Overset Grid Technology Applied to Maneuvers of Marine Vehicles

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Background for ship hydrodynamics applications

- Challenges due to complex geometry, environment, and operating conditions
- Higher *Fr*, bluff geometry, high amplitude motions/maneuvering, incoming waves, etc. can lead to complex free-surface topologies
- Breaking waves can produce spray, foam and bubbles
- Impact hull and propulsor performance and increase air and water signatures

Overview

- Present formulation for free surface problems
- Discuss overset grid implementation and needs
- Applications
  - Self-propulsion computations
  - Tumblehome combatant dynamic stability (broaching)
  - Recovery of unmanned underwater vehicle
  - Submarine in overshoot and surfacing maneuvers

Mathematical Model

- Local, instantaneous equations for two-phase flow

$$\frac{\partial u_{k,j}}{\partial x_j} = 0$$

$$\frac{\partial u_{k,i}}{\partial t} + u_{k,j}\frac{\partial u_{k,i}}{\partial x_j} = -\frac{1}{\rho_k}\frac{\partial p_k}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\nu_k D_{k,ij}\right) + g_i$$

  - $k = w$ or a indicates fluid phase. Jump conditions apply across interface
  - for standard two-phase LS, fluid properties artificially smoothed
  - Ghost fluid method: maintain discontinuity and enforces jump conditions
- With averaging, we obtain RANS equations in water (k=w)

$$\frac{\partial u_j}{\partial x_j} = 0$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\frac{1}{\mathrm{Re}_{eff}}\frac{\partial u_i}{\partial x_j}\right) + s_i$$

  - Turbulence models: blended k-omega/k-epsilon model / DES / DDES
  - Piezometric pressure $p=p_{abs}/\rho U^2+z/Fr^2+2k/3$

Single-phase LS: Equations

- Location of interface given by transport of zero level-set

$$\frac{\partial \phi}{\partial t} + u_j \frac{\partial \phi}{\partial x_j} = 0$$

- BCs at the free surface from interfacial jump conditions

$$p_{\text{int}} = z_{\text{int}} / Fr^2$$

$$\left.\frac{\partial u_i}{\partial x_j} n_j \right|_{\text{int}} = 0$$

Single-phase LS: Equations

- Free-surface BC for pressure
  - Pressure is calculated and available only on points in water
  - In air, the pressure is extrapolated to satisfy the DFSBC
- The boundary condition at the interface requires

$$\vec{n} \cdot \nabla \varphi = 0$$

$$\varphi = u,\ v,\ w,\ k,\ \omega$$

- Enforced with pure convection equation, with transport velocity

$$\vec{n} = \frac{\nabla \phi}{|\nabla \phi|}$$

Single-phase LS: Reinitialization

- Reinitialization required so LS remains distance function
- Explicit reinitialization is problematic:

$$\frac{\partial \phi}{\partial t} = S(\phi_0)\left(1 - \left|\frac{\partial \phi}{\partial x_i}\right|\right) \qquad S(\phi_0) = \frac{\phi_0}{\sqrt{\phi_0^{\,2} + \alpha^2}}$$

- Instead, we use implicit reinitialization:

$$\hat{n} \cdot \nabla \phi = Sign(\phi_0)$$

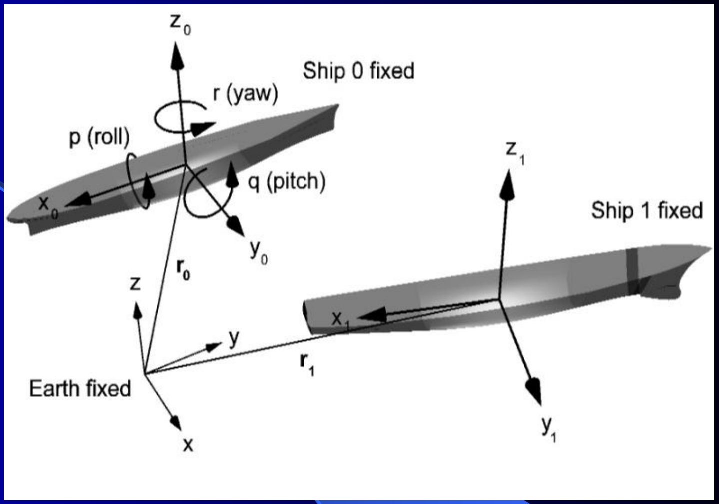
- Does not work on the interface itself, therefore a "close-point" algorithm is used to establish a set of Dirichlet BC's.

Numerical Details

- Structured body-fitted multi-block grids
  - Ghost-cells and interpolated multi-block boundary conditions
- Higher-order Finite Differences
  - Convection: 2nd, 3rd and 4th order upwind, linear and TVD
  - Diffusion: second order central
- Unsteady, single-phase level set (Carrica et al., *Int. J. Num. Meth. Fluids* 2007)
  - Backward 2nd order time derivatives
  - Lagrangian/Eulerian approach of the time derivatives near the free surface
  - Geometrical/convective reinitialization algorithm
- Dynamic overset grids (Carrica et al., Comput. Fluids 2007)
  - Complex topologies/local grid refinement, Moving objects, Control surfaces, Fluid-Structure interaction, Shape optimization
  - Uses Suggar, recently switched to Suggar++
- 6DOF motions
  - Free and captive model capabilities
  - First, second, third order explicit and implicit solvers, synchronized or lagged modes

Numerical Details

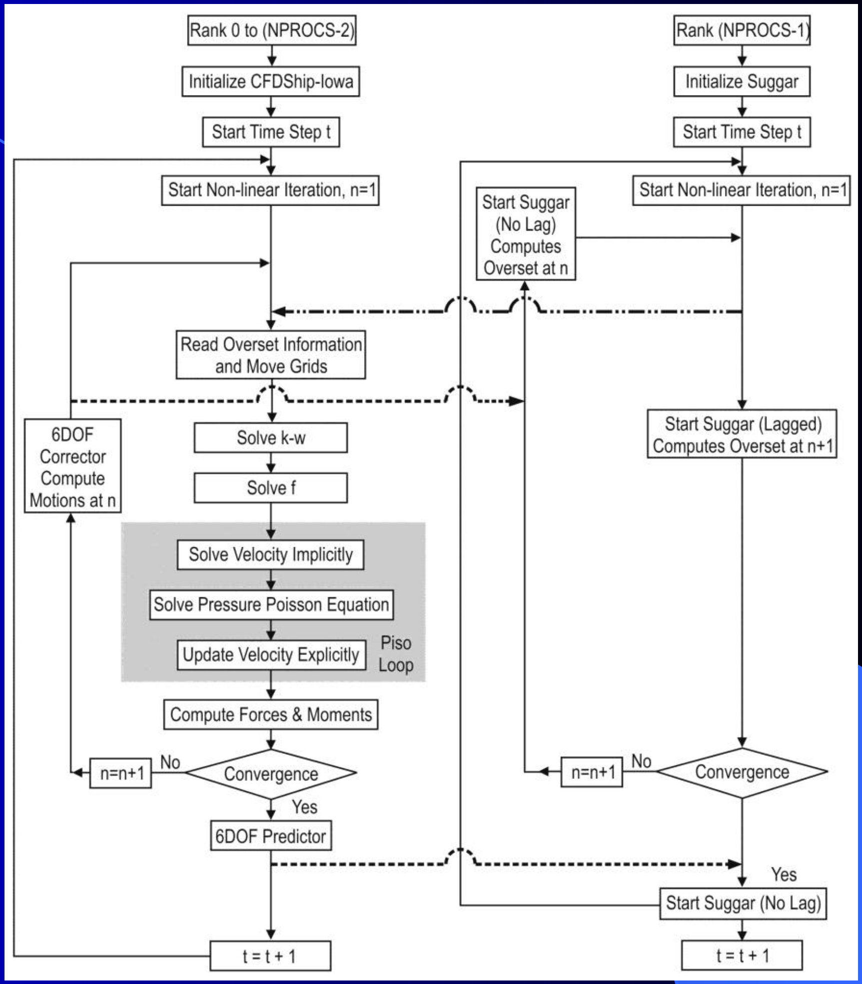
- 6DOF motions (continued)
  - Multi-object capability (interaction between ships, buoys, platforms, service vehicles, etc.)
  - Children to parent objects allow simulation of propulsors, control surfaces, and other moving parts attached to the parent.
  - Controllers for: speed, heading, roll, etc., acting on thrust or control surfaces



