Dynamic manoeuvres of KCS in waves using URANS computations with overset grids

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Abstract. This paper presents a CFD URANS approach to model self-propelled free running manoeuvres for autonomous or remote-controlled surface vessels in calm water and Stokes waves. The object of study in this paper is a benchmark container ship KCS. A hierarchy of overset grids are utilised, allowing active rudder motions while the vessel is undertaking 6 DoF turning circle and zig-zag manoeuvres. Body force propeller model (BFM) is adopted to drive the vessel at a constant approaching speed corresponds to Fr=0.26. Verification and validation study is performed for estimating the numerical uncertainties within the computations. In calm water, the computed vessel trajectories and velocities are compared against experimental data from literature and mathematical model (MM) based simulation results. Differences between URANS and experimental data are around 10.0%. After introducing waves, the manoeuvring behaviour of the vessel changes due to the presence of wave frequency loads and drift loads. The wave frequency loads exert fluctuations on measurements such as velocity, yaw rate, vessel encountered loads and etc., while the drift loads result in shift in the vessel’s trajectory especially for the turning circle manoeuvre.

1. Introduction
Predictions of ship manoeuvrability are typically carried out in calm water during conventional ship design process. However, the validity of such practice is debatable especially for vessels that are designated for autonomous or remotely-controlled operations in challenging sea-states. Environmental factors such as wind, waves, currents, restricted water depth as well as the presence of other vessels are known to influence vessel’s manoeuvring characteristics. Among them wave effects are perhaps the most important to consider since even moderate wave states can result in large magnitude of additional loads affecting its course-keeping and manoeuvrability. On the other hand, maintaining a given course in waves can induce severe ship motions, increase resistance and decrease propulsive efficiency and speed.

Up to the present, the most widely adopted approaches for studying ship manoeuvring in waves can be classified into three categories as experimental method, mathematical model-based method and CFD based method. Model tests, although are commonly regarded as the most reliable method to study wave effects on ship manoeuvrability, involve complex setup and instrumentations. Most importantly, they still possess defects to address scale effects even at full scale propulsion point.
Nonetheless, several experimental studies have been carried out for ship free running manoeuvres in waves. Ueno et al. [1] conducted turning, zig-zag and stopping manoeuvres of a VLCC model. Lee et al. [2] studied the effects of wave amplitude and length on the manoeuvrability of a KVLCC model in regular waves. Yasukawa and Nakayama [3] performed similar experimental studies on dynamic manoeuvres in waves for the containership model S-175. These experimental studies share a common conclusion that the second-order wave drift force has a dominant influence on ship manoeuvrability.

Mathematical model (MM) based or system based (SB) method for simulating dynamic manoeuvres in waves involves unifying conventional manoeuvring model with seakeeping analysis. The greatest advantage of such method is the rapid computational time. Zhang et al. [4] introduced two sub-categories to describe the current available mathematical models for ship manoeuvring in waves, the hybrid approach and the two-time scale approach. The hybrid model integrates wave loads and manoeuvring forces into a rigid body motion equation. The two-time scale method separates the high frequency wave induced ship dynamics from the low frequency manoeuvring problem. Since short computational time is often required to identify dangerous manoeuvring conditions from a huge number of suspect conditions, the MM based method shows great merits.

The CFD-based dynamic manoeuvres are mostly based on URANS or URANS-LES hybrid methods to resolve time domain hydrodynamic loads and motions. Such computations require self-propulsion, moving rudders and are typically performed with full 6 DoF in a free surface environment, and are able to provide rich details of flow physics during manoeuvres. For dynamic manoeuvres in waves, limited CFD studies can be found in recent years’ publications. Carrica et al. [5] simulated turning circle manoeuvres of the DTMB 5415M at 35 degrees of rudder in regular waves. Relatively long wave conditions ($\lambda/L_{pp}=1.0$ and 1.5) were selected, and the results were compared with calm water trajectories which demonstrated the significant influence of waves. Driven by this cause, the authors are motivated to conduct CFD computations to explore the hydrodynamic behaviour of vessel undertaking standard manoeuvring motions in waves. The work is also regarded as a necessary intermediate step towards deriving real-time hydrodynamic digital twin of autonomous or remote-controlled vessels, together with basin validation and full-scale trials.

