プロペラ及び主機の波浪中負荷変動が燃料消費量に与える影響の考察

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Summary

Summary

◻ Goal and Methods:

- The present research investigated through CFD (Computational Fluid Dynamics) the effects of waves on the propeller wake, evaluated the unsteady propeller torque through propeller curves, and computed the engine dynamic response to such a torque with GT-Suite, with a focus on **fuel consumption of ocean-going vessels in heavy seas**. The high fidelity of the simulations allows to draw conclusions on the unsteady effects of waves on fuel consumption, which phenomenon has not been thoroughly investigated before.

◻ Findings:

① Fluid dynamic analysis showed that, because of the large inertia of large ocean-going vessels, the effect of wave-generated ship motion on the wake can be generally discarded, and only the wave-generated fluctuations on the propeller wake can be considered.

② Engine analysis showed that, for a large marine engine in heavy seas and normal operations (i.e., no propeller emergence, etc.), the average propeller torque with the ordered engine speed can be adopted to satisfactorily predict the fuel consumption, as long as fast modern engine control techniques are assumed, as unsteady effects due to scavenging or turbocharger delays triggered by a fluctuating load were shown not to significantly affect the average fuel consumption.

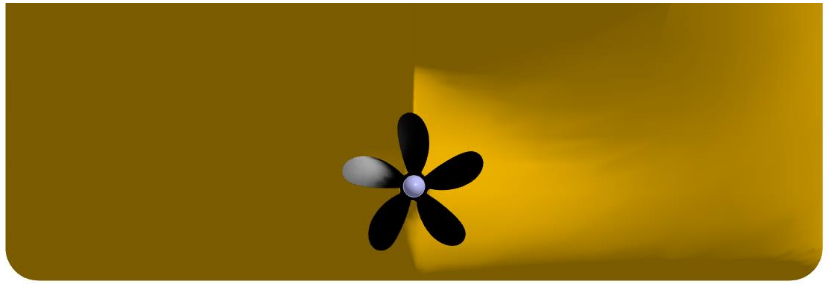
Fluid-Dynamic Analysis and Propeller Torque Assessment

Ship Specifications: JBC

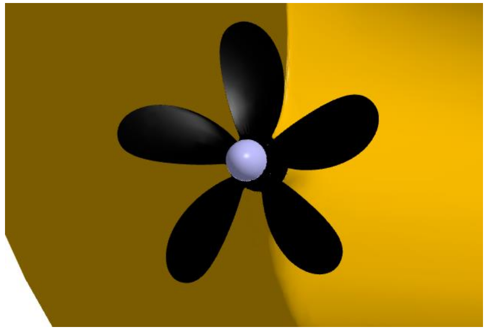
- A bulk carrier whose shape, hydrodynamic hull resistance, and propeller performance data are available was adopted: JBC, whose data were published by NMRI.

Hull Side View

Hull Bottom View



Propeller Stern View

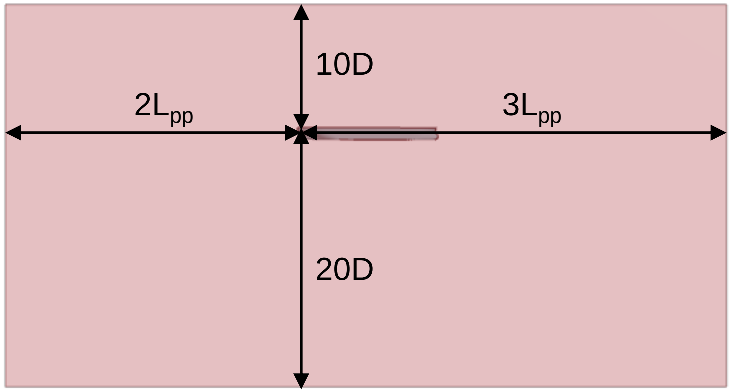


Propeller Close View

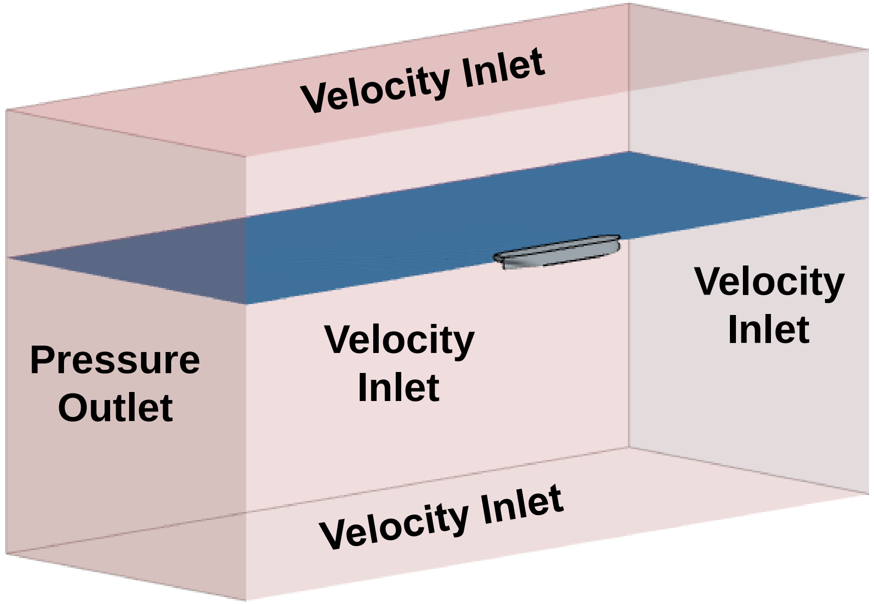
Main particulars			Full scale: DESIGNED FULL	Full scale: BALLAST CONDITION[*2]
Length between perpendiculars		L_{PP} (m)	280.000	same as on the left
Length of waterline		L_{WL} (m)	285.000	278.281
Maximum beam of waterline		B_{WL} (m)	45.000	same as on the left
Depth		D (m)	25.000	same as on the left
Draft(Ballast)	aft	T_A (m)	16.500	10.015
	mid	T_M (m)	16.500	8.615
	fore	T_F (m)	16.500	7.215
Displacement volume of a hull		∇ (m^3)	178369.9	89185.9
Displacement volume of a rudder[*2]		∇_R (m^3)	50.2	36.9
Wetted surface area of a hull[(1)]		$S_{0\_w/oESD}$ (m^2)	19556.1	14668.3
Wetted surface area of a hull with ESD[(1)]		$S_{0\_withESD}$ (m^2)	19633.9	14746.1
Wetted surface area of a rudder[*2]		S_R (m^2)	164.3	127.9
Block coefficient (C_B)		$\nabla/(L_{PP}B_{WL}T_M)$	0.8580	0.8216
Midship section coefficient (C_M)			0.9981	0.9964
L_{CB} ($\%L_{PP}$), fwd+			2.5475	1.5589
Vertical Center of Gravity (from keel)		KG (m)	13.29[*1]	12.20
Metacentric height		GM (m)	5.30[*1]	10.91
Moment of Inertia		K_{xx}/B	0.4[*1]	same as on the left
Moment of Inertia		K_{yy}/L_{PP}, K_{zz}/L_{PP}	0.25[*1]	same as on the left
Propeller center, long. location (from FP)		x/L_{pp}	0.985714	-----
Propeller center, vert. location (below WL)		$-z/L_{pp}$	-0.0404214	-----
Propeller rotation direction (view from stern)			clockwise	same as on the left

CFD Analysis: Problem Set-Up

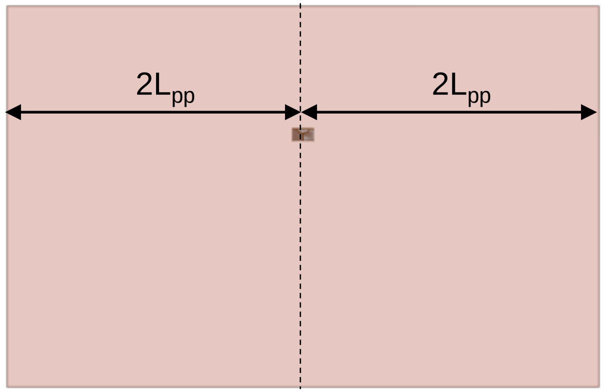
- A ship scale of 1:40 was adopted to validate the model against towing-tank tests. The full (not half) domain was modeled.
- The size is large enough to guarantee the upstream flow and the downstream wake are fully resolved.
- The domain reference frame is inertial and stationary with respect to the ship nominal speed of 14.5 kn. Boundary conditions on water and air speed and pressure were imposed.



