Turning Circle Maneuvers of the ONR Tumblehome in Bidirectional Waves Using a Fast-Running CFD Approach

Bradford G. Knight[a]
a. Dept. of Ocean Engineering, University of Rhode Island, Narragansett, RI, USA
Email: bradford.knight@uri.edu

Highlights

This work analyzes the effects of bidirectional waves on the turning circle maneuvering characteristics of the ONR Tumblehome using a fast-running CFD approach. The computational cost of the CFD simulations is reduced through the use of a data-driven propeller and rudder model. The analysis demonstrates that an increase in the angle between the two wave trains in bidirectional waves leads to a decrease in second order drift distance, but has a small effect on the drift angle. The results also demonstrate that forward velocity fluctuations and maximum roll angle decrease with increased angle between the two wave trains.

1 Introduction

Ships must operate effectively in waves and the ocean environment. Computational Fluid Dynamics (CFD) is a popular tool for examining ship maneuvering in both calm water and in waves (Carrica et al. (2012), Huang et al. (2021), Aram & Mucha (2023), Di Paolo et al. (2023)). Frequently, the seakeeping and maneuvering characteristics of ships operating in a seaway are evaluated with modeling the waves as long-crested and regular waves. However, modeling a vessel in irregular waves is important, especially for analyzing extreme events such as slamming, green water on deck, and broaching (Knight et al. (2020), Silva et al. (2022)). It is also important to understand the differences in maneuvering characteristics between long-crested waves and multi-directional waves. Huang et al. (2021) examined the seakeeping characteristics of a vessel in bidirectional waves and demonstrated that in certain conditions the motions of the vessel are larger than in unidirectional waves.

The objective of this work is to evaluate the turning circle maneuvering characteristics for the ONR Tumblehome in bidirectional waves. This work utilizes a fast-running CFD method that uses a data-driven propeller and rudder model (Knight & Maki (2022), Knight & Maki (under review)). The present work demonstrates that the maneuvering characteristics of the vessel are affected by the angle between the wave propagation direction of the two wave trains in a bidirectional seaway.

2 Methodology

This work uses a Reynolds Averaged Navier Stokes (RANS) Volume of Fluid (VOF) CFD approach to model the vessel maneuvering in bidirectional waves. The simulations use the waves2Foam package developed by Jacobsen et al. (2011) with an implicit relaxation zone. The OpenFOAM platform is used with a customized 6-degree-of-freedom motion solver (White et al. (2022)). The bidirectional waves are modeled with two regular wave trains operating at an angle μ as shown by Figure 1. The vessel initially operates in head seas and is accelerated from rest to an initial velocity u_o of 1.11 m/s in the positive X direction, which correlates to a Froude number of 0.2. The ONR Tumblehome is analyzed at model scale with a length between perpendiculars L_{PP} of 3.147 m and a displacement of 0.0726 m^3. In each of the CFD simulations a bidirectional seaway is specified with two first order wave trains such that the wave elevation η is specified by Eqn. 1, in terms of the wave index i, the wave amplitude of each wave train a, the wave frequency ω, the time t, the wavenumber k, the position $\vec{x}$, the

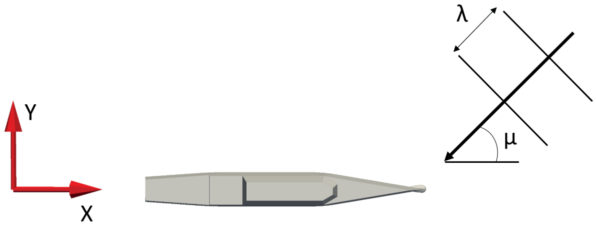

Figure 1: Schematic of reference frame and wave characteristics.

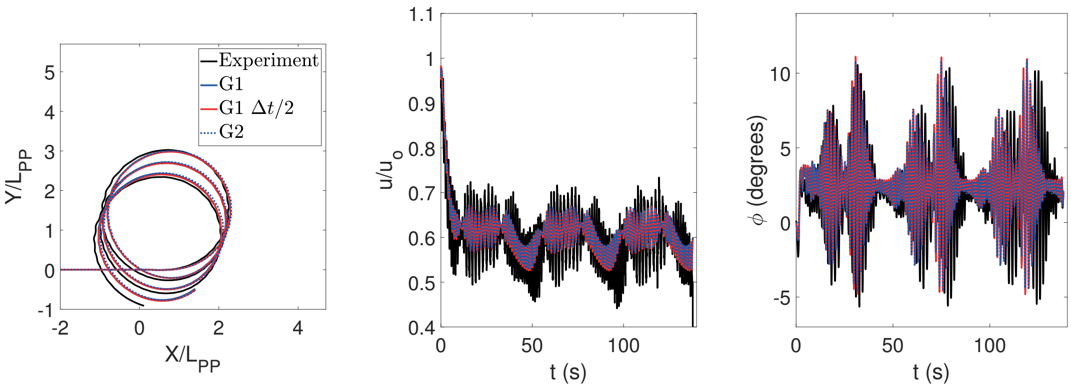

Figure 2: Trajectory, forward velocity, and roll as a function of time for vessel maneuvering in regular waves with $\lambda = L_{PP}$ and H/λ=1/50.