Most of the up-to-date CFD-based dynamic manoeuvring studies were carried out by research groups with their own in-house codes which have limited access. In the present work the dynamic manoeuvres are performed by the commercial URANS solver Star-CCM+ using its embedded overset grid function. The turning circle and zig-zag manoeuvres of KCS in calm water and regular waves are carried out using body force propeller model (BFM). For the calm water condition, verification and validation study is performed based on experimental data gathered from SIMMAN 2008 [6]. The computed vessel trajectories and local motions are compared with predictions from the mathematical model (MM) based on Yoshimura and Masumoto [7]. The dynamic manoeuvres are also conducted in head sea Stokes waves, where comparisons of vessel manoeuvrability are made between the calm water and regular wave cases.

2 Ship geometry

The geometry of KCS was provided in Simonsen et al. [8]. This container ship model has been studied extensively by the ship hydrodynamics community, and with experimental data available from many publications. The fully appended model with rudder and propeller is given in Figure 1, where details and its operational conditions are available in the reference. The computed cases presented in this paper include turning circle manoeuvre at 35 degrees of rudder angle and 20/20 zig-zag manoeuvre. It is worth highlighting that port rudder is regarded as positive (+) while starboard rudder is treated as negative (-) rudder angle.
3 Computational method

The dynamic manoeuvres are carried out using commercial URANS solver STAR-CCM+. The code uses a finite volume discretisation on structured or unstructured grids consisting of arbitrary convex polyhedrals. The pressure-velocity coupling is solved using a PIMPLE algorithm, where its practical implementation is discussed in CD-adapco [9].

3.1 Computational domain, boundary conditions and grid

The computational domain is designed following the ITTC Practical Guidelines for Ship CFD Applications [10]. A schematic drawing of the computed fluid domain is given in Figure 2. For the calm water conditions, a velocity inlet boundary is applied at the upstream end and side walls of the fluid domain. At the downstream end of the fluid domain, a pressure outlet boundary is imposed. Damping is applied at these surfaces to prevent reflections of surface waves. The top and bottom sides are selected as velocity inlet to avoid velocity gradient occurring at the boundaries. For the wave cases, the up and downstream ends of the domain are both set as velocity inlet boundary while the top side of the domain is modified to be a pressure outlet boundary. Instead of using damping, wave forcing is applied at the upstream, downstream and side walls to minimise reflection.
Slow cell growth rate is selected to create smooth mesh transition between the refined hull surfaces and the overset boundaries. Hexahedral trimmer and surface remesher are adopted to generate global volume mesh as well as local refinements. To resolve the turbulent boundary layer, all y+ wall treatment is utilised as well as the prism layer mesh, achieving minimum y+ value of 30 along the hull for all computations. At the free surface, anisotropic trimmer refinement is applied in the vicinity of the ship hull to capture the Kelvin wave generated during the dynamic manoeuvres. For the wave cases, the free surface mesh refinement contains a number of 80 cells per wavelength and 20 cells in wave height.

3.2 Wave generation for dynamic manoeuvres
The waves are generated by applying time-varying water particle velocity and pressure at the boundaries of the fluid domain that is initialised using the Volume of Fluid (VoF) technique. For the present study, fifth-order Stokes waves are used for the manoeuvring in waves simulation. The theory is based on Fenton [11] and resembles a real wave more closely than one generated by the method using the first order wave theory. Previous work by Tezdogan et al. [12] adopted this wave theory to generate regular waves for wave added resistance predictions of KCS. Their results show a 3.20% difference between generated wave height and the input values, which was considered to be acceptable for their purpose.

