Propeller in a Seaway

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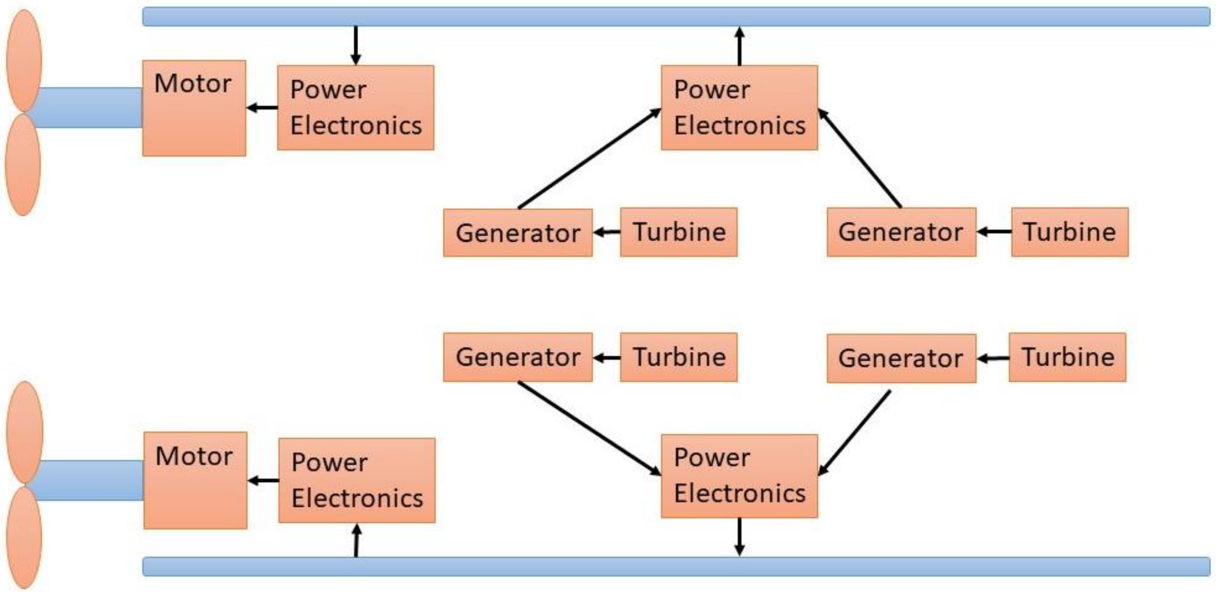
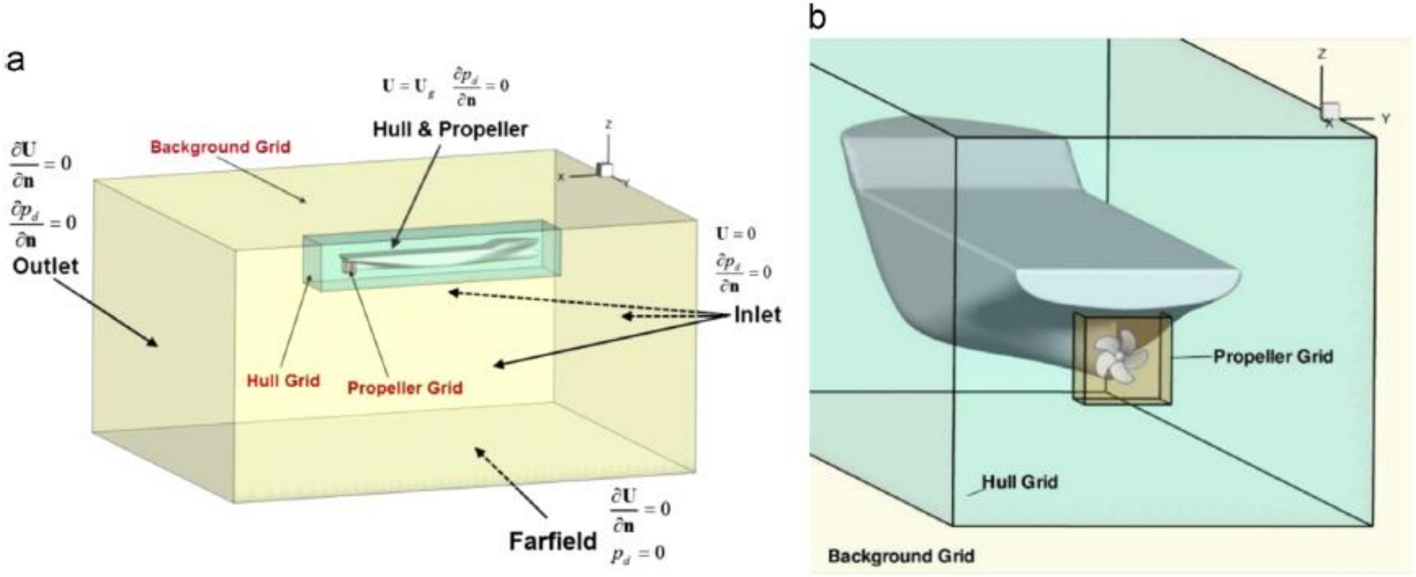
Motivation