Domain Starboard View



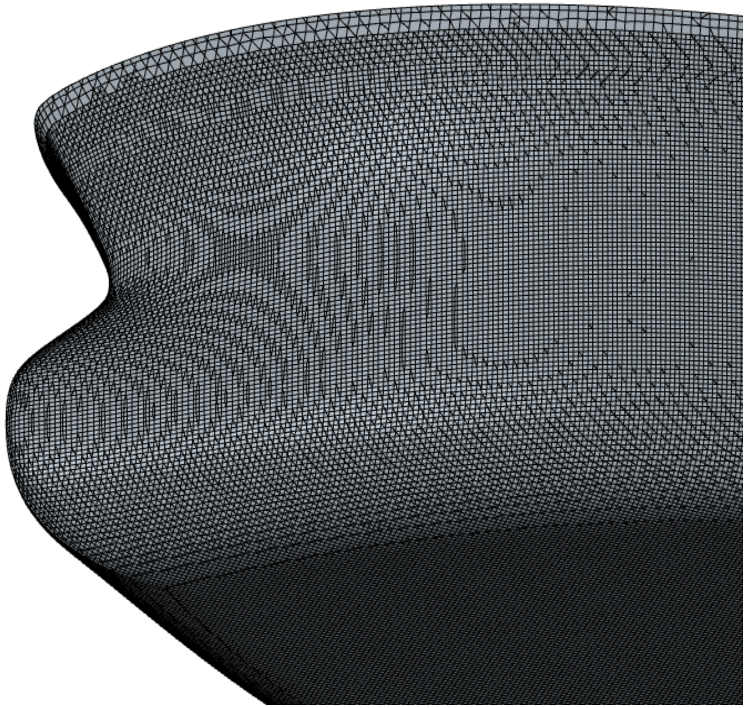
Boundary Conditions



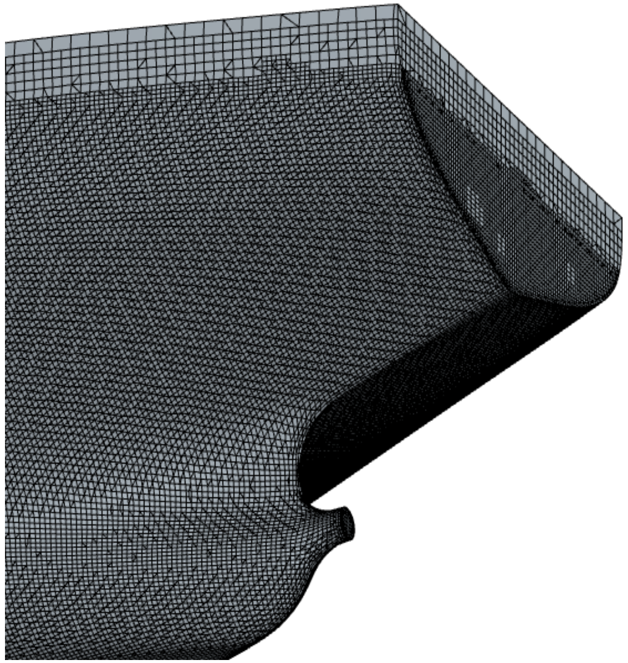
Domain Stern View

CFD Analysis: Numerical Settings

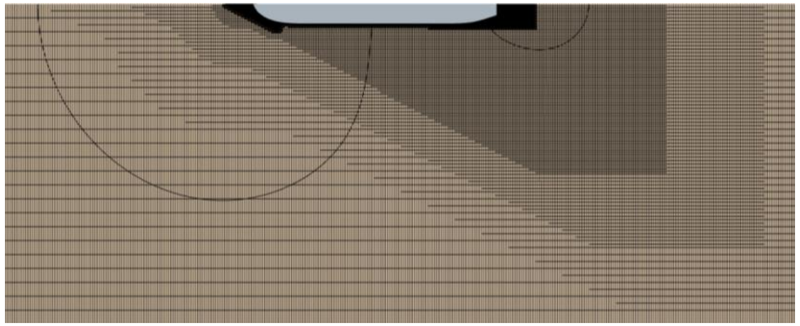
- A suitable mesh of around 13.1 million cells was cut.