3.3 Modelling of ship motion, rudder control and propulsion
The motions of ship 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 in Figure 1. 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 acts as a child object to the ship overset body and moves together with it. The strategy to compute the angular motion of rudder depends on the type of manoeuvres required. For the turning circle manoeuvre, the rudder is fixed at zero degree angle until the ship reaches a constant speed, and then it deflects to a prescribed angle allowing the ship to carry out the manoeuvring motion. To compute the zig-zag manoeuvre, the rudder angle is governed by a field function referring to the yaw angle of the ship.

The ship model is self-propelled at model scale propulsion point by a momentum disk. The angular velocity of BFM is initially adjusted manually to match the vessel’s advancing speed, and then maintained constant throughout individual manoeuvres. The approach applies the actuator disk concept to account for the presence of the propellers. A field of body forces are distributed over the cylindrical virtual disk, and varies in its radial direction following the Goldstein optimum. The distributed axial and tangential body forces are used to simulate the acceleration and the increase in swirl that the flow undergoes when passing through the propeller. In this paper, the propeller speed is set to 11 rps to ensure a constant self-propulsion velocity which corresponds to Fr=0.26. The greatest advantage of the BFM is its rapid computational time. However, it is evident from literature that the velocity profile upstream of the propeller plane has significant spatial variation. Besides that, the propeller is also under the influence of cross flow, waves and wave-induced ship motion. Current approach of using the BFM method may not able to fully captures these important aspects. Research is underway to investigate alternative propulsion modelling approach to better address these physics.
4 Verification and Validation

Prior to performing computations on the dynamic manoeuvres, it is essential to verify and validate the present computational approach. Due to availability of experimental data, the port side turning circle manoeuvre at $\delta = +35^\circ$ in calm water is selected as the base case for conducting the verification and validation study.

4.1 Numerical uncertainties

Verification study is carried out using the triplets method recommended by Stern et al. [13] and Wilson et al. [14]. It decomposes the numerical uncertainty $U_{SN}$ into iterative uncertainty $U_I$, grid spacing uncertainty $U_G$ and time-step uncertainty $U_T$.

$$U_{SN}^2 = U_I^2 + U_G^2 + U_T^2$$

The uncertainty analysis in this paper focuses on quantifying $U_G$ and $U_T$, since the magnitude of $U_I$ is normally trivial. The grid and time-step convergence study are both conducted with triple solutions systematically, where the grid uncertainty is estimated with the smallest time-step, whilst the time-step independence study is carried out with the finest mesh. Details of the grid and time-step adopted in the verification study are presented in Table 1. The refinement ratios of the grid spacing ($r_G$) and time step ($r_T$) are selected to be $\sqrt{2}$ and 2 respectively. The quantified uncertainties are relatively small, demonstrate the feasibility of the adopted medium grid-spacing and time step for undertaking further systematic simulations.

Table 1. Computational grids and time-steps employed in the verification study

| Number of elements ($\times 10^6$) | Time-step ($\Delta t$) |
|-----------------------------------|------------------------|
| Fine (1)                          | 10.6                   |
| Medium (2)                        | 3.74                   |
| Coarse (3)                        | 1.23                   |

4.2 Benchmarking calm water manoeuvres

To validate the presented computations, the absolute comparison error $E$ between numerical and experimental fluid dynamics (EFD) results are compared with the validation uncertainty $U_V$ in Table 2. $U_V$ is calculated as a combination of numerical uncertainty $U_{SN}$ and experimental uncertainty $U_D$ as in Equation (2),

$$U_V = \sqrt{U_{SN}^2 + U_D^2}$$

The experimental uncertainty $U_D$ is not provided in the literature, therefore it is approximated as 5.00%. By comparing $U_V$ against $E$, one can find that the present URANS model is validated for the tactical diameter and steady surge velocity predictions. The advance distance and steady yaw velocities are not validated, primarily due to the relatively large discrepancies (around 10.0%) with the experimental data obtained from literature.