wave phase Φ, and the number of wave components N (Jacobsen et al. (2011)). All simulations use a wavelength λ equal to the L_{PP}. The amplitude of each wave component is 0.01575 m. Simulations are first performed for long-crested waves and compared to the SIMMAN (2023) experiments for a wave height of 0.063 m. For the long-crested waves, the μ is 0° for both wave components. For the bidirectional waves, the two wave components are specified with $\pm\mu$. Φ is specified such that the wave crest is at the vessel center of gravity when the rudder is actuated.

$$\eta = \sum_{i=1}^{N} a_i \cos(\omega_i t - \vec{k}_i \cdot \vec{x} + \Phi_i) \tag{1}$$

The propeller and rudder forces are determined with a data-driven propeller and rudder model, which uses Gaussian Process Regression to determine the propeller and rudder forces as a function of the vessel velocity, the propeller revolution rate, and the orbital wave velocity at the propeller and rudder plane. The propeller and rudder model is implemented in OpenFOAM to apply the propeller and rudder force to both the equations of motion and to the flow. The basis for the data-driven propeller and rudder framework is described in Knight & Maki (2022). This work utilizes an improved Gaussian Process Regression based propeller and rudder model developed in Knight & Maki (under review). The data-driven model is trained with steady drift RANS CFD simulations of the propeller and rudder in the behind condition, such that the hull-propeller-rudder interaction is accounted for in the model. Details of the propeller and rudder model can be found in Knight & Maki (under review).

3 CFD Prediction of Maneuver in Long-Crested Waves

Fig. 2 shows the agreement for the turning circle maneuver calculations between CFD compared to the experimental results of SIMMAN (2023) for the vessel in long-crested waves. The rudder is actuated to rotate to a rudder angle of $\delta = -35°$ at the origin ($X = Y = 0\ L_{PP}$ and $t = 0\ s$)

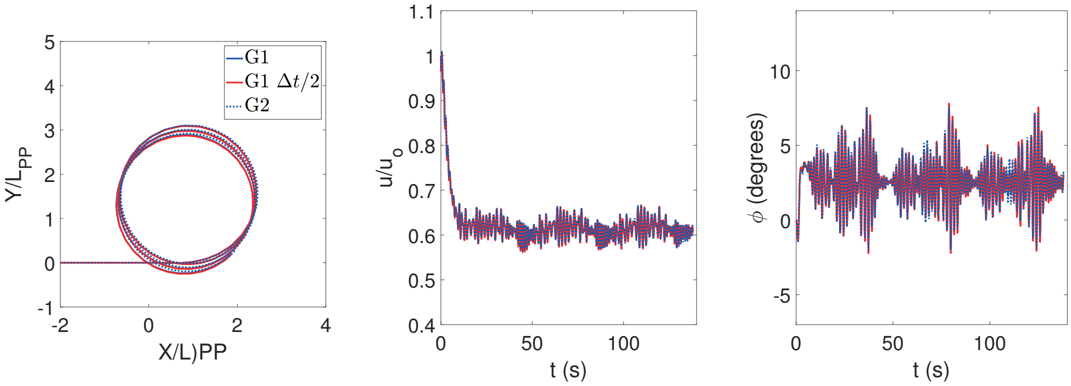

Figure 3: Trajectory, forward velocity, and roll as a function of time for vessel maneuvering in bidirectional waves with $\mu = \pm 45°$.