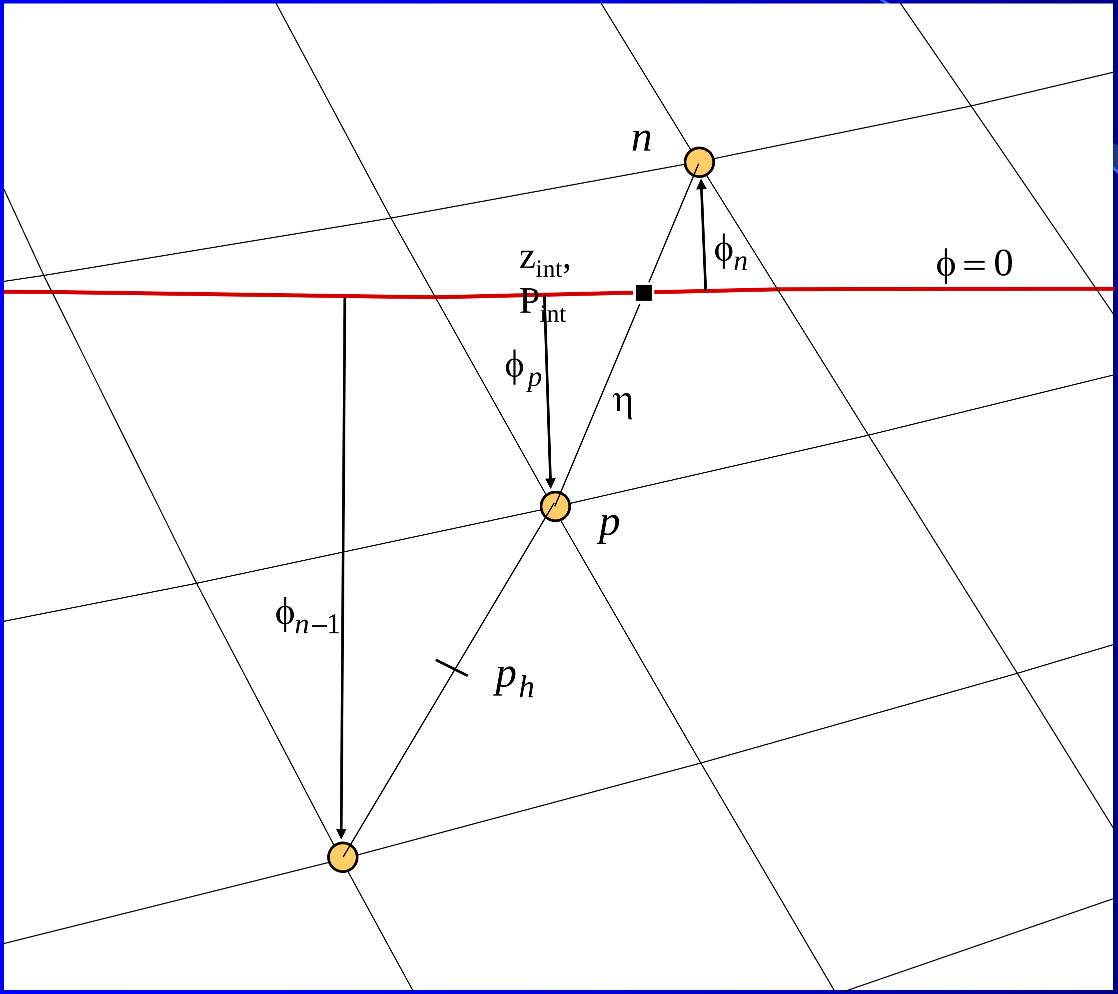
- Turbulence modeling
  - RANS: blended *k-w/k-ε* turbulence model or EARSM, near wall or wall functions
  - DES: DES, DDES based on *k-w/k-ε* or EARSM
    - 4^{th} order upwind biased or central (hybrid) convective terms
- Wave modeling
  - Regular and irregular waves, of arbitrary direction, long or short crested
  - Bretschneider, Jonswap, Pierson-Moskowitz and Hurricane spectra.

Dynamic Overset Implementation

- Implicit and explicit modes
  - Implicit requires domain connectivity at every non-linear iteration
  - Explicit is computed once per time step
- Lagged and non-lagged modes
  - Implicit can lag one nonlinear iteration
  - Explicit can lag one or more time steps
- Multiple domain connectivity groups
  - The grid positions have to be predicted several time steps in advance
  - Great option to speed up explicit computations with naturally small time step



Interface detection and pressure BC interpolation



$$\eta = \frac{\phi_p}{\phi_p - \phi_n}$$

$$P_{int} = \frac{(1-\eta) z_p + \eta z_n}{Fr^2}$$

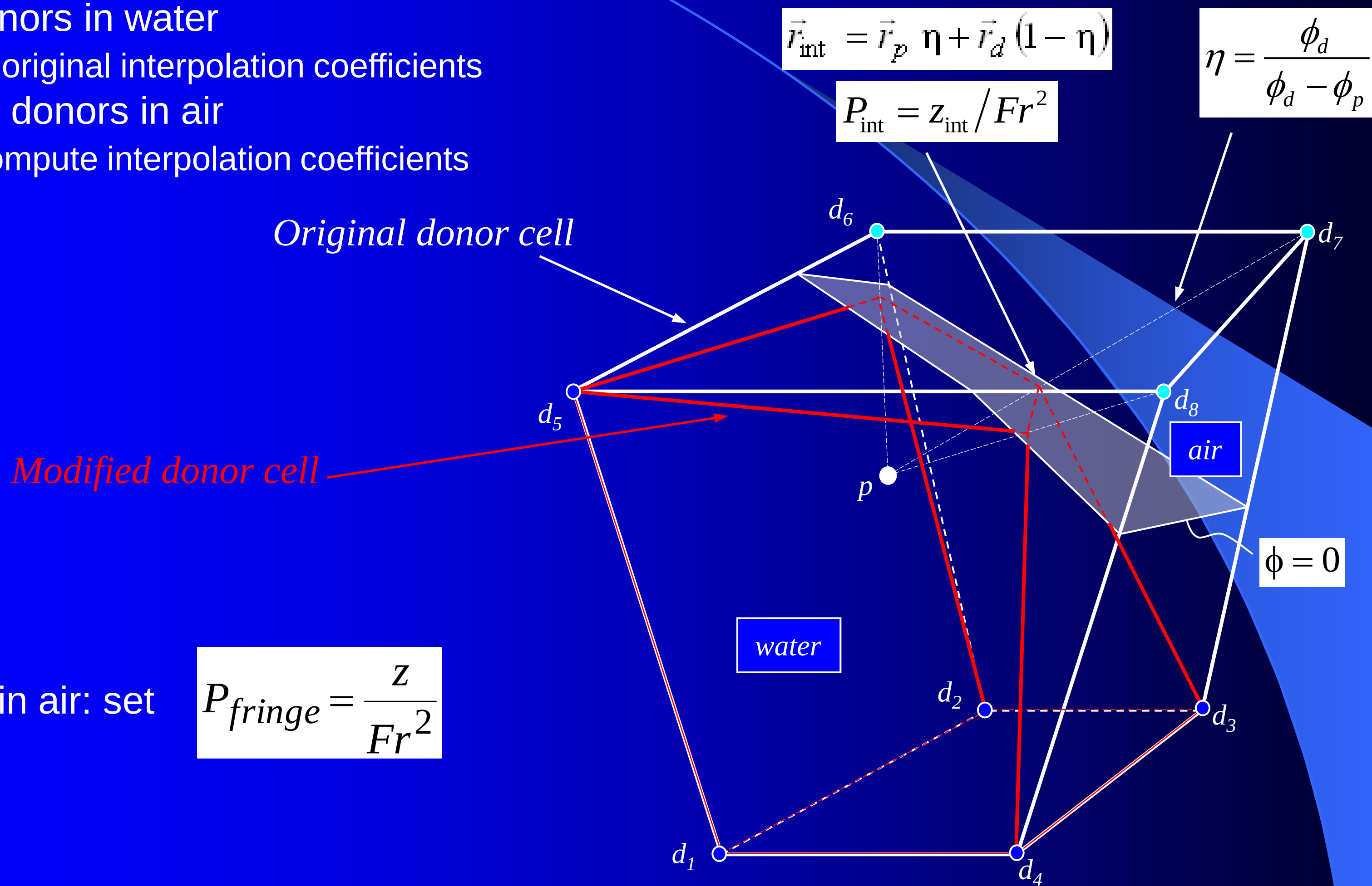
$$p_n = (p_{int} - p_h)\frac{1-\eta}{\eta + 0.5} + p_{int}$$

Donor points in air

Point in water:

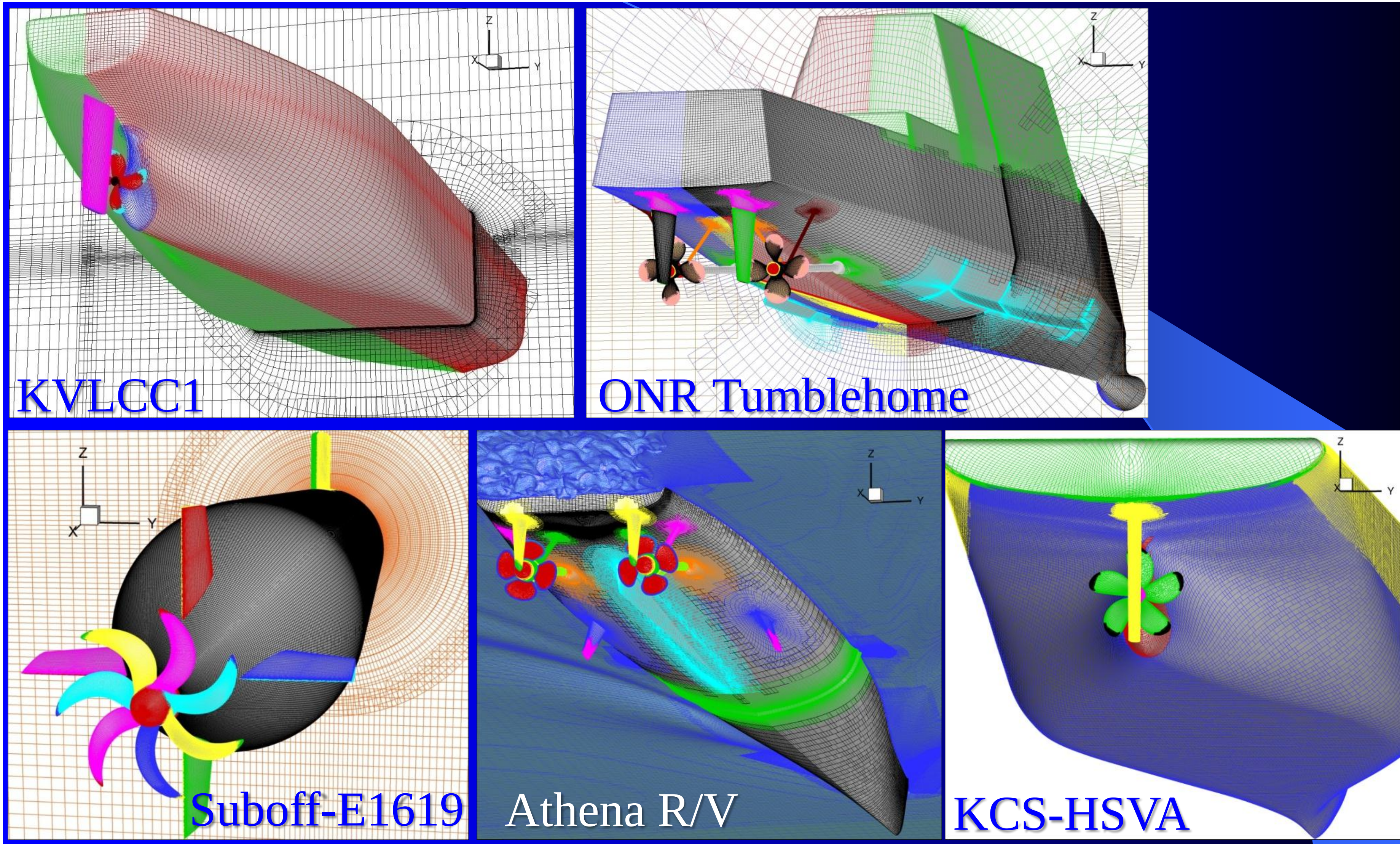
all donors in water
- use original interpolation coefficients

some donors in air
- recompute interpolation coefficients

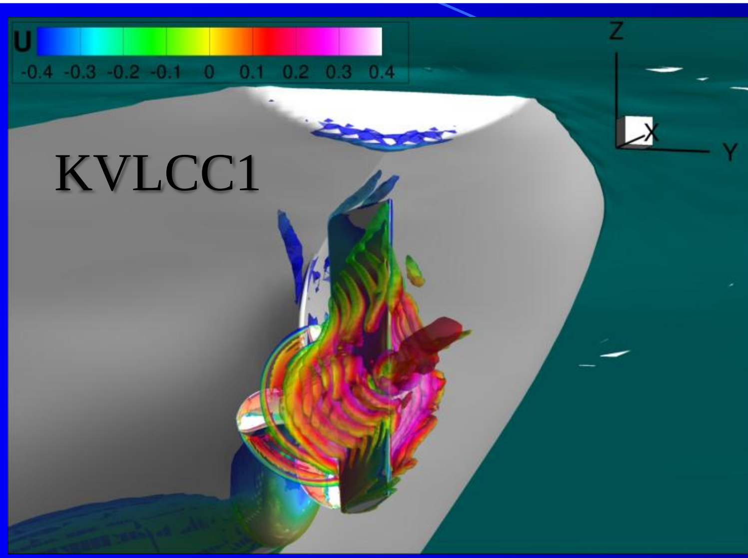


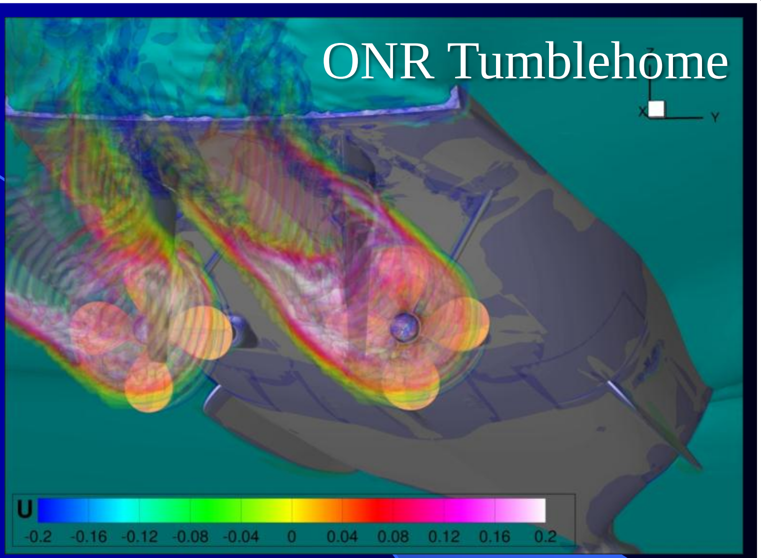
Point in air: set $P_{fringe} = \dfrac{z}{Fr^2}$

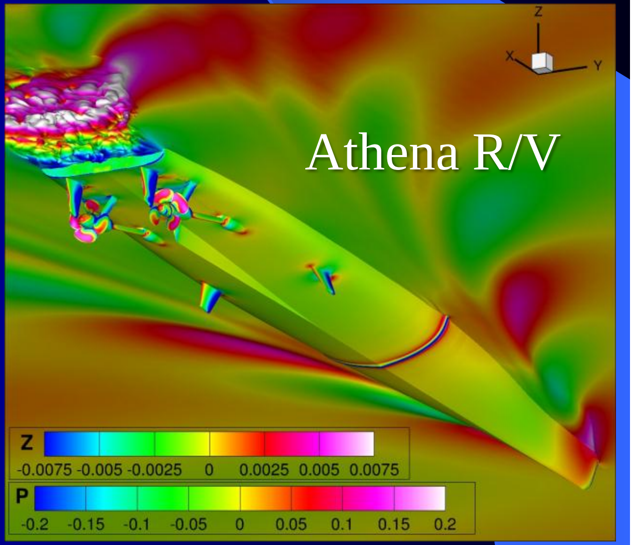
Gridding strategies



Self-propulsion computations





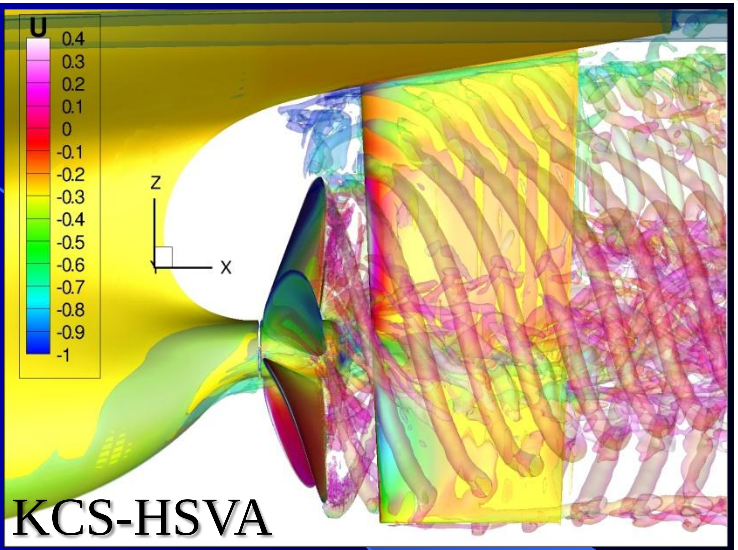


P. M. Carrica, A. M. Castro & F. Stern, “Self-Propulsion Computations Using Speed Controller and Discretized Propeller with Dynamic Overset Grids,” *J. Marine Sci. Technol.* **15**, 316-330 (2010).

Self-propulsion computations

Results

A. M. Castro, P. M. Carrica & F. Stern, "Model and Full Scale Self-Propulsion Computations of the KCS Containership," submitted to *Comput. Fluids* (2010).