Table 2. Validation of URANS computation of turning circle manoeuvre

|                      | $U_{SN}$ (% EFD) | $U_D$ (% EFD) | $U_V$ (% EFD) | $E$ (% EFD) |
|----------------------|------------------|---------------|---------------|-------------|
| Tactical diameter $D_T$ (/Lpp) | 2.24             | 5.00          | 5.48          | 0.76        |
| Advance distance $A_D$ (/Lpp)   | 4.74             | 5.00          | 6.89          | 12.6        |
| Steady surge velocity $u$ (m/s)  | 10.4             | 5.00          | 11.5          | 10.5        |
| Steady yaw velocity $\phi$ (deg/s) | 3.88             | 5.00          | 6.33          | 12.2        |
Figure 3 provides an overview of the agreement between different techniques for predicting KCS manoeuvrability in calm water. The CFD and EFD data are also compared with MM simulated results, based on the MMG manoeuvring model from Yoshimura and Masumoto [7]. The EFD data are based on the free running (FR) and planar motion mechanism (PMM) model test from MARIN and FORCE. One can observe that the MM results correlate well with our URANS computational results. When comparing with model test free running manoeuvres, both MM and URANS approaches under-predict the manoeuvrability of the KCS model. For the URANS computation, this may due to inaccurate resolving of the propeller rudder interaction using the BFM technique. An additional study will be carried out with overset grid to compute the discretised propeller motion, to better capture the rudder performance under propeller induced flow.

Free surface elevations in the vicinity of the KCS model at different phases during the turning circle manoeuvre are presented in Figure 4. The Kelvin wave pattern aft of the vessel is generally well resolved. One can notice that the surface wake amplitude decreases gradually as the vessel reaches the end phase of the turning circle. This is primary due to the significant reduction in the advancing speed of the vessel, which drops from 2.2m/s at excution of the manoeuvre to about 0.9m/s when reaching the steady state of turning.

**Figure 3.** Dynamic manoeuvres of KCS in calm water (a) trajectory of port side turning at $\delta=35^\circ$ (b) zigzag manoeuvres 20° stbd rudder/ 20° yaw angle

(a) $\phi=270^\circ$  
(b) $\phi=180^\circ$
Figure 4. Turning circle manoeuvre at different yaw angles in calm water

5 Manoeuvres in regular waves

Once the grid configurations and time-step are selected, the vessel is set to undertake different standard dynamic manoeuvres in head sea Stokes waves. Prior to releasing 6 DoF motions of the vessel, the model is superimposed with an advancing speed which corresponds to Fr=0.26 until its wake is properly developed. Matrix of the studied cases is listed in Table 3. The important aspect is to understand whether existing calm water characteristics are sufficient to describe vessel manoeuvring behaviour in waves.

Table 3. Study matrix of the KCS dynamic manoeuvres

| Case | Fr  | Manoeuvre          | Wave direction | Wave Height H (m) | λ/Lpp |
|------|-----|--------------------|----------------|-------------------|-------|
| 1    | 0.26| Turning circle δ=35° | -              | -                 | -     |
| 2    | 0.26| Turning circle δ=10° | -              | -                 | -     |
| 3    | 0.26| Turning circle δ=35° | Head sea       | 0.07              | 0.5   |
| 4    | 0.26| Turning circle δ=10° | Head sea       | 0.20              | 1.1   |
| 5    | 0.26| Zigzag -20/20       | Head sea       | 0.07              | 1.1   |

5.1 Turning circle manoeuvre

The turning circle manoeuvre was first carried out in head sea Stokes waves of λ/Lpp=0.5 at a port-side rudder angle of δ=+35°. An overview of the wave pattern around the the vessel during such manoeuvre is provided in Figure 5. As the vessel starts to make the turn in waves, it creates a large shadow zone at the port side of the hull. This also indicates the vessel experiences a great amount of wave drift loads at the same time, due to the significant wave reflection happening simultaneously. The shadow zone at the port side will remain for a period of time, and interact with the vessel and incident waves after the 180° of turning. A much more chaotic wave patterns are expected afterwards.