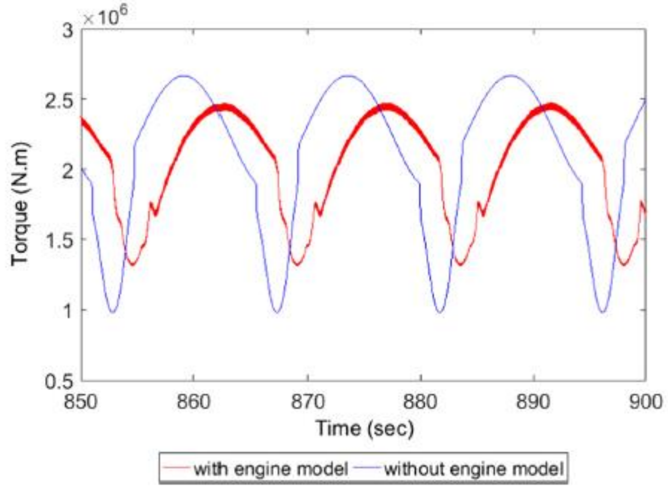
- Understand interaction of modern electric power system with propeller torque variation in waves.
- Most electric power simulations use constant propulsive loads.



Propeller-Hull-Engine Interaction in Literature

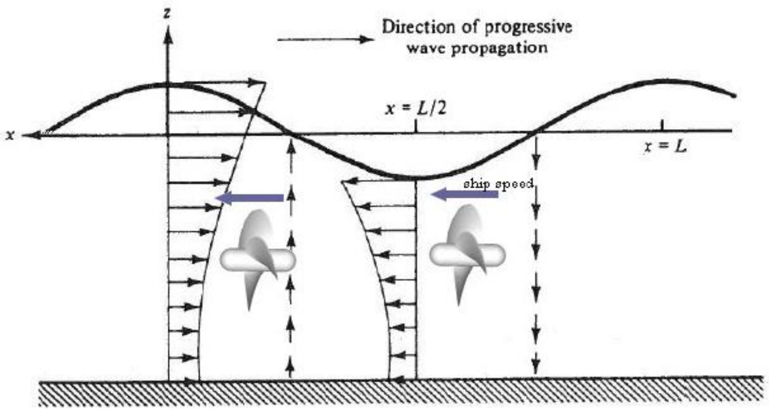
- Z. Shen, D. Wan, P.M. Carrica, “Dynamic Overset Grids in OpenFOAM with Application to KCS Self-Propulsion and Maneuvering,” *Ocean Engineering,* vol. 108, pp. 287-306, 2015.
- O. el Moctar, et al. “RANS-Based Simulated Ship Maneuvering Accounting for Hull-Propulsor-Engine Interaction,” *Ship Technology Research,* vol. 63, no. 3, pp. 141-161, 2015.
- J. Hou, J. Sun, and H. Hofmann, “Mitigating Power Fluctuations in Electric Ship Propulsion With Hybrid Energy Storage System: Design and Analysis,” *IEEE Oceanic Engineering,* vol. 43, no. 1, pp. 93-107, 2018.
- B. Taskar, et al., “The Effect of Waves on Engine-Propeller Dynamics and Propulsion Performance of Ships,” *Ocean Engineering,* vol. 122, pp. 262-277, 2016.