Animations:

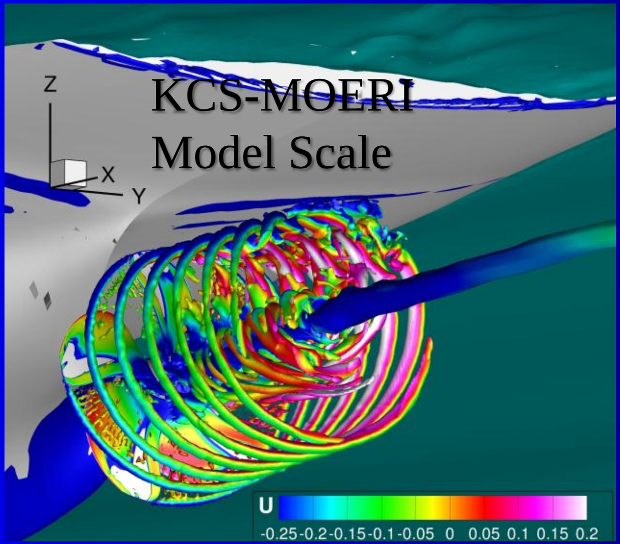
-KCS-Moeri Model Scale

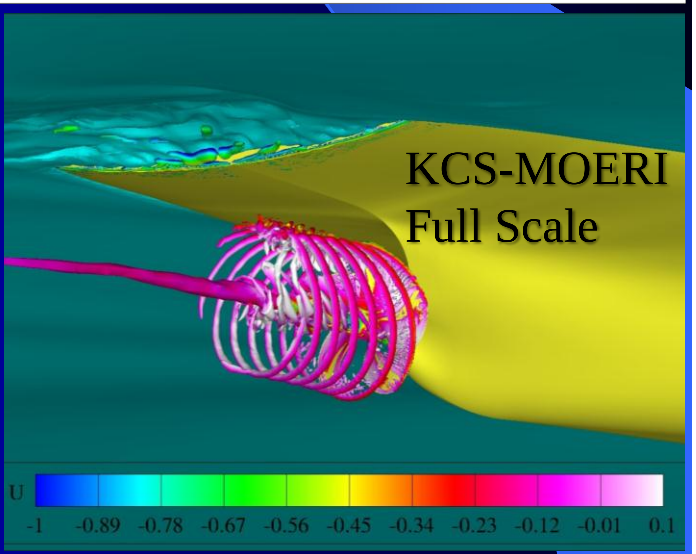
-KCS-Moeri Full Scale

-KCS – HSVA 1

-KCS – HSVA 2

-KCS – HSVA 3





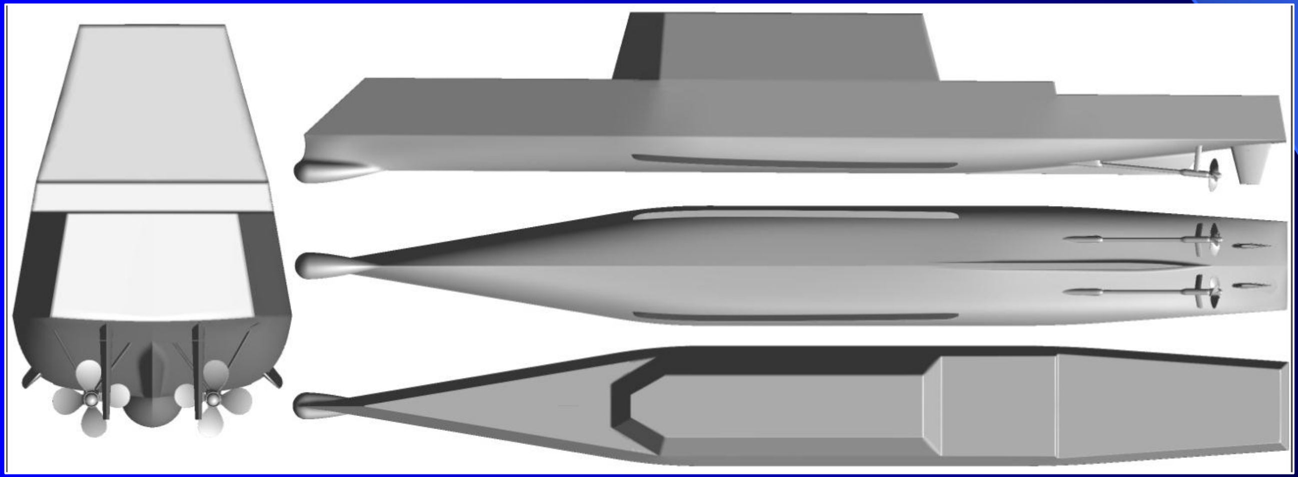
Self-propulsion computations

Quantitative Results

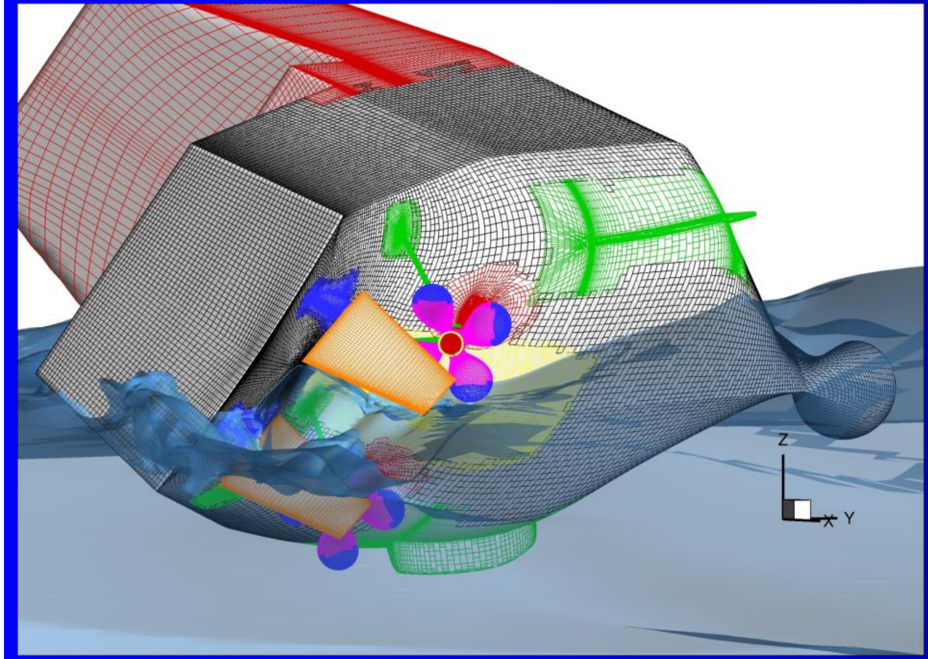
		KCS MOERI	KCS HSVA	KVLCC1	ONR Tumblehome	Athena R/V (full scale)
Froude number		**0.26**	**0.26**	**0.14**	**0.4**	**0.25**
n (RPS)	CFD	9.62	14.44	11.25	18.9	3.09
	EFD	9.5	14.15	11.4	18.8	3.05
Sinkage (mm)	CFD	-	-11.83	-5.67	-12.0	-
	EFD	-	-10.5	-5.19	-	-
Trim (degrees)	CFD	-	-0.172	-0.123	0.33	-
	EFD	-	-0.155	-0.135	-	-

ONR Tumblehome dynamic stability

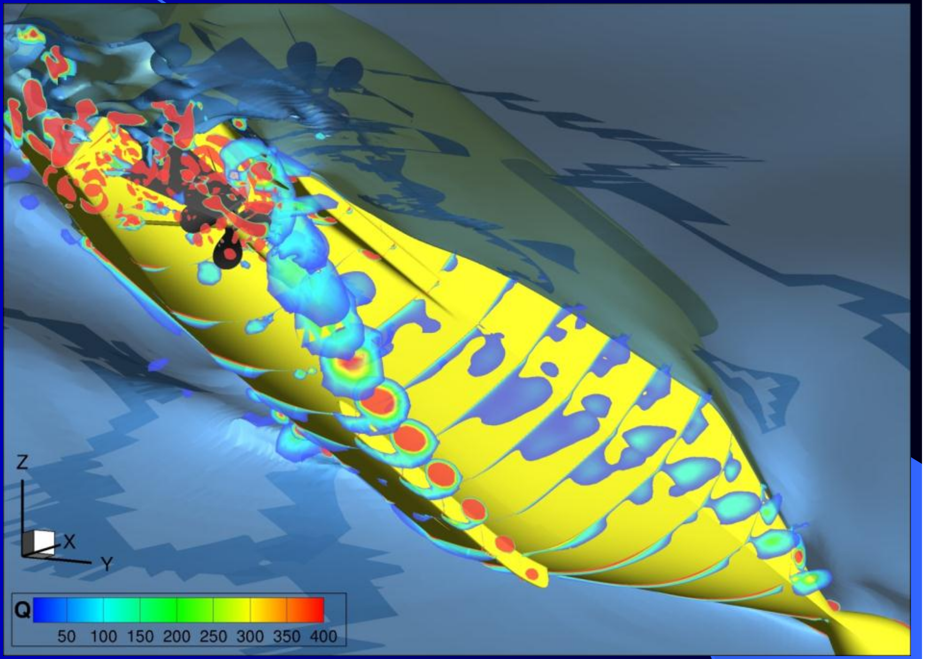
- Study the mechanisms leading to broaching
- Identify the factors causing dynamic instability
- Demonstrate the role of controllers on extending the safe operational envelope



ONR Tumblehome dynamic stability



Overset grid system (21.1 M grid points) and instantaneous view of the free surface.