The trajectory and yaw velocity of the vessel are also compared against that computed from corresponding calm water condition in Figure 6. It was found the vessel has drifted significantly along the wave direction as shown in Figure 6(a). This is understood by the fact drift sway force and drift yaw moment tend to be of great magnitude at λ/Lpp=0.5, when reflection is profound as the vessel turns in the front of the waves. Similar finding can be seen in Zhang et al. [4] for the S175 container ship turning circle manoeuvres in regular head sea waves. From their results, it was found the magnitude of drift sway force and drift yaw moment in beam sea waves could be utilised as an indicator of the significance of drift in trajectory. Their work reveals drift sway force and drift yaw moment in beam sea declines as the wave length increases from λ/Lpp=0.5 to 1.25. This tendency was also reflected in the drift of their experimentally measured vessel trajectories. That is from
\[ \lambda/L_{pp} = 0.5 \text{ to } 1.25, \text{ the significance of trajectories drift decreases. On the other hand, the general trend and magnitude of the yaw velocity for the studied wave condition does not differ from the calm water case. The primary influence is found to be the wave frequency effect and large fluctuations appear when there is a solid oblique angle between the waves and the vessel for example, between } 45^\circ \text{ to } 135^\circ \text{ and } 245^\circ \text{ to } 315^\circ \text{ yaw angle, headings for which large yaw moment occurs. It is clear that the vessel manoeuvres differently in short wave length compared to calm water and its ability to safely execute turns in restricted waters must account for the influence of such waves.}

A similar port side turning circle manoeuvre has also been computed in head sea regular waves of \[ \lambda/L_{pp} = 1.1 \] at the rudder angle \[ \delta = 10^\circ \]. As opposed to the short waves of \[ \lambda/L_{pp} = 0.5 \], wave reflection during the turning is found to be insignificant for \[ \lambda/L_{pp} = 1.1 \]. The long waves pass through the vessel even when they are at \[ 90^\circ \] of the vessel’s heading. Referring back to Maruo’s formula [15], the wave drift force is proportional to the square of reflected wave potentials. Therefore, the wave drift effect in oblique and beam seas at wave length of \[ \lambda/L_{pp} = 1.1 \] is expected to be less significant than it is for \[ \lambda/L_{pp} = 0.5 \] assuming the same wave amplitude. After turning \[ 180^\circ \], the vessel also has the tendency to interact with its own wake field. Again this chaotic phenomena requires further validation from experimental work.

![Figure 5](image-url)

**Figure 5.** Port side turning circle manoeuvres (\( \delta = \pm 35^\circ \)) at different yaw angles in regular head sea waves \( H=0.07\text{m}, \lambda/L_{pp}=0.5 \)
Figure 6. Comparison of port side turning circle manoeuvres at $\delta=+35^\circ$ in calm water and regular head sea waves (a) trajectory (b) yaw velocity

