c) and (d) show the improvement in correlation when the added resistance in the first 30 s is increased by a factor of 4. In these simulations, coefficients from [21] are used.

Another source of discrepancy could relate to the angle of incidence with respect to the vessel’s drift angle. Currently WASIM simulations are generated with zero drift angle. Errors in wave loads may arise when actual drift angles are nonzero. Calculations of wave loads should be done at instantaneous positions, yaw and drift angles and speeds, however at present prescribed motions/manoeuvres cannot be readily implemented in WASIM.

4. Conclusions
Hydrodynamic derivatives for the KCS benchmark vessel are identified using URANS-CFD simulations for turning-circle and zig-zag manoeuvres in calm water and in regular waves. In particular, hull derivatives in a MMG manoeuvring model are estimated using a state-augmented extended Kalman filter. Parallel processing of multiple manoeuvres is implemented to improve the convergence of state estimates. Added resistance due to waves are calculated using a potential-flow based solver and prescribed into the manoeuvring model. Estimated coefficients are in fairly good agreement to reference values, however differences in trajectories and yaw rates are more noticeable, especially when wave loads increase. More accurate calculations of instantaneous wave loads should improve the agreement with CFD simulations.

Not included in this study is the effect of waves on rudder and propeller performances. As a simplifying measure, we assume that these coefficients are time and phase invariant. However, it is known that in certain regimes, waves have a substantial effect on propulsor performances due to pressure fluctuations and flow distortions (see [2, 10, 17], for example). In future work, we will explore wave-induced effects on control appendages through CFD and experimental analyses. Moving forward, we will also explore the use of manoeuvring models in the development of control algorithms for navigational autonomy. The goal with this is to replicate human-in-the-loop actions and active compensations for environmental disturbances through better predictions of a vessel’s manoeuvrability.

Appendix

Propeller forces are defined as

$$
X_P = (1 - t_P) \rho K_T D_P^4 n_P^2,
Y_P = 0,
N_P = 0
$$

(14)

where $t_P$ is the thrust deduction factor and $D_P$ the propeller diameter. The open water propeller thrust characteristic $K_T$ is represented as a second order polynomial function of the propeller advance ratio $J_P$,

$$
K_T = k_2 J_P^2 + k_1 J_P + k_0,
$$

(15)

with $k_0, k_1, k_2$ coefficients obtained by fitting (15) to the $K_T$-$J_P$ curve for the KP505 propeller used with the KCS model (see [14], Figure 8). The propeller advance ratio is calculated as

$$
J_P = \frac{u(1 - w_P)}{n_P D_P},
$$

(16)

where wake fraction of the propeller in a manoeuvre is

$$
w_P = 1 - [1 + (1 - e^{-C_1|\beta_p|})(C_2 - 1)](1 - w_{P0}).
$$

(17)
Here $C_1, C_2$ are experimental wake constants, $w_{P0}$ is the wake fraction of the propeller in straight vessel motions, and $\beta_P = \beta - x_P^r r'$ is the geometric inflow angle to the propeller in a manoeuvre. Rudder forces are defined as

$$
X_R = -(1 - t_R) F_N \sin \delta \\
Y_R = -(1 - a_H) F_N \cos \delta \\
N_R = -(x_R + a_H x_H) F_N \cos \delta
$$

where $t_R$ is the steering resistance deduction factor, $a_H$ the rudder force increase factor, and $x_R, x_H$ are the $x$-coordinate of the rudder position and acting point of additional lateral force from steering respectively. The rudder normal force,

$$
F_N = \frac{\rho}{2} A_R U_R^2 f_\alpha \sin \alpha_R
$$

with $A_R$ the rudder’s profile area and $f_\alpha$ the rudder lift gradient. The remaining terms in (19) are the resultant rudder inflow velocities and angles,

$$
U_R = \sqrt{u_R^2 + v_R^2}
$$

$$
\alpha_R = \delta - \arctan \frac{v_R}{u_R}
$$

where the longitudinal and lateral inflow velocities to the rudder are

$$
v_R = U \gamma_R (\beta - l_R^r r')
$$

and

$$
u_R = \varepsilon u (1 - w_P) \sqrt{\eta \left\{ 1 + \kappa \left( \sqrt{1 + \frac{8K_T}{\pi J_P^2}} - 1 \right) \right\} + (1 - \eta)}.
$$

In the above $\gamma_R$ is the flow straightening coefficient, $l_R$ the effective $x$-coordinate of the rudder position, $\varepsilon$ the wake fraction ratio at propeller and rudder positions, $\eta$ the ratio of $D_P$ to rudder span, and $\kappa$ an empirical constant for $u_R$. Table 3 lists the propeller and rudder coefficients used in this paper. Values below are taken with reference to [21, 19].