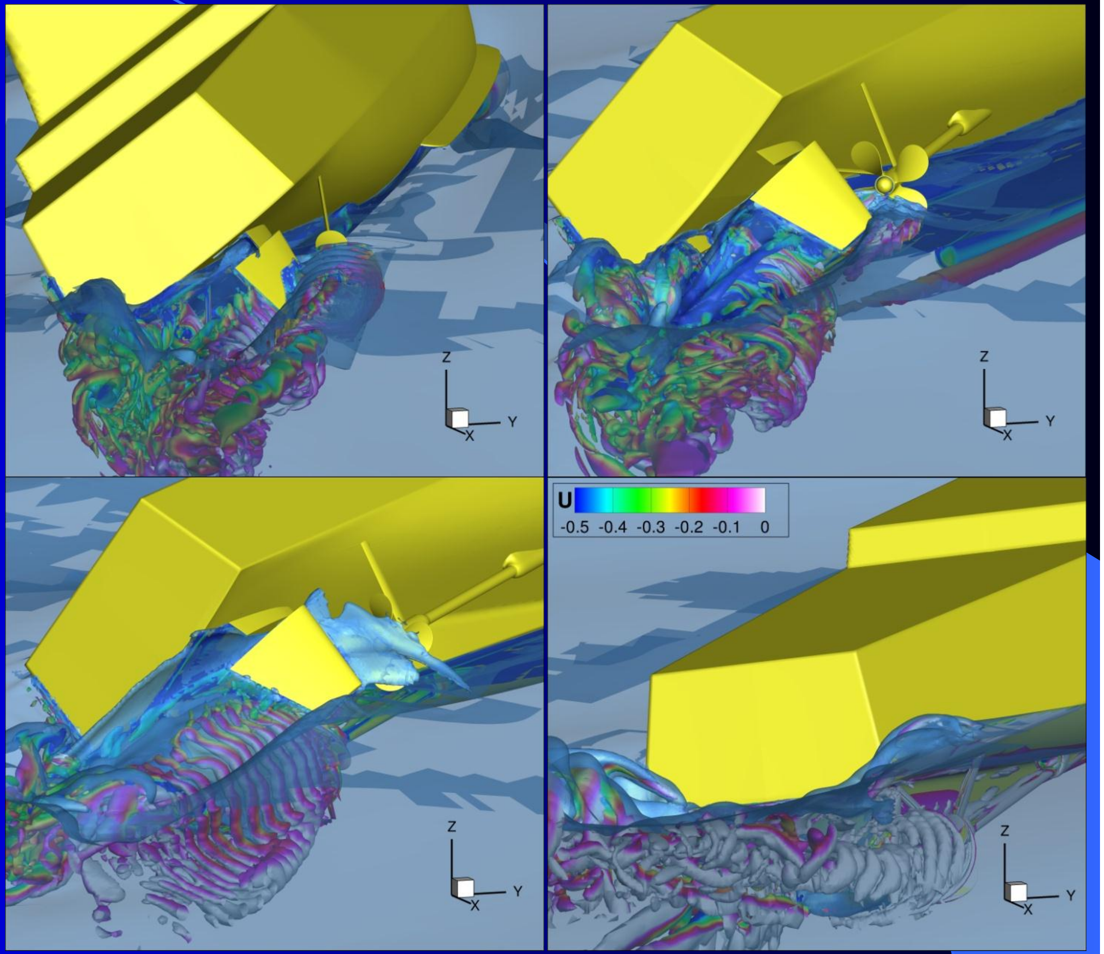


Boundary layer during extreme broaching event. Notice the bilge keel vortex hitting the port propeller.

ONR Tumblehome dynamic stability

Instantaneous views of the broaching process (increasing roll angle, top two images) and recover (decreasing roll angle, lower two images).

Notice the violent wake produced by the starboard propeller as it returns to the water.

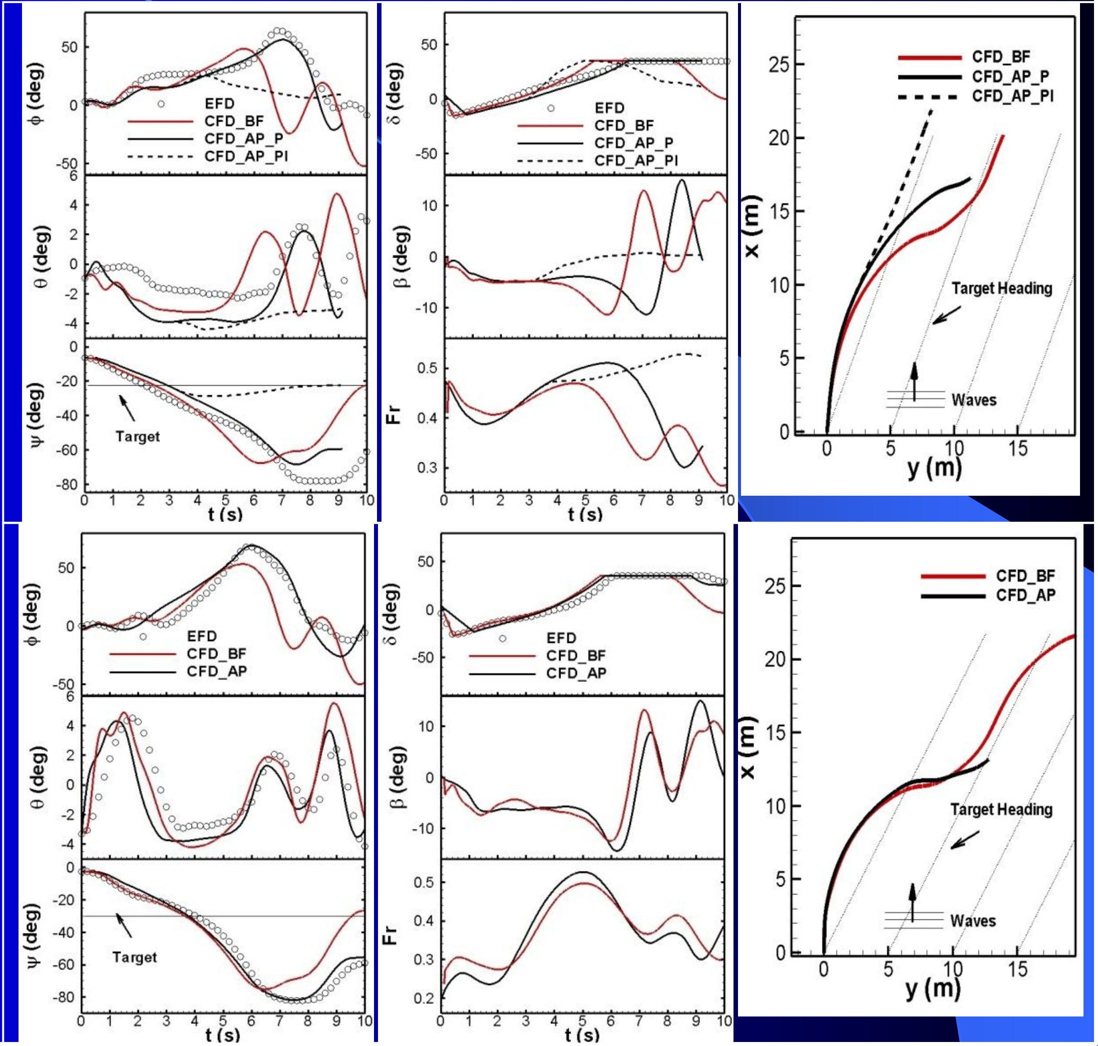


ONR Tumblehome dynamic stability

Predicted and measured roll, pitch and yaw angles, and rudder action. Case 1 (top) with Fr=0.4, heading 22.5 degrees, Case 2 (bottom) with Fr=0.45, heading 30 degrees.

Predictions using a discretized rotating propeller are far superior to a simple, non-interactive body force propeller model.

The use of a better PI controller prevents broaching for Case 1, which in the experiment uses a simpler P controller.