Figure 7 captures the trajectory, surge velocity, yaw rate and roll angle of the vessel within the first 360° of turning. The wave height was increased to 0.20m intentionally in order to emphasise the drift of the circular trajectory as shown in Figure 7(a). The presence of large waves also leads to a greater and more rapid drop of surge velocity throughout the manoeuvre as seen in Figure 7(b). The yaw velocity of the vessel during such maneuvre is reported in Figure 7(c). The general trend is similar to that observed for the shorter waves in Figure 6(b) but with larger fluctuations along the time history. Large yaw rates are found in the head quartering and following quartering seas. The roll motion of the vessel in the studied wave condition is seen to be much more violent comparing to calm water condition in Figure 7(d). The maximum roll angle (approx. 25 degs) appears at the first beam sea position ($\phi=90^\circ$). As the vessel turns from beam sea to following sea ($\phi=180^\circ$), the roll motion declines gradually. When the vessel rotates from the first following sea position to the second beam sea position ($\phi=270^\circ$), the roll motion rises slowly but reaches a less significant amplitude compared to the peak roll response. The second peak of roll motion appears at the second head quartering sea position ($\phi=315^\circ$), and it decays as the vessel returns back to a head sea position ($\phi=360^\circ$). This part of results indicates turning in rough sea states will bring significant motion responses to the vessel, such operations have to be evaluated carefully before hand to ensure safe voyage, under remote or autonomous control. Presently, such decisions are made by experienced mariners onboard. It will be challenging to develop intelligent algorithms to maintain safe operations under such challenging environmental conditions.
Figure 7. Comparison of port side turning circle manoeuvres at $\delta=+10^\circ$ in calm water and regular head sea waves (a) trajectory (b) surge velocity (c) yaw velocity (d) roll angle

5.2 Zig-zag manoeuvre

The -20/20 zig-zag manoeuvre has also been carried out in Stokes waves from ahead, and compared with the corresponding calm water condition. Unlike in the turning circle manoeuvre, the vessel seldom encounters its own diffracted and radiated waves. This makes the free surface relatively easier to capture with the current setup.

The CFD computed hydrodynamic loads and vessel velocities during the manoeuvre in waves are recorded and compared with calm water predictions in Figure 8. One can observe from Figure 8(a) that the major differences within surge force between the two cases are the extra wave frequency and drift force on the vessel. This induces fluctuations and reduction of the vessel’s advancing speed when compared with calm water condition in Figure 8(d). On the other hand, only wave frequency effect is observed for the sway force acting on the vessel. The influence of drift force is insignificant and this is reflected by the recordings of sway velocity during the manoeuvre in Figure 8(d). The magnitude of sway velocity remains almost unaltered as it is in calm water condition. The performance of rudder force between the two cases are also seen to be very close to each other. The presence of waves does not result in significant reduction of the steering force for the studied case. It is worth highlighting that the zig-zag manoeuvre carried out is only for benign sea-state in head sea. The outcome may vary when performing the same manoeuvre in waves with more significant wave height or at different wave headings.
Figure 8. Comparison of zigzag manoeuvres (-20/20) in calm water and regular waves (a) surge force (b) sway force (c) rudder lateral force (d) surge and sway velocities

6 Conclusions and future work

The dynamic manoeuvres of KCS in calm water and regular head sea waves are studied by using URANS CFD method in this paper. Propulsion of the vessel is modelled through BFM based on open water performance curve of the appended propeller. The calm water computations are verified and benchmarked against experimental results from the literature. At an approaching speed corresponding to Fr=0.26, the dynamic manoeuvres in waves are compared with corresponding calm water cases. For the turning circle manoeuvre, wave effects are dominated by drift force exerted on the ship hull, causing spatial shift in its spiral trajectory along time. The magnitude of this trajectory drift depends on the incident wave frequency and wave height. For the zig-zag manoeuvre, waves effects mostly appear in the surge force of the vessel resulting in reduction in the free running speed. The manoeuvrability of the vessel seems to be unaffected for the studied wave condition, however more wave conditions need to be studied to reach a more general conclusion.

Future research will be carried out on validating and implementing more sophisticated propeller model to account for cross flow encountered during the dynamic manoeuvres. Alternative approaches will be using moving reference frame or solving discretised propellers directly using overset grid in the manoeuvring simulations. More wave cases will be computed at different incident wave headings will be computed to quantify wave effects and validate MM/SB simulation results. The simulation results will be used to help developed advanced control for future autonomous and remotely operated vessels.
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