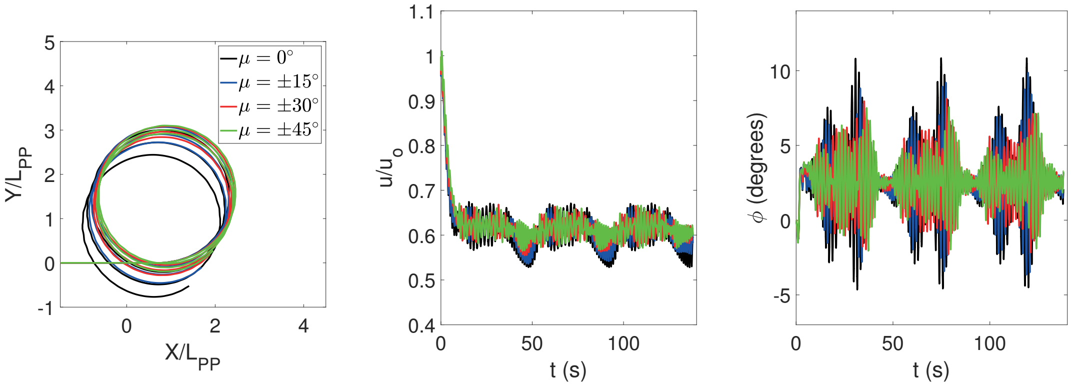

Figure 4: Trajectory, forward velocity, and roll as a function of time for vessel maneuvering in bidirectional waves on the G2 grid.

to start the turning circle maneuver. Two VOF grids are considered, a G1 grid with 1.0 million cells and a G2 grid with 2.8 million cells. Additionally, the effect of temporal discretization is considered with a nominal time step Δt of 0.0033 s and a half time step denoted $\Delta t/2$.

4 Effect of μ in Bidirectional Waves

Fig. 3 shows results of the turning circle maneuver calculations for the different spatial and temporal discretizations for the CFD for bidrectional waves with $\mu = \pm 45°$. The three simulations agree well with each other such that the minimum forward velocity is within 1% for all of the cases, and the maximum roll in the maneuver is within 0.31° for all of the cases. For all subsequent CFD predictions examining the dependence upon μ the G2 grid is used.

Fig. 4 shows the trajectory, forward velocity, and roll angle as a for $\mu = \pm[0°, 15°, 30°, 45°]$. As μ increases, the advance of the maneuver also increases, such that, the advance distance increases by 6.5% from $\mu = 0°$ to $\mu = \pm 45°$. The long-crested waves case also leads to the largest roll angle and most significant slowdown in waves. The long-crested wave case has a minimum velocity that is 7% less than the $\mu = \pm 45°$ case. The long-crested wave case also has a maximum roll angle that is more than 40% (3.27°) larger than the $\mu = \pm 45°$ case. The plot of the trajectory demonstrates that the second order drift distance decreases as μ increases in bidirectional waves. Fig. 5 shows the second order drift distance and drift angle as a function of μ in 5° increments of μ. The second order drift distance decreases substantially as μ increases, however, the drift angle does not change substantially as a function of μ.

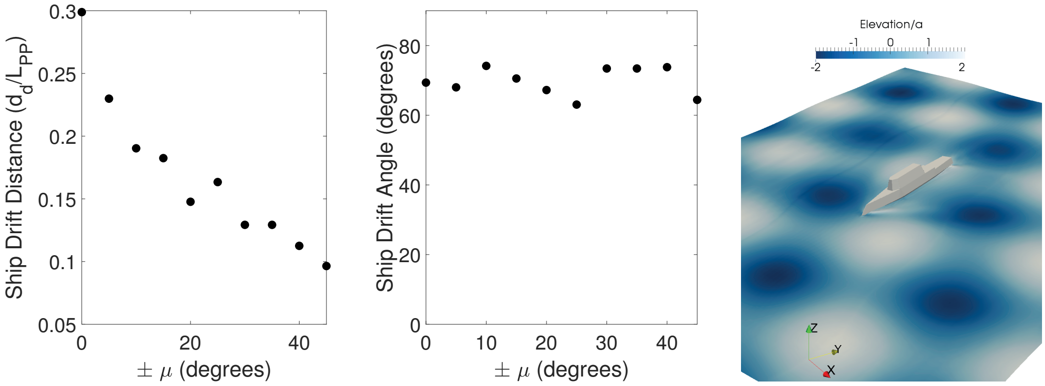

Figure 5: Images on left and middle: second order drift distance drift angle as a function of μ. Image on right: CFD calculation of vessel maneuvering in $\mu = \pm 45°$ bidirectional waves.

The right-most image in Fig. 5 illustrates the vessel at the point of maximum roll during the maneuver with $\mu = \pm 45°$ with the water surface shown in terms of elevation.

5 Conclusions

This work demonstrates that the angle between two wave trains in a bidirectional seaway affects the maneuvering characteristics of a vessel. In a long-crested seaway the second order drift distance is larger than in a bidirectional seaway. As the angle between the two wave trains increases, the second order drift distance decreases, but the drift angle does not change substantially. Furthermore, the maximum roll angle and the velocity fluctuations decrease in bidirectional waves compared to the long-crested seaway examined.

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