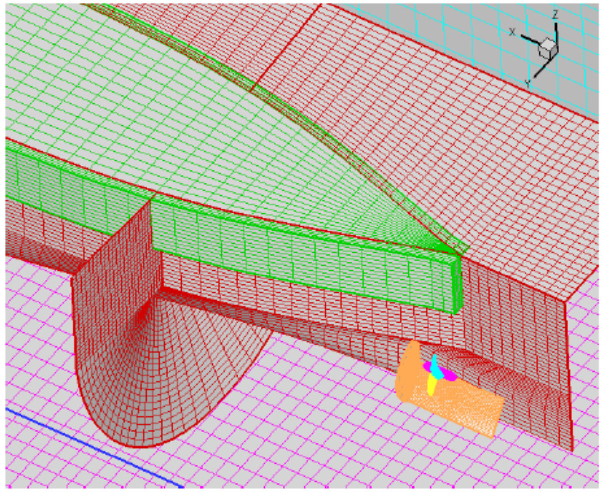


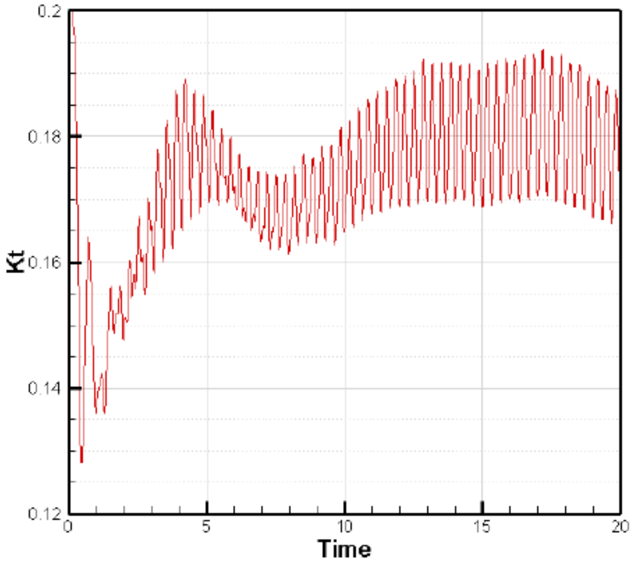


A good "in-between" solution

- S.K. Lee, K. Yu, H.C. Chen, R.K.C. Tseng, "CFD Simulation for Propeller Performance under Seaway Wave Condition," *International Offshore and Polar Engineering Conference,* 2010.







Setup for a Steady-State Propeller in OpenFOAM

Reynolds-Averaged Navier Stokes Equations

- Continuity

$$\frac{\partial(\rho\bar{u}_i)}{\partial x_i} = 0$$

- Momentum

$$\frac{\partial(\rho\bar{u}_i)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho\overline{u_i u_j} + \rho\overline{u_i' u_j'}\right) = -\frac{\partial\bar{p}}{\partial x_i} + \frac{\partial\bar{\tau}_{ij}}{\partial x_j}$$

$$-\rho\overline{u_i u_j} = \mu_T\left(\frac{\partial y}{\partial x} + \frac{\partial y}{\partial x}\right) - \frac{2}{3}\rho\delta_{ij}k$$

$$\bar{\tau}_{ij} = \mu\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right)$$

k-omega SST Turbulence Model

- Transport of turbulent kinetic energy:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial\left(\rho\bar{u}_j k\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\mu\frac{\partial k}{\partial x_j}\right)-\frac{\partial}{\partial x_j}\left(\frac{\rho}{2}\overline{u_j'u_i'u_i'}+\overline{p'u_j'}\right)-\rho\overline{u_i'u_j'}\frac{\partial\bar{u}_i}{\partial x_j}-\mu\overline{\frac{\partial u_i'}{\partial x_k}\frac{\partial u_i'}{\partial x_k}}$$