ONR Tumblehome dynamic stability

ONR Tumblehome Dynamic Stability

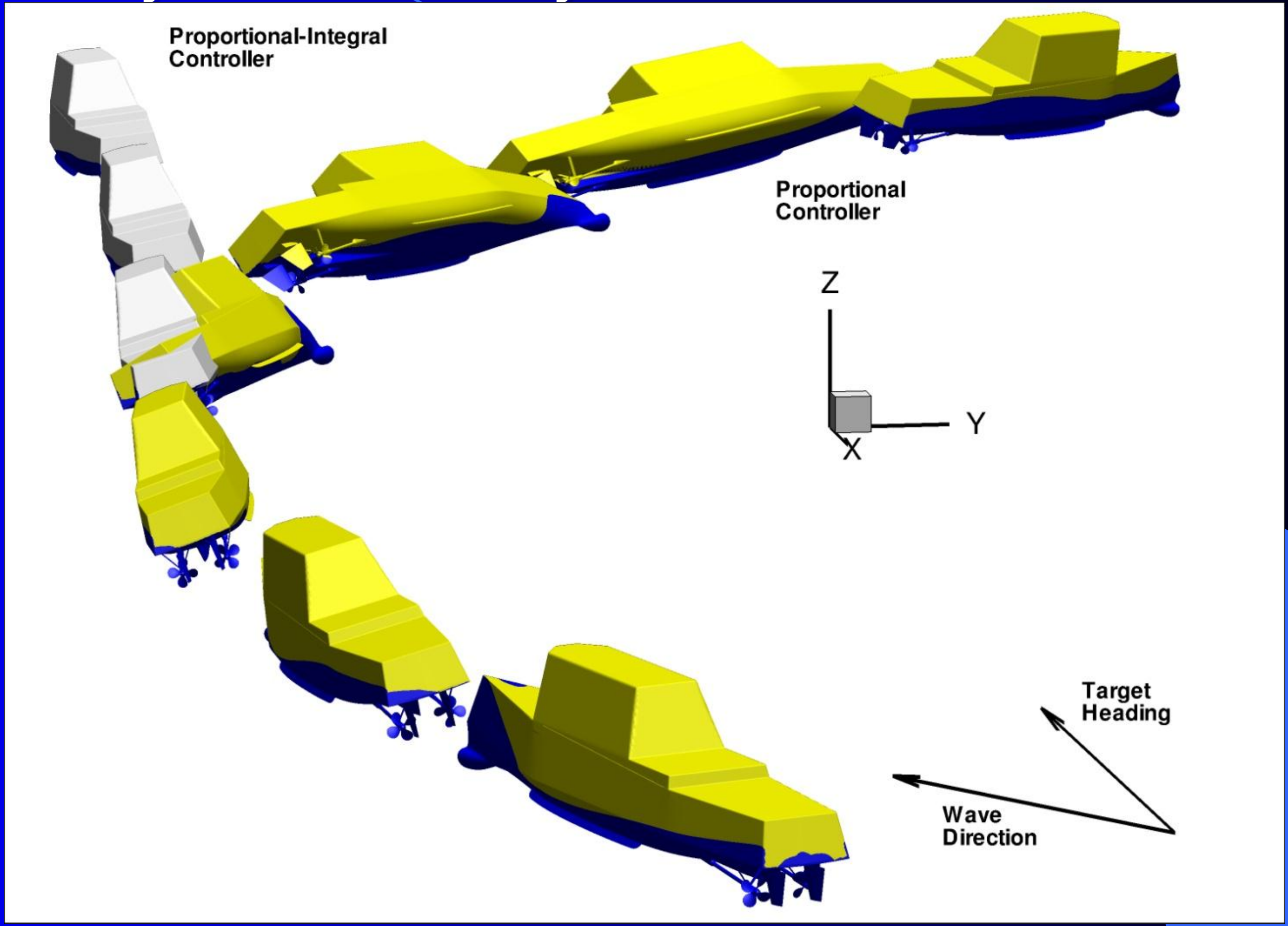
Effect of the controller

Animations:

- P controller Case 1

- Close-up of the broaching instant

- PI controller Case 1



Recovery of UUV

- Unmanned underwater and surface vehicles are launched and recovered from host ships
  - Applications include research, industry, naval, search and rescue
- Launch and recovery of the deployed craft can be from the side or the stern of the host ship
  - From the stern, the deployed craft will pass through the wake of the host ship
  - Presented here is the approach of an underwater vehicle

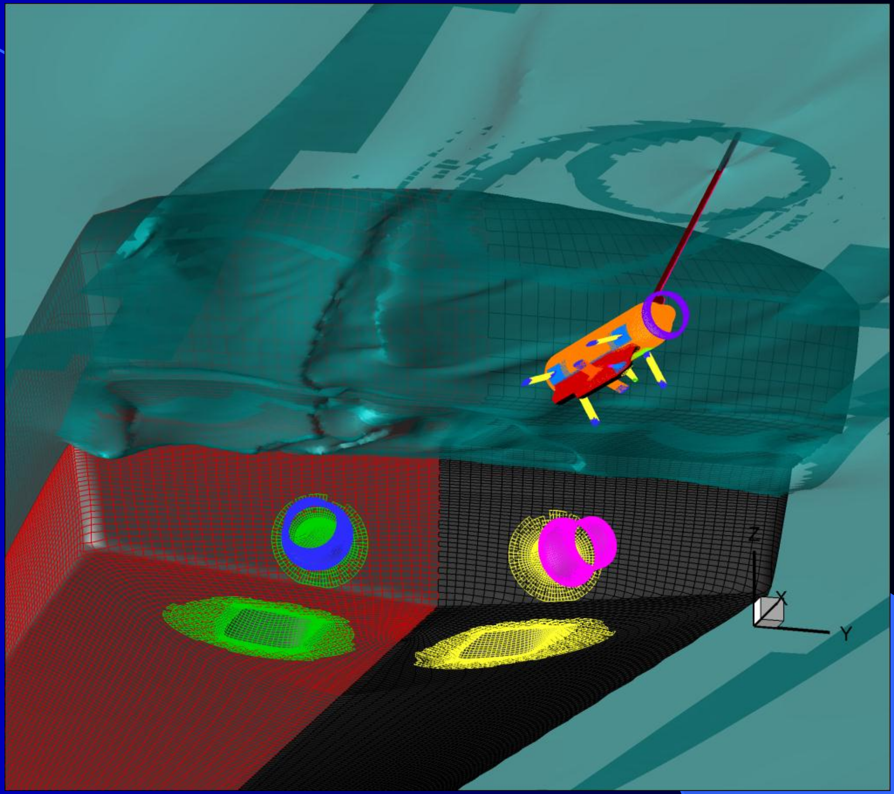
http://en.wikipedia.org/wiki/Autonomous_underwater_vehicle, May 2, 2011

http://www.naval-technology.com/features/feature98410/feature98410-7.html, May 2, 2011

Recovery of UUV

5 cases studied for various ship control mechanisms and sea states:

- Calm Water
  - Moving bucket control
  - Differential thrust with 20 degree bucket splay
  - Single moving bucket control
- Sea state 4
  - Differential thrust with 20 degree bucket splay
  - Moving bucket control

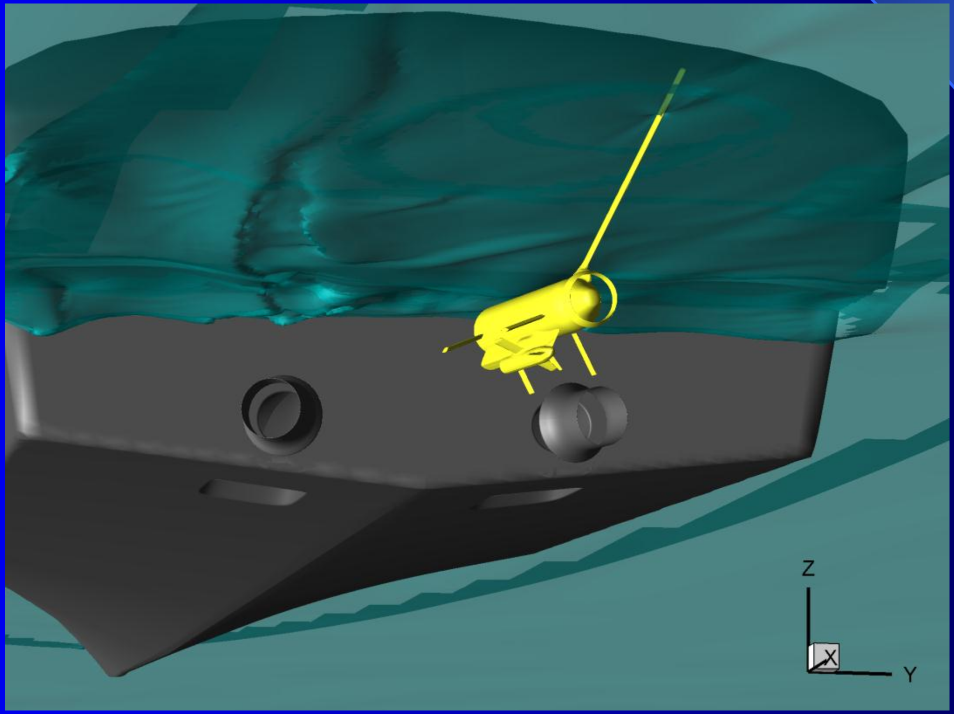


The UUV controller causes the vehicle to slow down and surface as it approaches the collection point