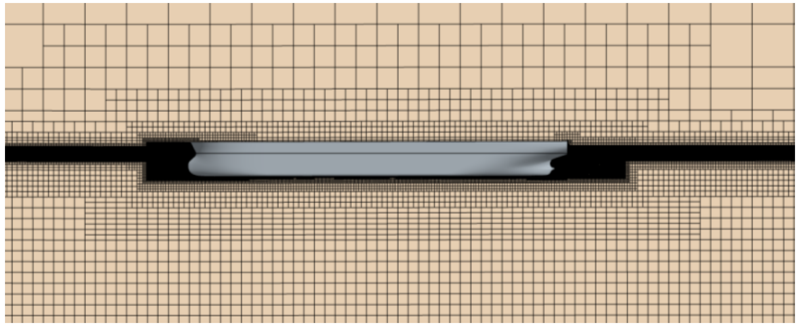
Mesh Bow View



Mesh Stern View



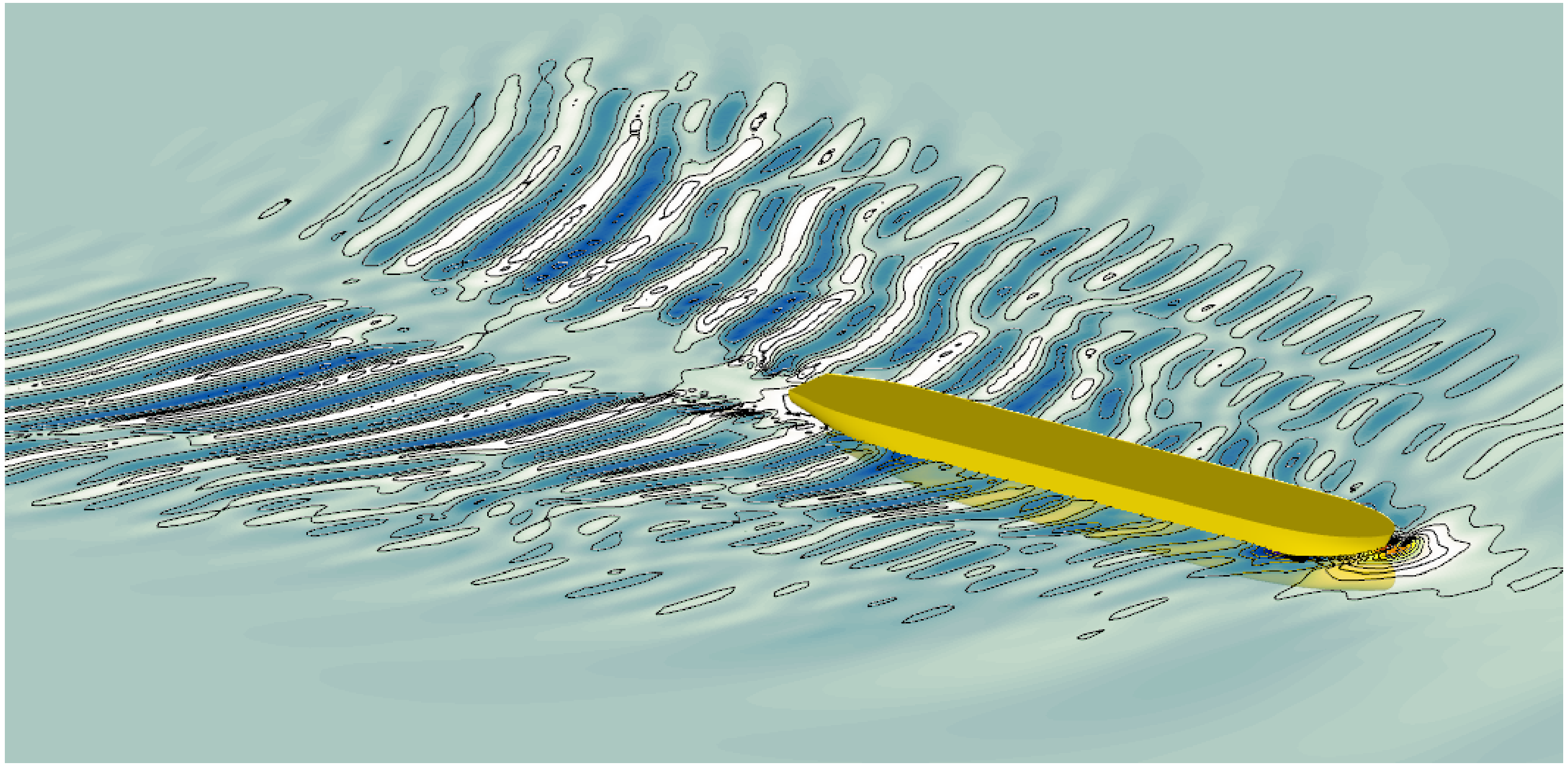
Mesh Free-Surface View: Top



Mesh Free-Surface View: Port

CFD Analysis: Numerical Settings

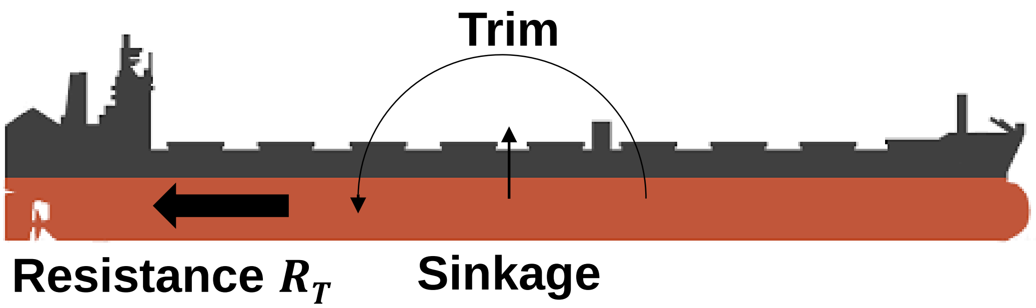
- Solver:
  - ◆Unsteady Reynolds Averaged Navier Stokes set of equations with SST (Menter) k-ω turbulence.
  - ◆Implicit Segregated Multiphase Flow with VOF-HRIC Method to model the free surface.
  - ◆DFBI to model the ship motion.

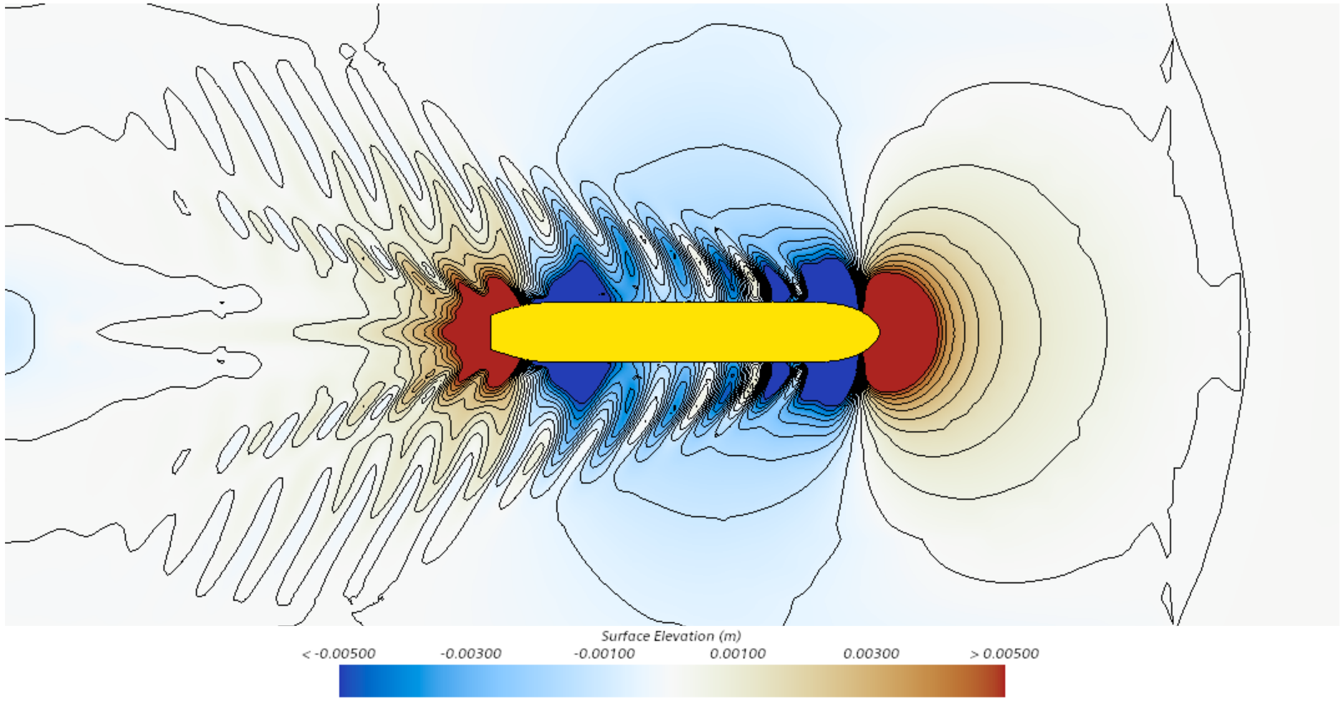


CFD Analysis: Validation

- CFD was validated in flat-water conditions consistently with the experiment without propeller.
- Excellent agreement was observed against experimental data.

	Experiment	CFD
Resistance R_T [N]	36.36	36.22
Sinkage [mm]	-6.02	-6.02
Trim [deg]	-0.103	-0.108

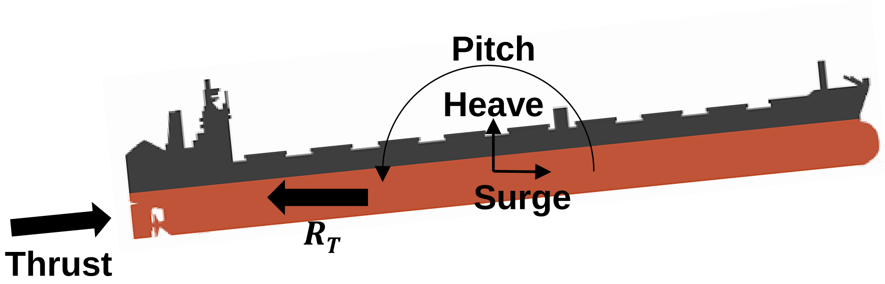


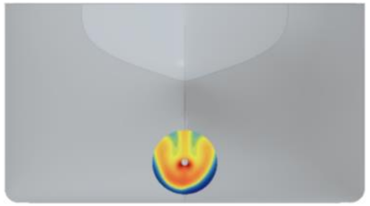


Details of the Flow Field with Wake

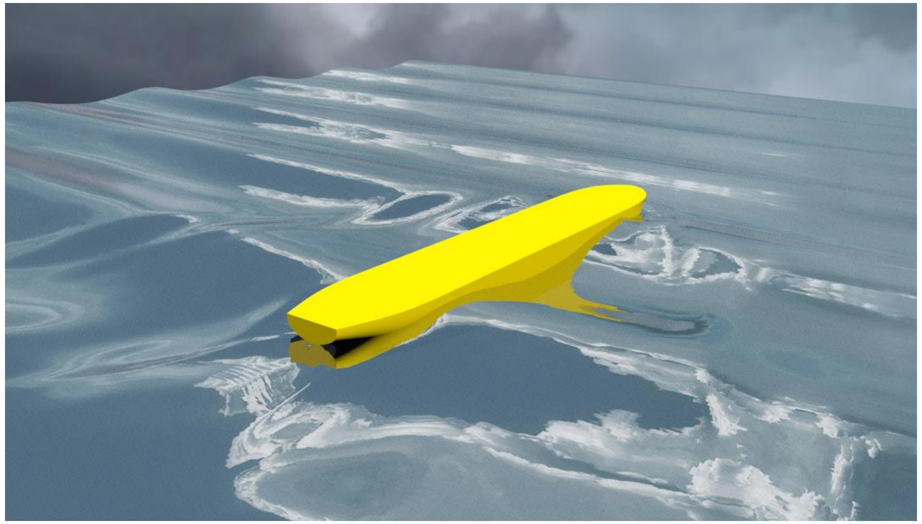
CFD Analysis: Motion in Waves

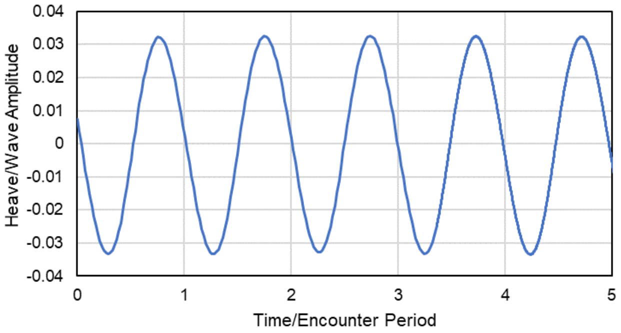
- CFD, which does not include the propeller, was adjusted to include the propeller resistance from experimental data and the skin-friction correction to correctly estimate the resistance for an equivalent ship at full scale.
- Surge, which had been fixed during validation, was freed, and a constant thrust preventing drift was imposed on the propeller location.