**Table 3.** Propeller and rudder coefficients.

| $t_P$ | $D_P$ | $k_0$ | $k_1$ | $k_2$ | $C_1$ | $C_2$ | $w_{P0}$ | $x_P^r$ |
|-------|-------|-------|-------|-------|-------|-------|----------|---------|
| 0.22  | 7.9   | 0.5375| -0.4666 | -0.0408 | 5     | 2     | 0.4      | -0.513   |
|       |       |       |       |       |       |       | 1.5 ($\beta_P \leq 0$) |

| $t_R$ | $a_H$ | $x_R^r$ | $x_H^r$ | $A_R$ | $f_\alpha$ | $\gamma_R$ | $l_R^r$ | $\varepsilon$ | $\eta$ | $\kappa$ |
|-------|-------|---------|---------|-------|----------|----------|--------|-----------|------|--------|
| 0.258 | 0.361 | -0.491  | -0.436  | 45.2  | 2.75     | 0.492    | -0.755 | 0.956     | 0.798 | 0.6    |
|       |       |         |         |       |          | 0.338    | (\beta_P \leq 0) |

References

[1] M. A. Abkowitz. Measurement of hydrodynamic characteristics from ship maneuvring trials by system identification. SNAME Transactions, 88:283–318, 1980.

[2] O. M. Faltinsen, K. J. Minsaas, N. Liapis, and S. O. Skjordal. Prediction of Resistance and Propulsion of a Ship in a Seaway. Proceedings of the 13th Symposium on Naval Hydrodynamics, 1980.

[3] J. D. Fenton. A fifth-order Stokes theory for steady waves. Journal of Waterway, Port, Coastal and Ocean Engineering, 111:216–234, 1985.

[4] T. I. Fossen. Guidance and Control of Ocean Vehicles. John Wiley & Sons, 1994.

[5] E. R. Herrero and F. J. V. González. Two-step identification of non-linear maneuvring models of marine vessels. Ocean Engineering, 53:72–82, 2012.

[6] W.-Y. Hwang. Application of system identification to ship maneuvering. PhD thesis, Massachusetts Institute of Technology, 1980.

[7] ITTC. The Manoeuvring Committee - Final Report and Recommendations to the 25th ITTC. Technical report, 2008.

[8] K. Kijima, Y. Nakiri, T. Katsuno, and Y. Furukawa. On the maneouvring performance of a ship with the parameter of loading condition. Journal of the Society of Naval Architects of Japan, 168:141–148, 1990.

[9] Y. Liu, L. Zou, Z. Zou, and H. Guoa. Predictions of ship maneuverability based on virtual captive model tests. Engineering Applications of Computational Fluid Mechanics, 12(1):334–353, 2018.

[10] S. Nakamura and S. Naito. Propulsive performance of a container ship in waves. The Society of Naval Architects of Japan, 15(158):24–48, 1977.

[11] J. F. Otzen and C. D. Simonsen. Manoeuvring predictions for the kcs container ship based on experimental and numerical pmm tests. In Proceedings of Workshop on Verification andValidation of Ship Maneouvring Simulation Methods, Copenhagen, Denmark, 2014.

[12] Z. Pan, T. Vada, and K. Han. Computation of Wave Added Resistance by Control Surface Integration. In Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering, pages OMAE2016–54353, 2016.

[13] R. Schneider and C. Georgakis. How to NOT make the extended kalman filter fail. Industrial and Engineering Chemistry Research, 52(9):3354–3362, 2013.

[14] Z. Shen, D. Wan, and P. M. Carrica. Dynamic overset grids in OpenFOAM with application to KCS self-propulsion and maneouvring. Ocean Engineering, 108:287–306, 2015.

[15] SIMMAN. Workshop on verification and validation of ship maneouvring simulation methods. Retrieved from http://www.simman2014.dk/, Copenhagen, Denmark, 2014.

[16] C. D. Simonsen, J. F. Otzen, S. Joncquez, and F. Stern. EFD and CFD for KCS heaving and pitching in regular head waves. Journal of Marine Science and Technology, 18(4):435–459, 2013.

[17] B. Taskar, K. K. Yum, S. Steen, and E. Pedersen. The effect of waves on engine-propeller dynamics and propulsion performance of ships. Ocean Engineering, 122:262–277, 2016.

[18] T. Tezdogan, Y. K. Demirel, P. Kellett, M. Khorasanchi, A. Incceik, and O. Turan. Full-scale unsteady RANS CFD simulations of ship behaviour and performance in head seas due to slow steaming. Ocean Engineering, 97:186–206, 2015.

[19] H. Yasukawa and Y. Yoshimura. Introduction of MMG standard method for ship maneouvring predictions. Journal of Marine Science and Technology, 20:37–52, 2015.

[20] H. K. Yoon and K. P. Rhee. Identification of hydrodynamic coefficients in ship maneouvring equations of motion by Estimation-Before-Modeling technique. Ocean Engineering, 30(18):2379–2404, 2003.

[21] Y. Yoshimura and Y. Masumoto. Hydrodynamic force database with medium high speed merchant ships including fishing vessels and investigation into a maneouvring predicition method. Journal of the Japan Society of Naval Architects and Ocean Engineers, 14:63–73, 2011.