Recovery of UUV

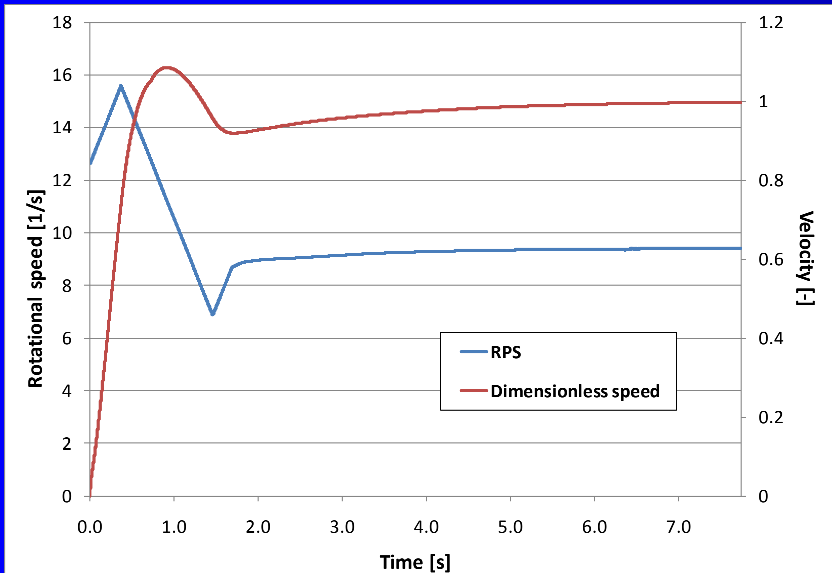
Animations:

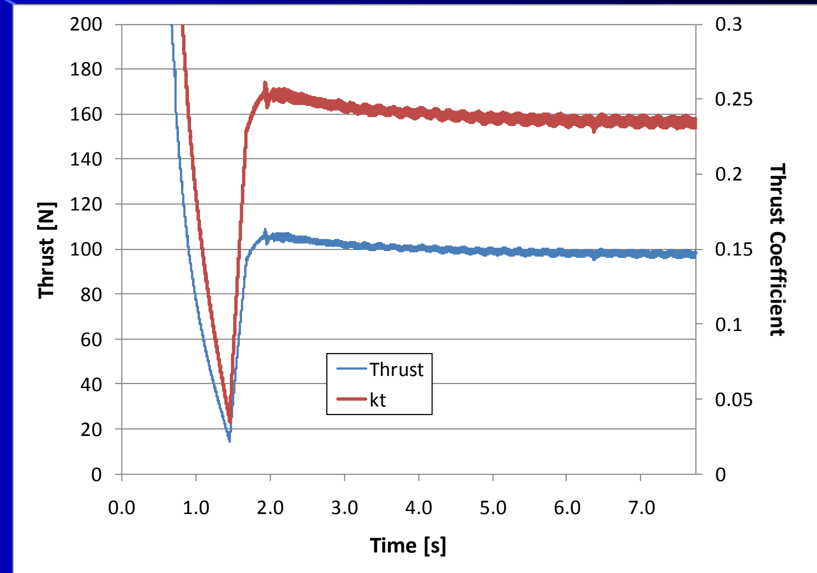
- Splayed buckets, thrust control, SS4 JONSWAP spectrum
- Calm water, single bucket waterjet control

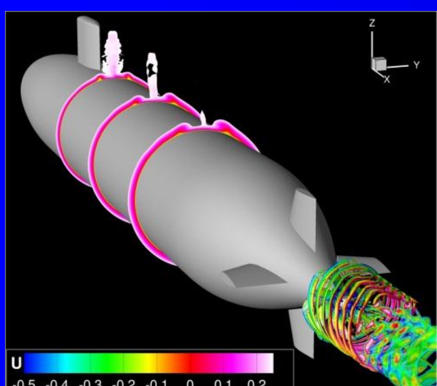


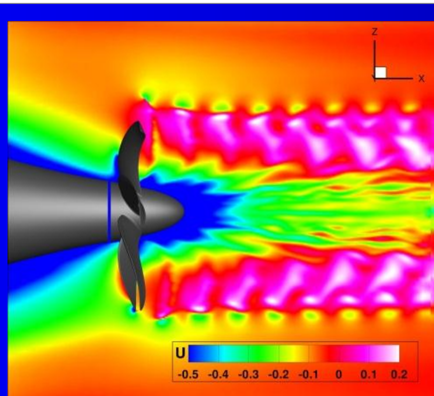
Suboff Maneuvers

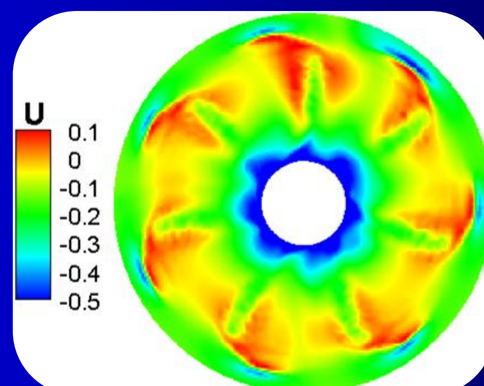
Self-Propulsion (video)



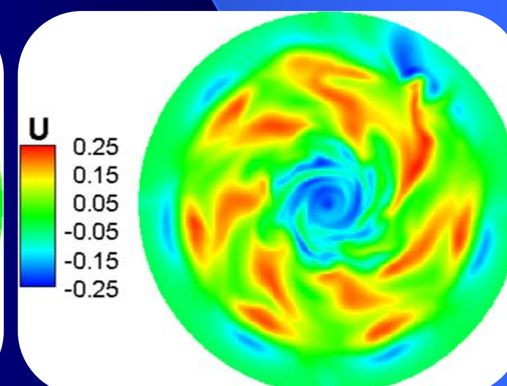








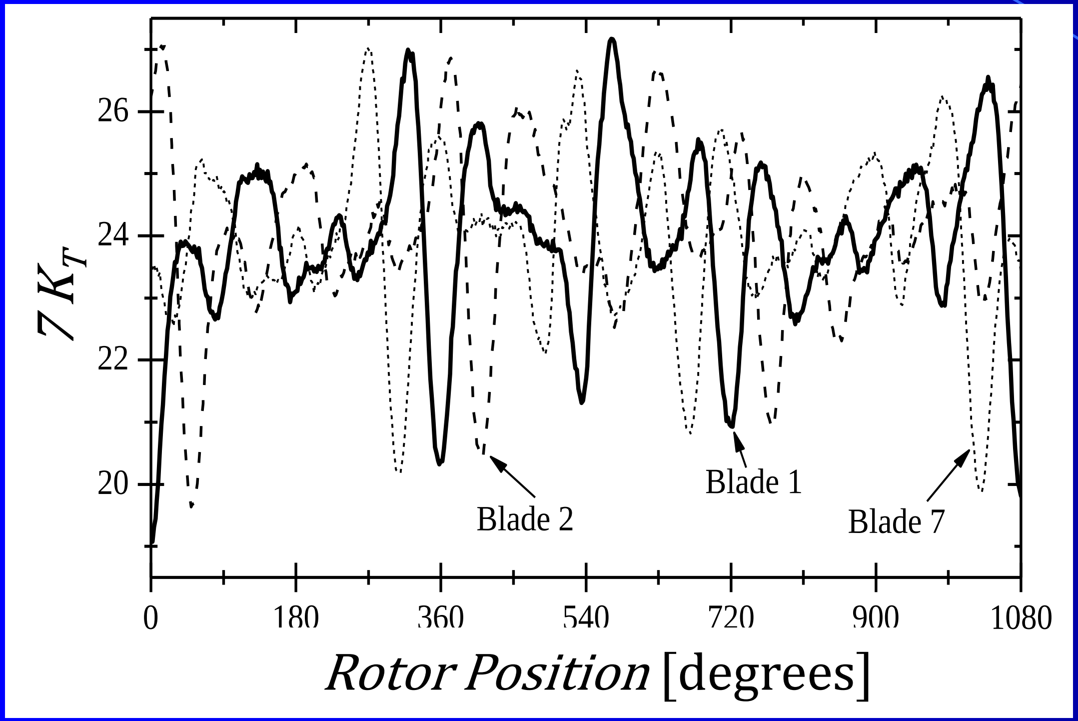
x/L = 0.975

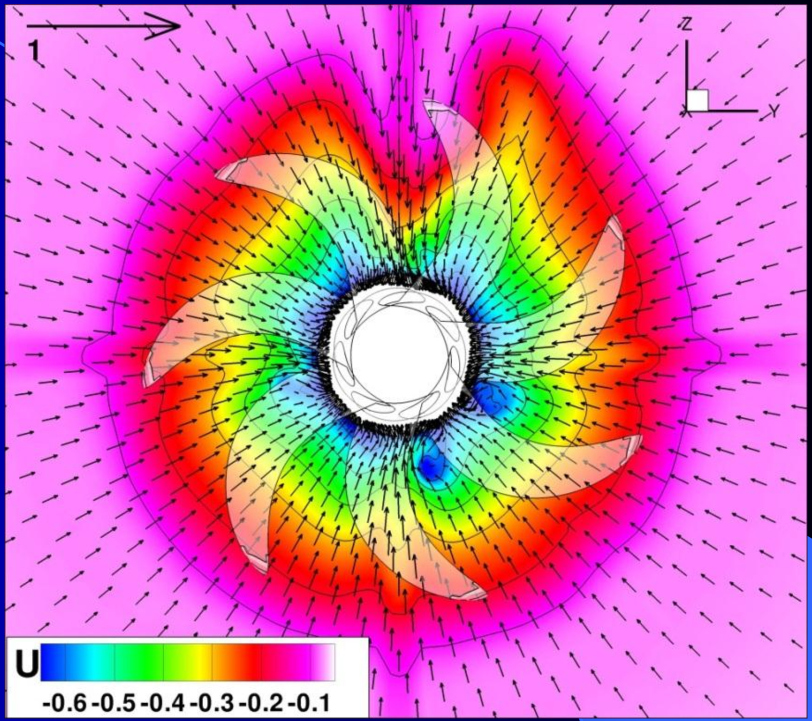


x/L = 1.04

Suboff Maneuvers

Self-Propulsion (blade analysis)