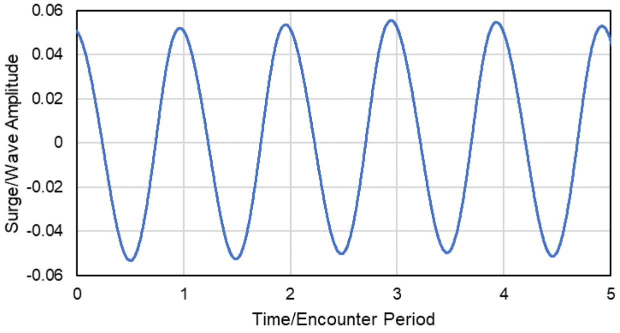


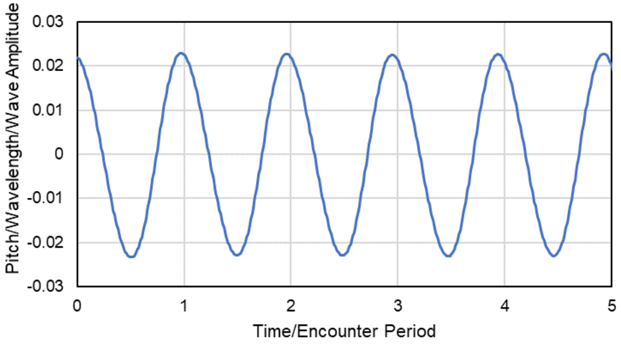


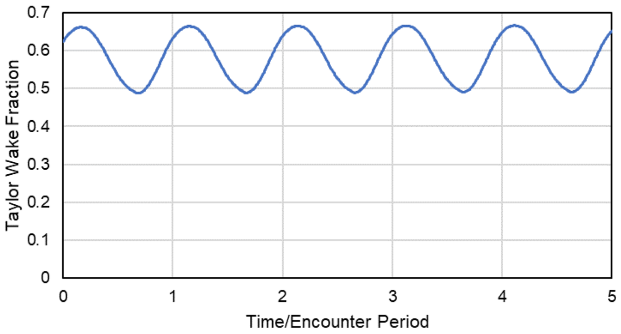
Stern View of Propeller Region for Taylor Wake







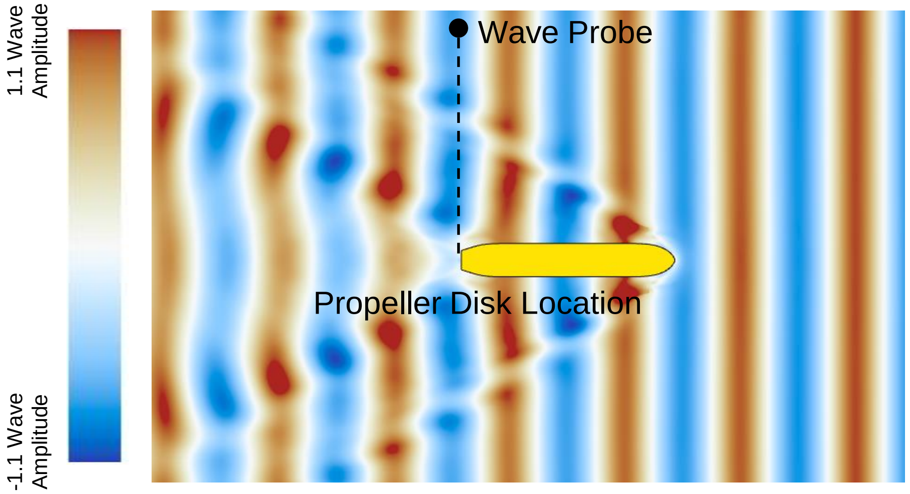




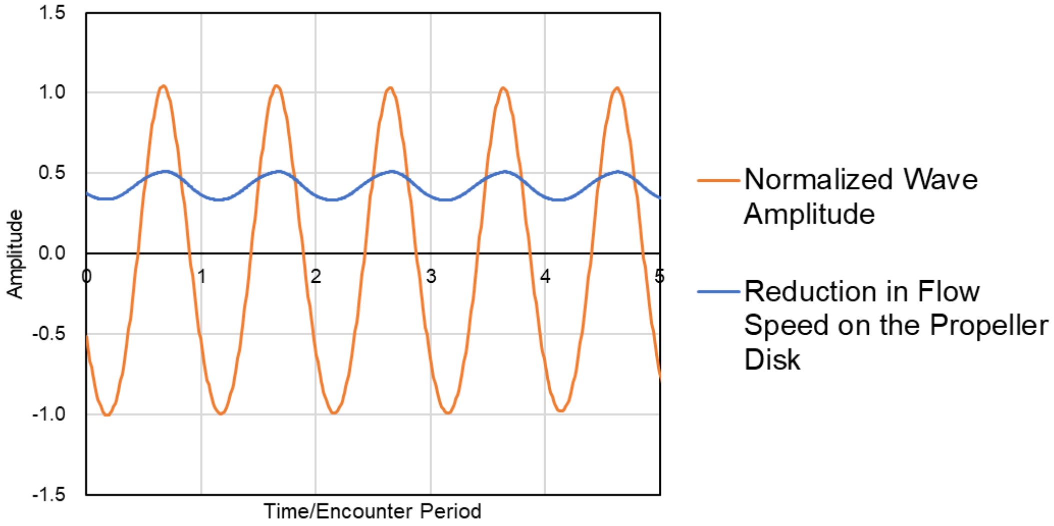
CFD Analysis: Wake in Waves

- The reduction in flow speed on the propeller disk due to the ship presence is the complement of the Taylor wake fraction w by definition.

$$Reduction\ in\ Flow\ Speed\ on\ the\ Propeller\ Disk = \frac{Flow\ Speed\ on\ the\ Propeller\ Disk}{Ship\ Speed} = 1 - w$$



CFD Overview



- Such a reduction is exactly in phase with the wave amplitude as measured at a location along the propeller disk that is not disturbed by the ship presence. This shows that the wake fraction is determined mainly by the incident wave and the ship wave diffraction and not by the waves radiated by the ship oscillation. That is, for large ships, the ship oscillations are so small that the propeller does not perceive them.

CFD Analysis: Torque in Waves

- The propeller rotational speed at full scale n such that the thrust T generated by the propeller equates resistance was found through the propeller thrust curve for both calm water resistance (R_c) and average resistance in waves ($\bar{R}_w$). The flow speed on the propeller (U_p) was evaluated through CFD. A factor r accounting for the effect of the propeller on the wake speed was assessed.
- For the fluctuating wave case, the same ordered propeller speed as in the average wave resistance case (n_w) was assumed. This is valid as long as the engine governor is fast enough. Here, $U_{p,w}$ is not an average value but a fluctuating value.
- The torque Q can be computed through the propeller torque curve. The power can be computed.