- Transport equation for specific dissipation rate:

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial\left(\rho\bar{u}_j\omega\right)}{\partial x_j}=\alpha\frac{\omega}{k}P_k-\rho\beta\omega^2+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_T}{\sigma_\omega^*}\right)\frac{\partial\omega}{\partial x_j}\right]$$

- Blending k-ε and k-ω

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial\left(\rho\bar{u}_j\omega\right)}{\partial x_j}=\alpha\frac{\omega}{k}P_k-\rho\beta\omega^2+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_T}{\sigma_\omega^*}\right)\frac{\partial\omega}{\partial x_j}\right]+(1-F_1)2\rho\sigma_{\omega2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j}$$

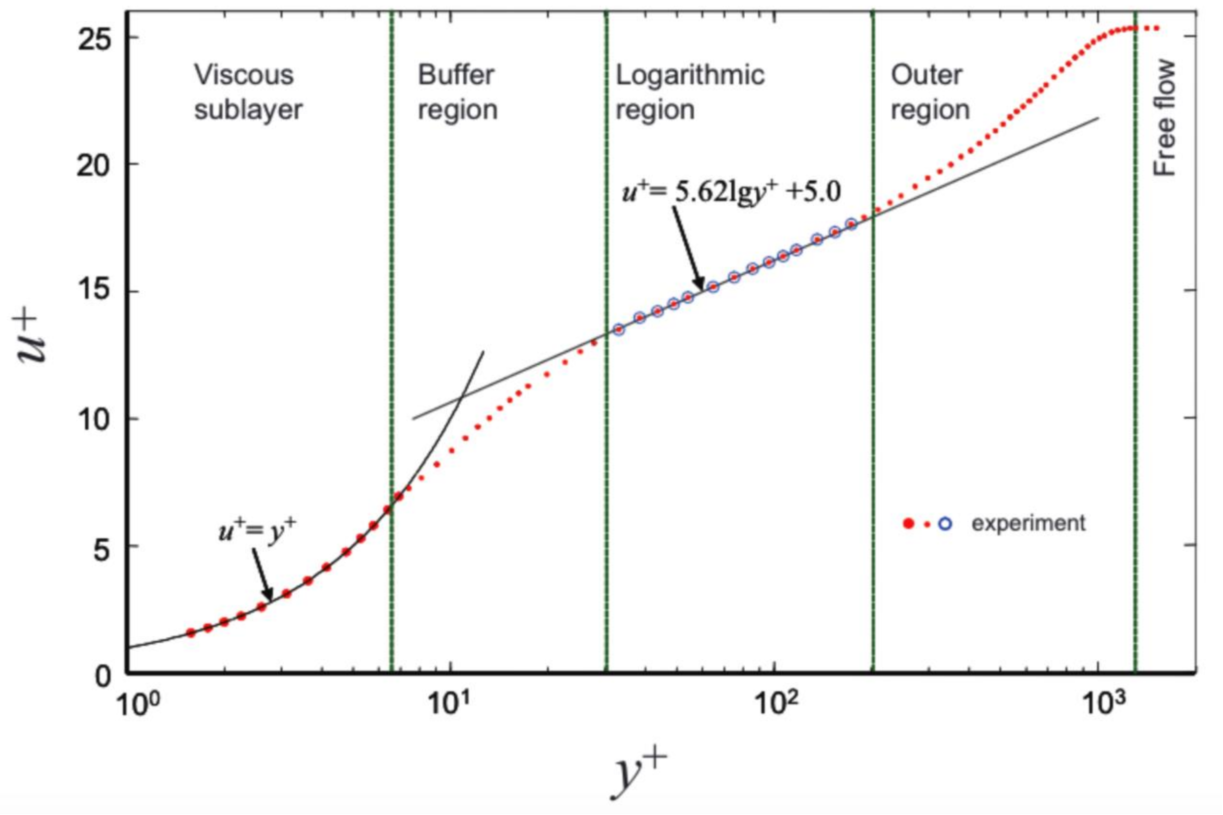
Wall Function

- Dimensionless wall distance:

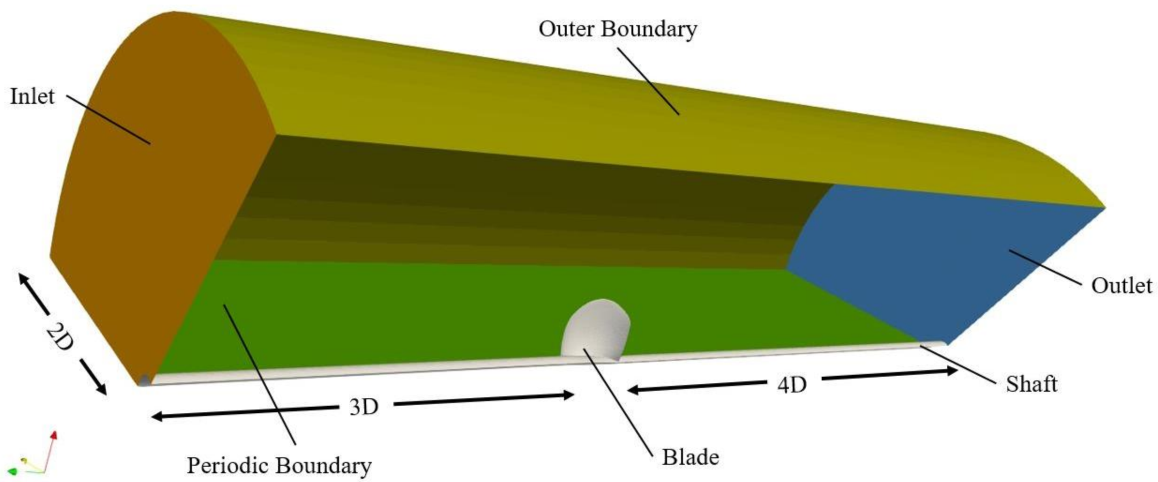
$$y^+ = \frac{\rho u_\tau \delta s}{\mu}$$