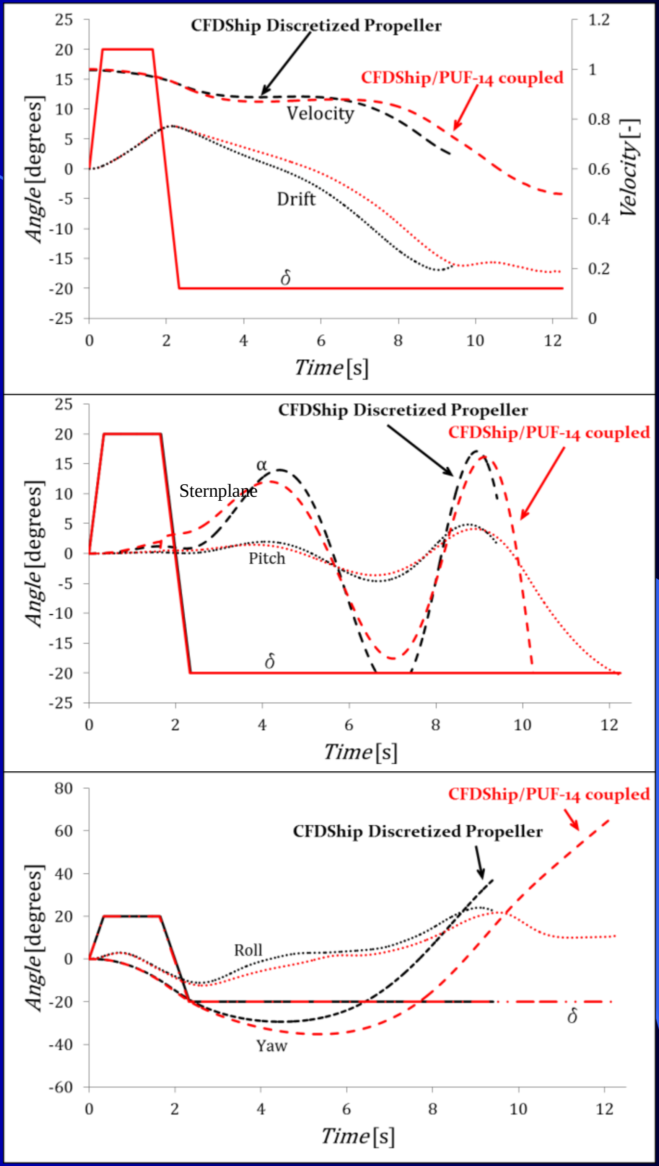
Thrust coefficient of three contiguous blades for three full rotations of the propeller. Blade 1 is on top at 0 degrees, with blade 2 the next one to port and blade 7 the previous to starboard.

Suboff Maneuvers

<u>Horizontal overshoot maneuver</u>

- Starting from self-propulsion
  - Turn rudder 20 degrees to starboard at maximum rate
  - At heading 20 degrees turn rudder to port at maximum rate
  - Propeller RPS held constant
  - Sternplanes control depth

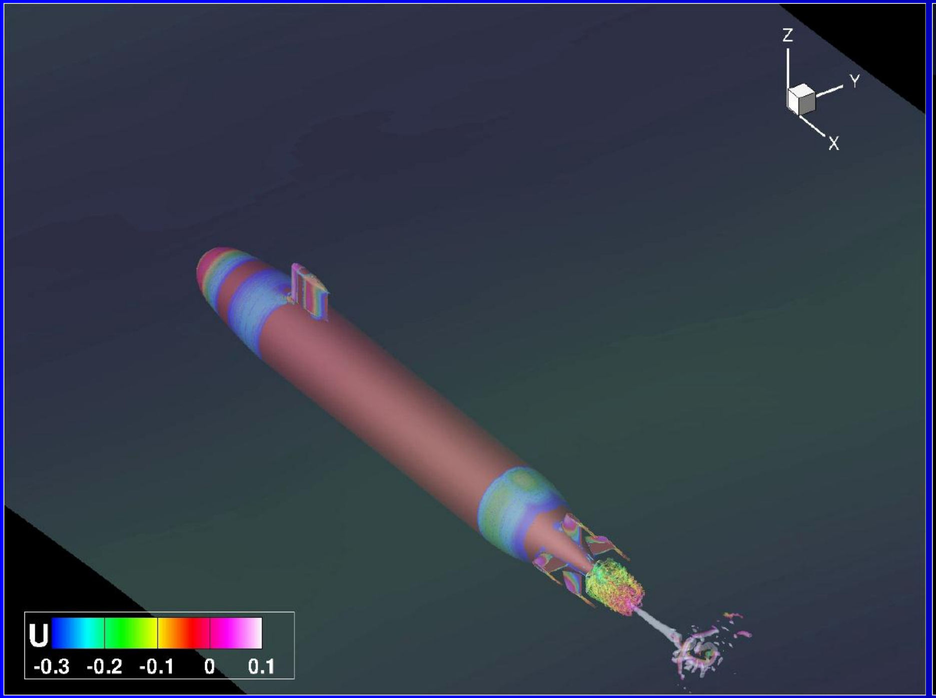
- Also computed coupling CFD with advanced propeller solver PUF-14

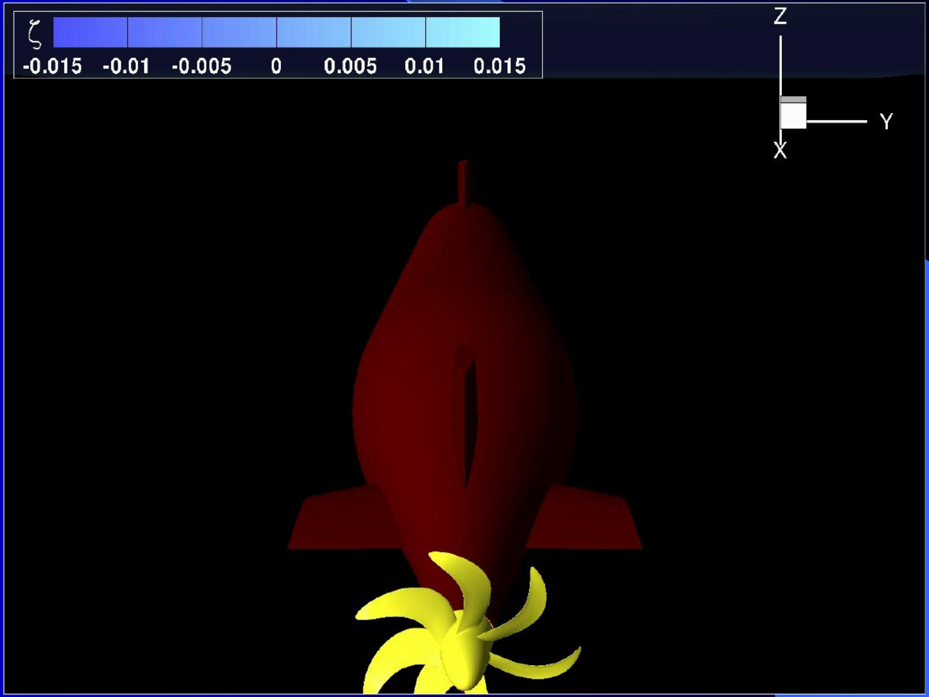


Suboff Maneuvers

<u>Surfacing submarine</u>

- Speed controlled at 12 knots full scale
  - Net weight at 95% buoyancy
  - Sternplanes control pitch at 0 degrees
  - Incoming waves at λ=1.5 *Lpp*, *a*=0.006 *Lpp*





Summary and Conclusions

- Overset technology provides capabilities to perform free running ship/submarine computations
- Self-propulsion computations with resolved propellers are today within reasonable wall clock times (less than a week for 40 M grid points, 250 procs.
- Maneuvers take longer, but still doable.
- Domain connectivity scalability is still the bottleneck to perform higher resolution computations
- Parallel hybrid MPI/OpenMP approaches, as in Suggar++, may enable dynamic maneuvering computations in the 100~1000 M grid points