Calm Water

$$T_c = R_c \;\rightarrow\; n_c \;\rightarrow\; Q_c = Q_c(U_{p,c}, r, n_c)$$

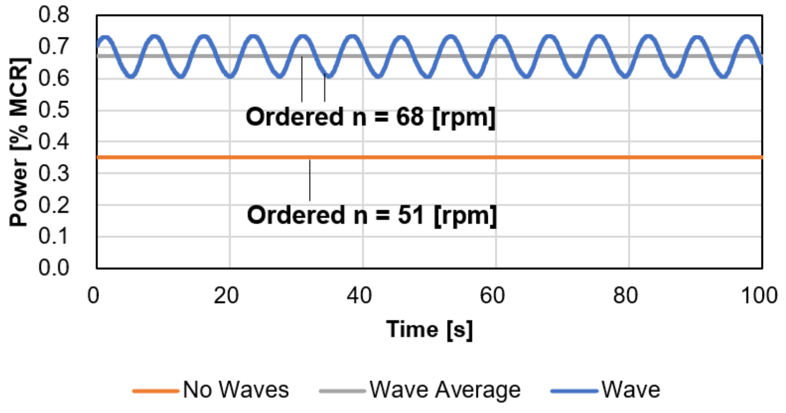
Wave Average

$$T_w = \bar{R}_w \;\rightarrow\; n_w \;\rightarrow\; \bar{Q}_w = \bar{Q}_w(\bar{U}_{p,w}, r, n_w)$$

Fluctuating Wave

$$n_w \;\rightarrow\; Q_w = Q_w(U_{p,w}, r, n_w)$$

Power History for a Frequently Encountered Wave Height and Period

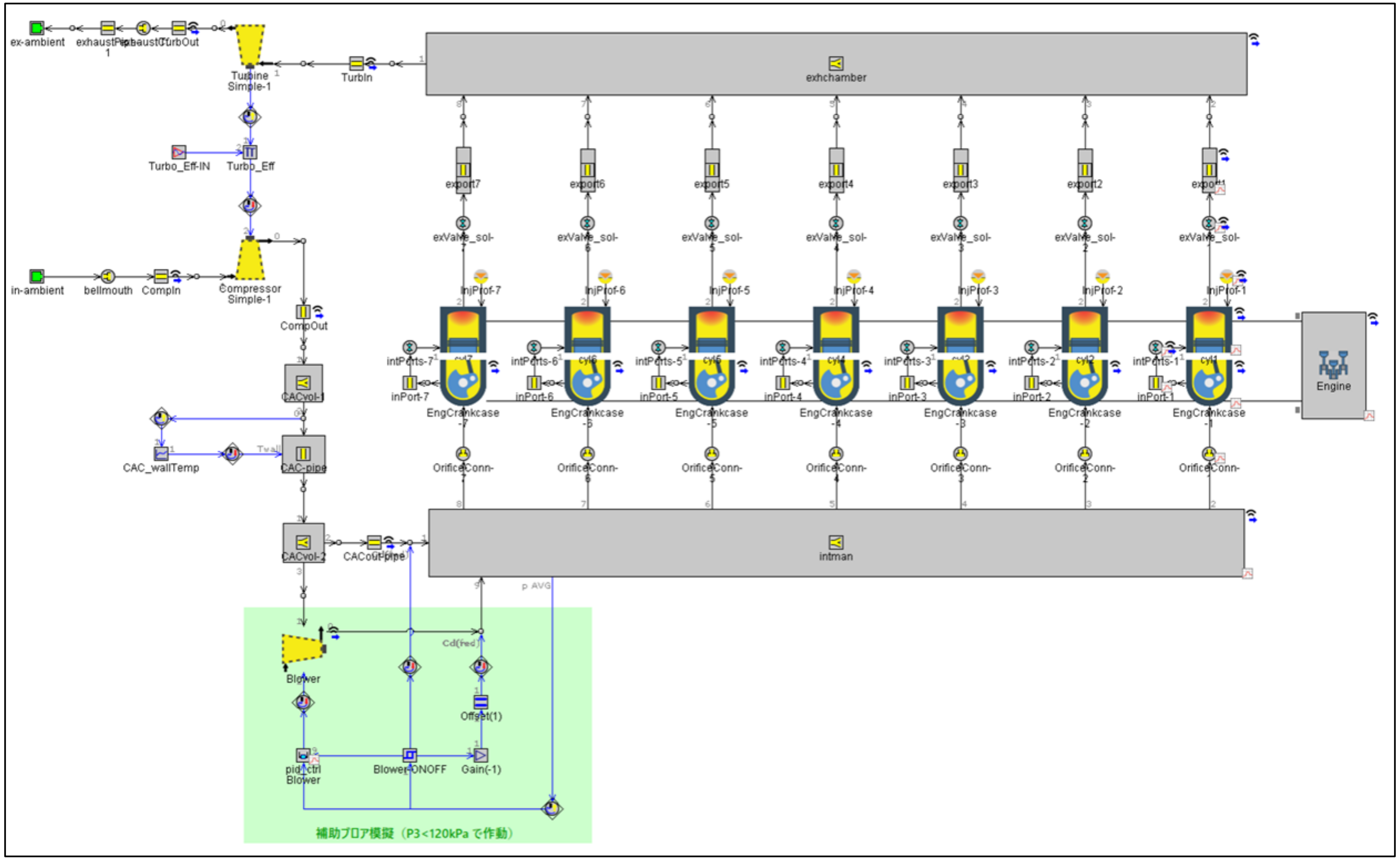


MCR: Maximum Continuous Rating

Engine Fuel-Consumption Analysis

Engine Analysis: Engine Model

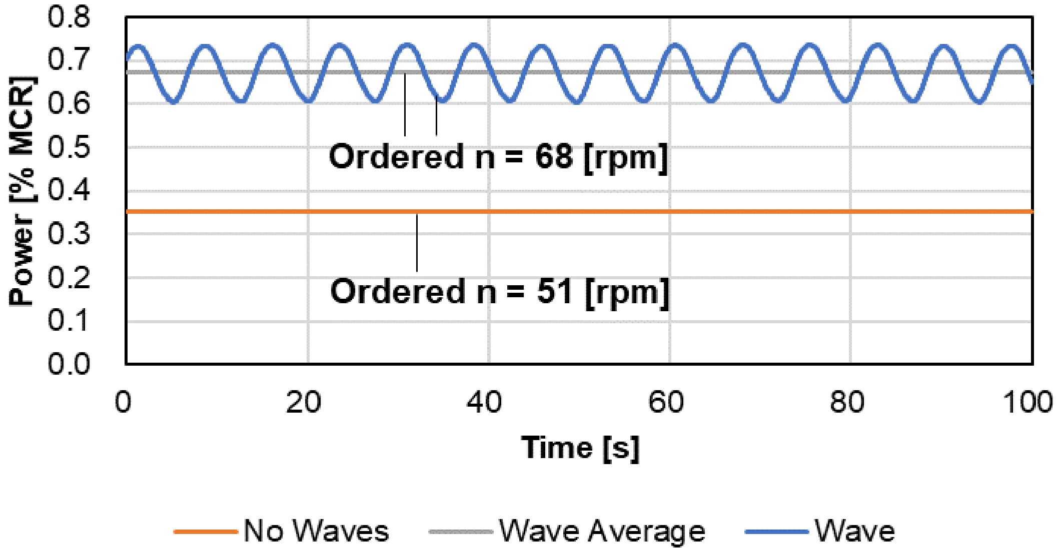
- An engine model was implemented in GT-Suite, which accounts for the full unsteady behavior of all engine components through mass and energy transfer. All the components are modeled as lumped components (0D), while combustion is solved along each cylinder (1D). The details of the engine governor and injection controller reflect realistic algorithms adopted for a bulk carrier of a similar size as JBC.



