

Modeling

General flow field: RANS equations and continuity equation
 Turbulence: Blended k- ω /k- ϵ 2-equation model
 Free surface: Single-phase level-set method

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p + \nabla \cdot \left[\frac{1}{\text{Re}_{eff}} (\nabla \mathbf{v} + \nabla \mathbf{v}^T) \right] + \mathbf{S}$$

$$\frac{\partial k}{\partial t} + (\mathbf{v} - \sigma_k \nabla v_i) \cdot \nabla k - \frac{1}{P_k} \nabla^2 k + s_k = 0$$

$$\frac{\partial \omega}{\partial t} + (\mathbf{v} - \sigma_\omega \nabla v_i) \cdot \nabla \omega - \frac{1}{P_\omega} \nabla^2 \omega + s_\omega = 0$$

$$\frac{\partial \phi}{\partial t} + \mathbf{v} \cdot \nabla \phi = 0$$

6DOF: Equations of motion for rigid-body linear transformation/rotation

$$m[\boldsymbol{\omega} \times \mathbf{v}_o + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}_G)] = \mathbf{F}_o; \text{ Linear transformation, } \boldsymbol{\omega} \times (\mathbf{I}_o \boldsymbol{\omega}) + m \mathbf{r}_G \times (\boldsymbol{\omega} \times \mathbf{v}_o) = \mathbf{M}_o; \text{ Rotation}$$

Propeller modeling: Axisymmetric body force propeller model

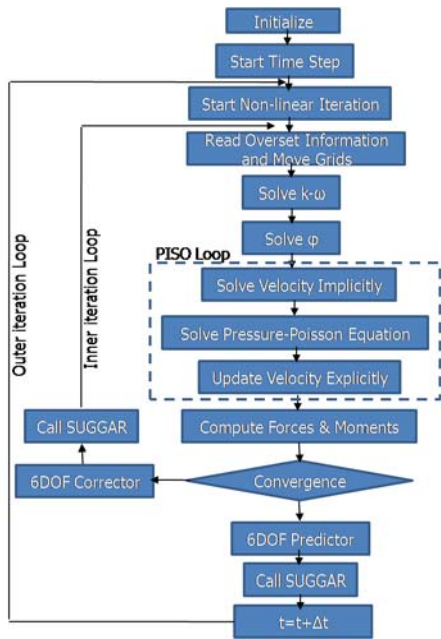
Numerical Method

Discretization: Finite Difference Method
 - Time: 2nd-order Euler backward, predictor-corrector scheme
 - Space: 2nd-order upwind for convection term, and 2nd-order central for diffusion term
 Velocity-pressure coupling : PISO
 Dynamic overset grid: SUGGAR, USURP
 Iterative solvers: ADI line solver, PETSc

High Performance Computing

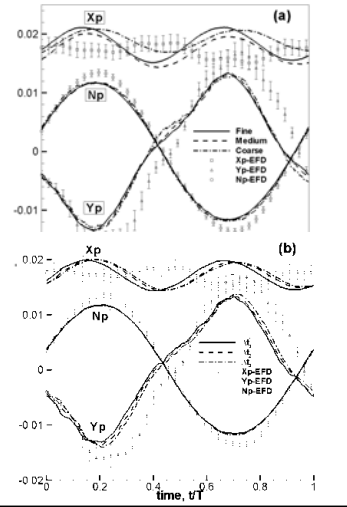
Computational expense:
 - 4.04M (fine), 1.40M (medium), and 0.61M (coarse) grid points
 - 42hrs CPU time to complete 1 yaw period by MPI parallel computing environment using 32 blocks decomposition for fine grid (DoD MSRC, IBM P4+ 1.7GHz, Distributed memory)

Overall Solution Strategy



Verification

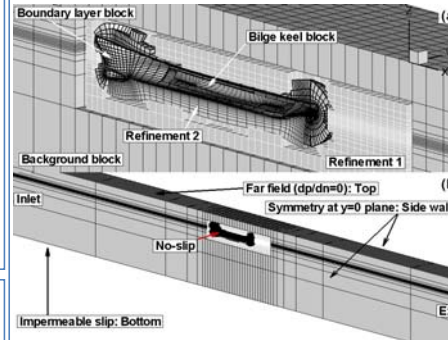
Hydrodynamic coefficients
 Pure yaw, $Fr=0.28$, $r=0.3$



	R	ρ	C	$U_{crit} \%$	
G	X_p	0.624	1.359	0.601	59.397
	Y_p	0.646	1.263	0.549	4.854
	N_p	0.553	1.708	0.807	1.306
T	X_p	2.596	-	-	-
	Y_p	0.889	0.339	0.125	45.436
	N_p	0.810	0.608	0.234	4.092

G: Grid study, T: Time-step study
 *: %solution-range of fine-grid solution in one yaw period.

Grid, Domain, Boundary Conditions and Test cases



	Motion parameters					Running condition
	β	S_{max}	ω	r'	R	
Pure drift	10	-	-	-	-	FEK, DST
Steady turn	-	-	-	0.3	3.33	DST
Pure sway	10	0.1039	1.6721	-	-	EFK, DST, 3DOF
Pure yaw	-	0.0537	1.6721	0.15	-	FEK
	-	0.1073	1.6721	0.3	-	
	-	0.1299	2.1499	0.6	-	
		0.1073	1.6721	0.3	-	DST, 3DOF

FEK: Fixed even-keel condition, DST: Dynamically sunk and trimmed condition
 3DOF: Free to pitch, heave and roll

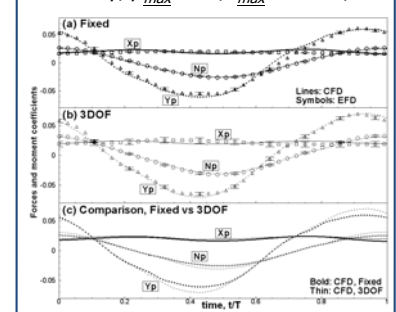
Results (All cases at $Fr=0.28$)

Pure drift, $\beta=10^\circ$, DST

	EFD	CFD	E (%)
X_p	0.0188	0.0230	-22.7
Y_p	0.0611	0.0602	1.53
N_p	0.0287	0.0281	2.25

$E = (D-S)/D * 100$

Pure sway, $\beta_{max}=10^\circ, S_{max}=0.1039$, FEK



Pure yaw, $r'_{max}=0.3, S_{max}=0.1073, \omega=1.6721$, FEK