- Dimensionless velocity

$$u^+ = \frac{\overline{v_t}}{u_\tau} = \frac{1}{\kappa}\ln y^+ + B$$

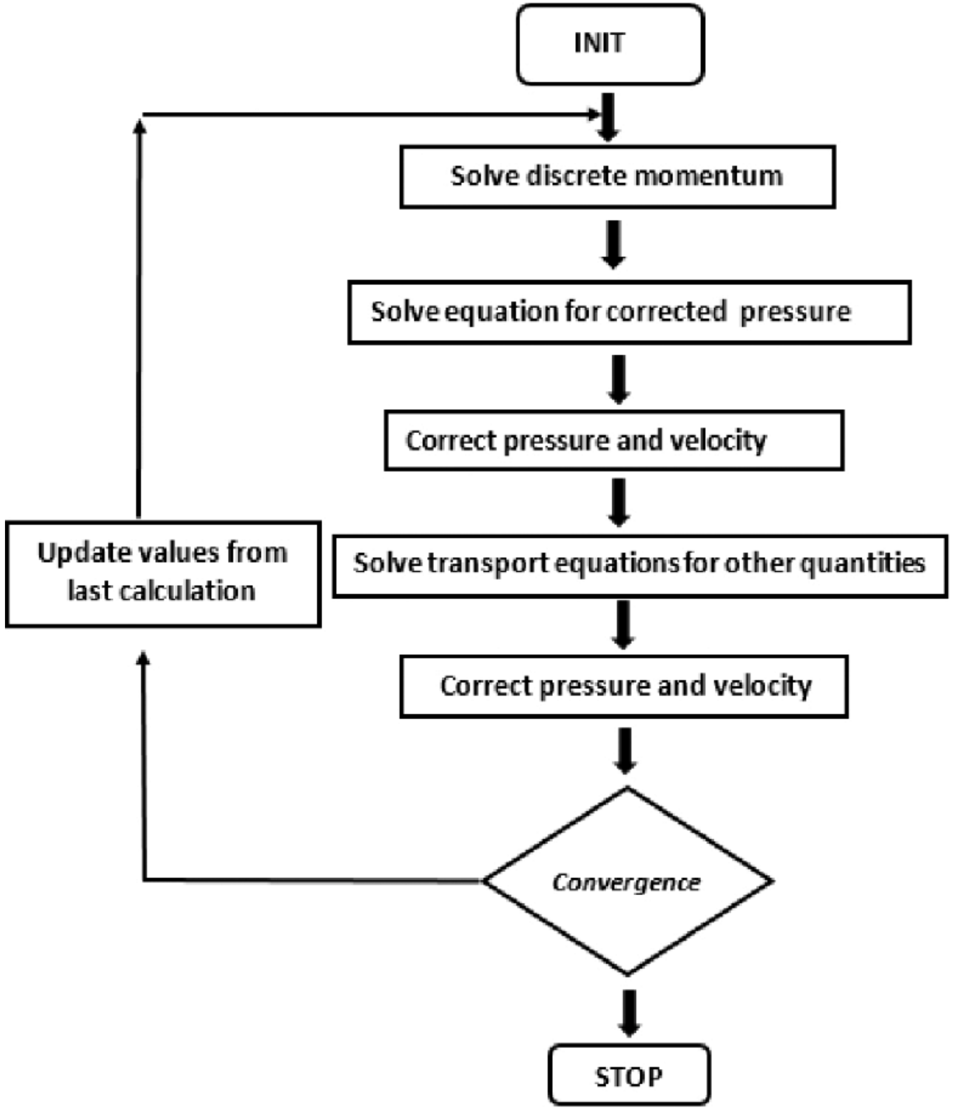


Boundary Conditions



	Velocity (m/s)	Pressure (Pa)	k (m^2/s^2)	ω (s^{-1})	ν_τ (Pa-s)
Inlet	Based on J	$\frac{\partial P}{\partial n} = 0$	$\propto I$	$\propto I$	$\propto I$
Outlet	$\frac{\partial u}{\partial n} = 0$	*Pref*	$\frac{\partial k}{\partial n} = 0$	$\frac{\partial \omega}{\partial n} = 0$	$\frac{\partial \nu_\tau}{\partial n} = 0$
Outer Boundary	$\frac{\partial u}{\partial n} = 0$	*Pref*	$\frac{\partial k}{\partial n} = 0$	$\propto I$	$\frac{\partial \nu_\tau}{\partial n} = 0$
Inner Boundary	Slip	$\frac{\partial P}{\partial n} = 0$	$\frac{\partial k}{\partial n} = 0$	$\frac{\partial \omega}{\partial n} = 0$	$\frac{\partial \nu_\tau}{\partial n} = 0$
Blade	No-Slip	$\frac{\partial P}{\partial n} = 0$	Wall Function	$\propto I$	Wall Function

Solver: SIMPLE



- Gradient Scheme: Gauss Linear
- Divergence Schemes
  - U Gauss Linear
  - k, ω: linear upwind
- Laplacian Schemes: Gauss Linear
- Interpolation Scheme: Linear
- **Pressure Term:**
- Solver: GAMG (Geometric Algebraic Multi-Grid Method)
- Smoother: Gauss Seidel
- Tolerance: 1e-8
- **Velocity, k, ω, ν terms:**
- Solver: smooth solver
- Smoother: Gauss Seidel
- Tolerance: 1e-7

Grid Generation - snappyHexMesh

1. Generate background grid (structured)
2. Import propeller geometry
3. Intersect STL with background grid
4. Refine grid close to propeller
4. Remove inside cells
5. Snap cells to surface
6. Add prism layer