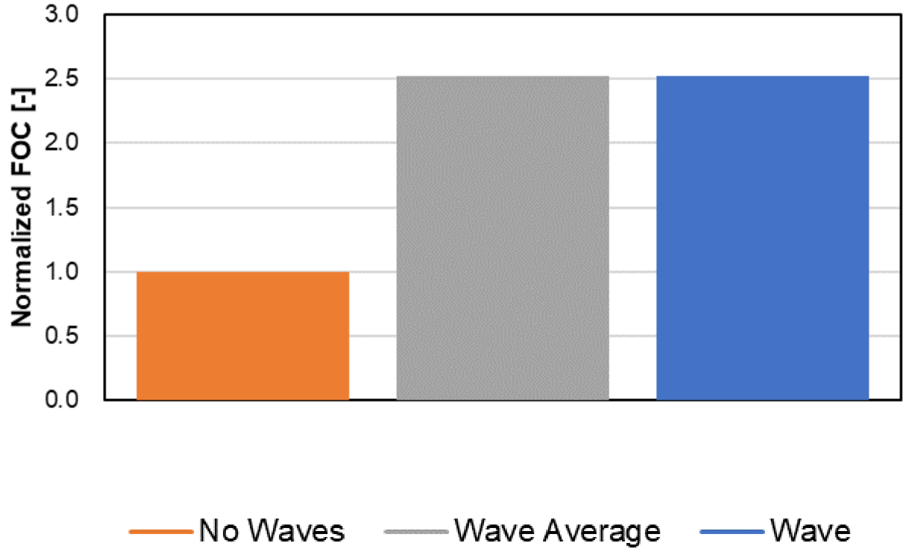
Fuel: Torque Fluctuations

- A comparison between the fuel consumed in calm water, in average wave-resistance conditions (average constant engine torque) and fluctuating wave resistance (fluctuating torque) for a wave height and period that represents a severe but frequently encountered sea state shows that the effects of fluctuating torque are negligible. That is, **averaged value for resistance and torque can be adopted to accurately estimate the fuel consumption in waves**.

Power History for a Frequently Encountered Wave Height and Period



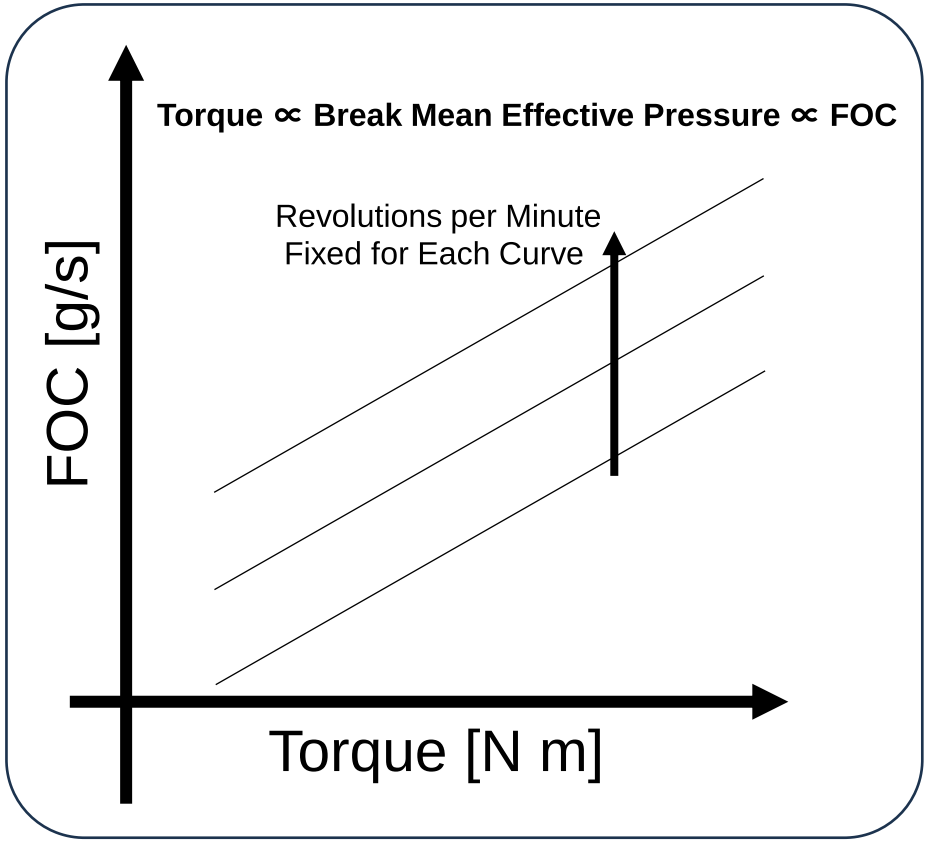
FOC (Fuel-Oil Consumption)



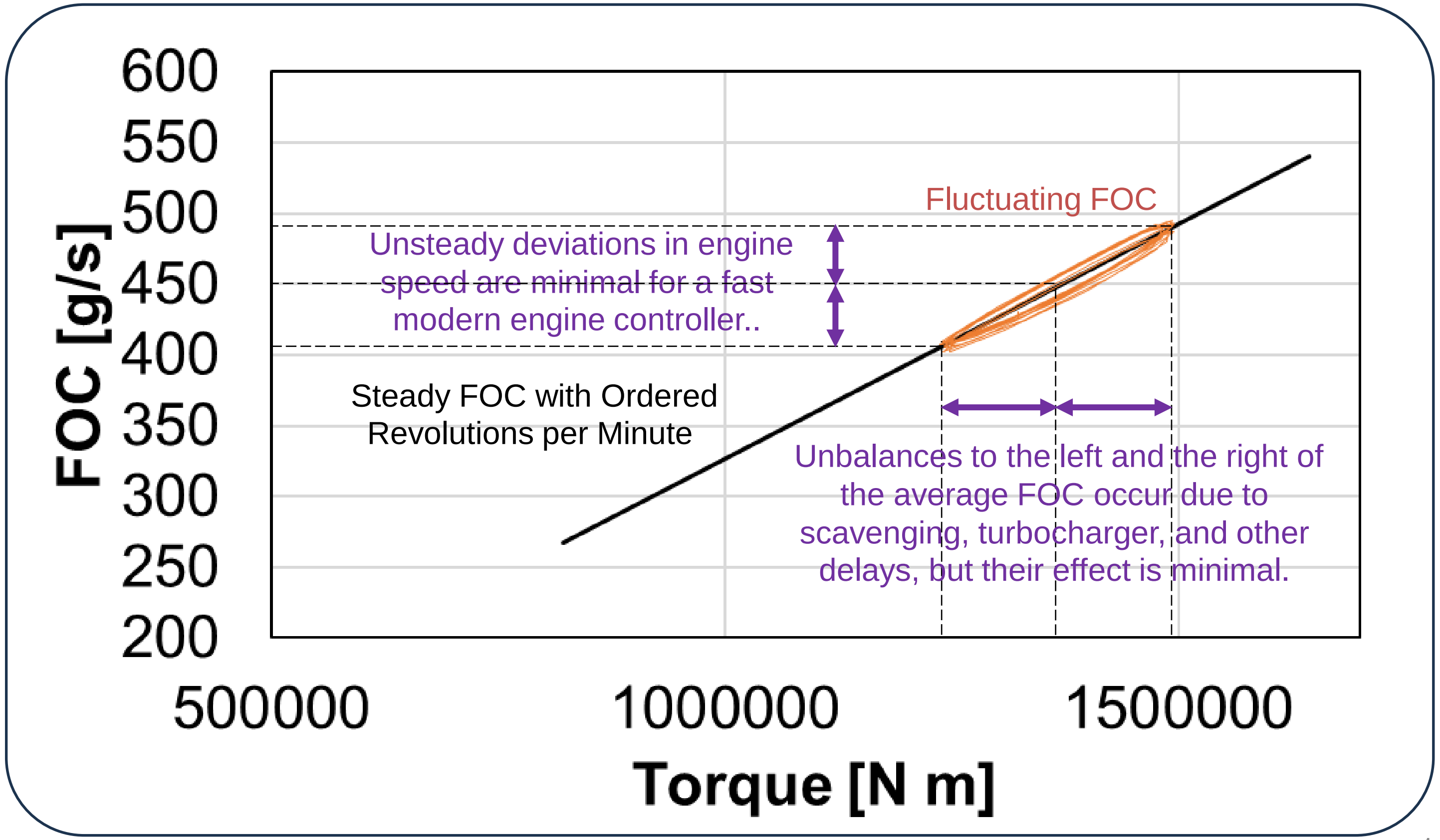
Fuel: Unsteady Behavior

- The key reason for this behavior is that, for large marine engines, the fuel consumption **obtained from steady simulations** is roughly a linear function of the torque for fixed engine speed. Therefore, the fuel consumption obtained for an average torque and ordered engine speed is close to the value obtained in fluctuating conditions.

Steady Fuel Map Schematic

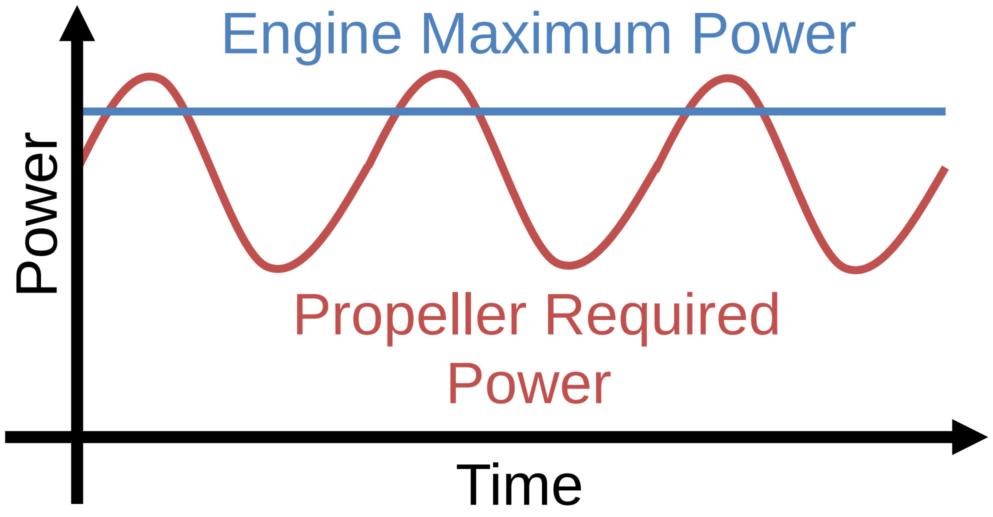


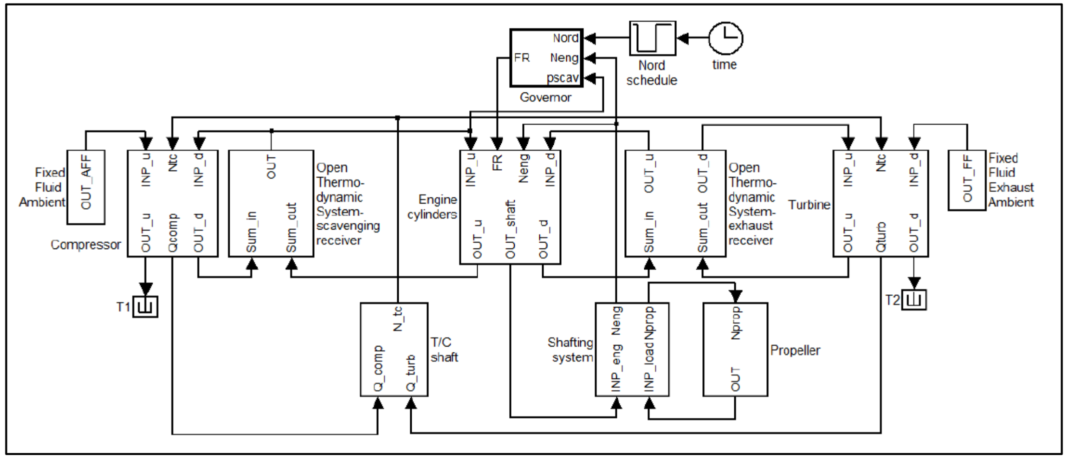
Unsteady Behavior Schematic



Fuel: Limitations and Next Modeling Steps

- This behavior does not hold if ① the engine controller is slow, which is not the case for modern controllers, ② in case of such wave heights that the propeller emerges from water, which is a rare event, ③ for step changes in torque, which still do not account for significant variations in fuel consumption, ④ or if the engine maximum power is reached, which is a relevant occurrence requiring a dynamic engine model.
- Therefore, for the purpose of assessing fuel consumption, to reduce computational cost, future investigations will rely on formula-based assessments of average ship resistance and propeller torque and mean-value engine models (MVEM), which discard fast dynamics, where CFD and GT-Suite will be used to calibrate and validate such models.





MVEM Schematic (G. Theotokatos et al., Development of an extended mean value engine model for predicting 2 the marine two-stroke engine operation at varying settings)

Conclusions

Conclusions and Next Steps

☐ Conclusions:

① The effect of wave-generated ship motion on the wake can be generally discarded as it is small due to the large inertia of ocean-going vessels, and only the wave-generated fluctuations on the propeller wake can be considered.

② For a large marine engine in heavy seas and normal operations (i.e., no propeller emergence, etc.), the average propeller torque with the ordered engine speed can be adopted to satisfactorily predict fuel consumption. This holds for fast modern engine controllers, which limit the variation in engine speed from its ordered value. Unsteadiness due to scavenging or other delays in waves do not to significantly affect the average fuel consumption.

③ An exception to the above which occurs in normal operations is the fluctuating torque causing the engine to overrun its maximum power for a given engine speed.

④ Because of the conclusions above, only the average wave-generated resistance and engine torque can be computed through formulas, which, however, require backing from fine models such as CFD models. Such average values can be plugged into a dynamic engine model, which, however, does not need to model very fast dynamics with compared to the wave encounter period, where a mean-value engine models (MVEM) represents a suitable candidate.

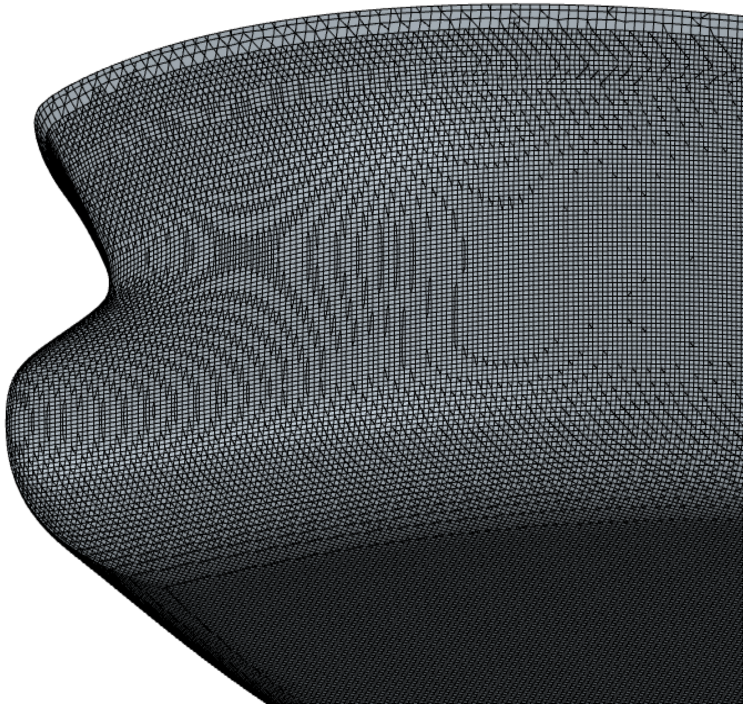
☐ Next Steps:

- Formula-based wave-generated resistance will be plugged into a propeller model and an MVEM to predict real-time with a reasonable computational cost fuel consumption for ocean-going vessels.

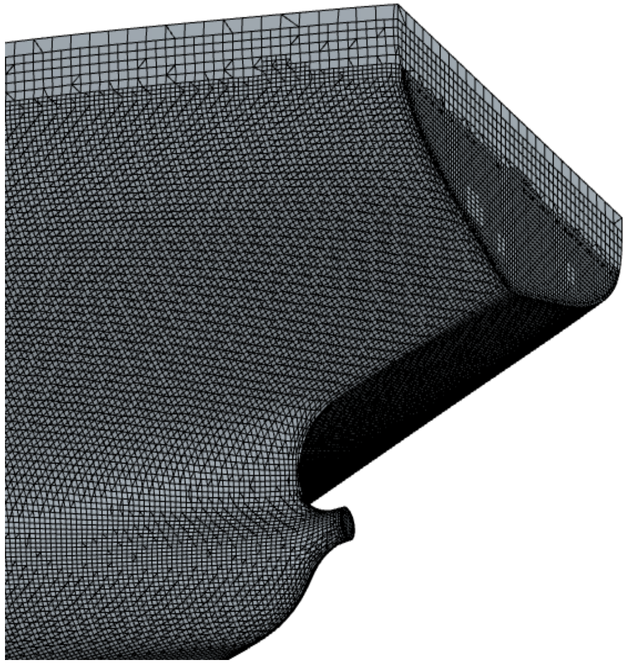
Appendix

Appendix: Mesh Details

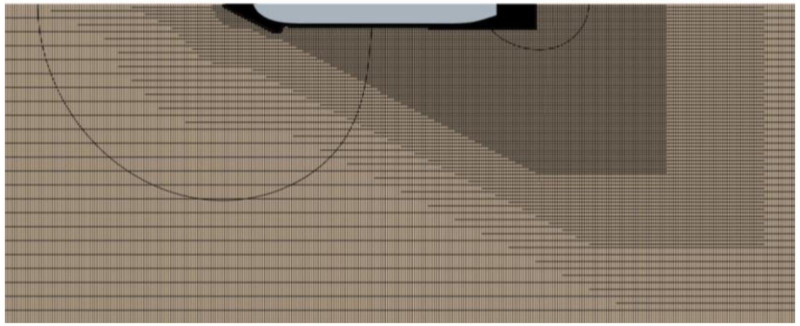
- A mesh of around 13.1 million cells was cut with the following features:
  - Hull surface mesh of 0.008 m with a 0.02-m thick prism layer of 6 layers. Hull near-field refinement with a characteristic size of 0.16 m.
  - Bows and stern near-field mesh of 0.008 m.
  - Wake refinement of 0.08 m.
  - Free surface refinement of 1/80 the wavelength in the wave traveling direction (x-direction), 1/14 the wave amplitude in the vertical direction (z-direction), and 1/10 the wavelength in the y-direction.



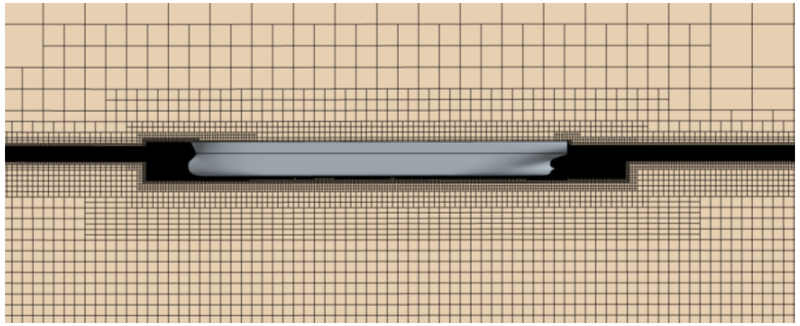
Mesh Bow View



Mesh Stern View



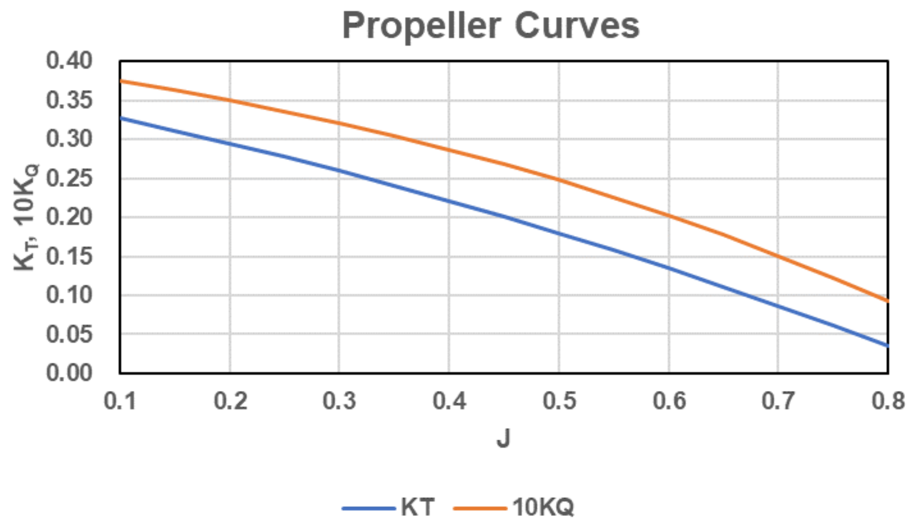
Mesh Free-Surface View: Top



Mesh Free-Surface View: Port

Appendix: Propeller Influence on Wake

- A factor r accounting for the effect of the propeller on the wake speed was evaluated from the experiment and the CFD simulation.
- The propeller curves K_T and K_Q, are also available from experiments.



Calm Water Experimental Data with Propeller

- n was imposed in the tests so that $T = R$.
- R was measured.
- The average speed on the propeller U_{prop} is computed in such a way that $T = R$.

$$J = \frac{U_{prop}}{nD}$$

$$T = \rho n^2 D^4 K_T(J)$$

$$T = R$$

➡ U_{prop}

Calm Water CFD Data without Propeller

- The average speed on the propeller disk without propeller $U_{no\ prop}$ is directly evaluated.

⬇

➡

$$r = \frac{U_{prop}}{U_{no\ prop}}$$

Appendix: Torque Evaluation (1)

- The propeller rotational speed at full scale n such that the thrust T generated by a propeller with diameter D in seawater with density ρ equates resistance (or average resistance over a period for waves) was found through the advance ratio J and the propeller K_T curves provided for JBC. Here, the subscript c stands for calm water, whereas w for regular wave, where the overline specifies average over the period. Once n is known, the torque Q can be computed through K_q.

Calm Water

$$J_c = \frac{U_{p,c} r}{n_c D}$$

$$T_c = \rho n_c^2 D^4 K_T(J_c) \rightarrow n_c \rightarrow Q_c = \rho n_c^2 D^5 K_q(J_c)$$

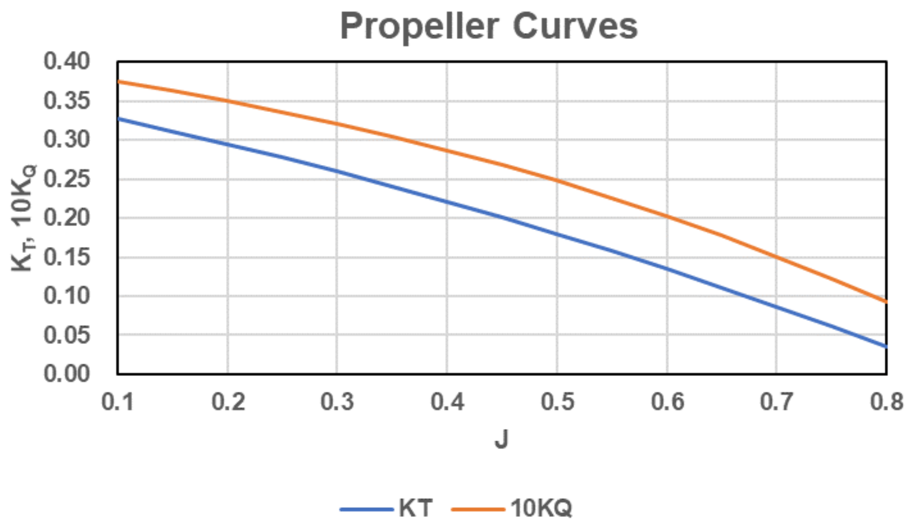
$$T_c = R_c$$

Wave Average

$$\bar{J}_w = \frac{\bar{U}_{p,w} r}{n_w D}$$

$$T_w = \rho n_w^2 D^4 K_T(\bar{J}_w) \rightarrow n_w \rightarrow \bar{Q}_w = \rho n_w^2 D^5 K_q(\bar{J}_w)$$

$$T_w = \bar{R}_w$$



Appendix: Torque Evaluation (2)

- The dynamic effect of regular waves was computed by substituting the instantaneous wake speed to its average value in the advance ratio and keeping n_w fixed as computed for average conditions, as it is assumed the governor is fast enough to attenuate large changes in propeller angular speed. This leads to an oscillating torque for an ordered engine angular speed n_w.
- Accordingly, the power for calm water, as an average for a regular wave, and the fluctuating power with the ordered crankshaft rotational speed are computed (see figure below for full-scale power for a regular wave with a height of 4 m, a period of 10 s, and a ship speed of 10 kn).

Wave

$$n_w \;\Rightarrow\; J_w = \frac{U_{p,w} r}{n_w D} \;\Rightarrow\; Q_w = \rho n_w^2 D^5 K_q(J_w)$$