Integrating CFD and Experiments.
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NUMERICAL SIMULATION OF FLUID-STRUCTURE INTERACTIONS ON LONG BODIES

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METHOD and APPLICATIONS

Many bodies in crossflow generate an unsteady flow field (due to separation or oscillation), which has weak variation in the spanwise direction and is effectively inviscid in the far field. For these cases a Helmholtz decomposition of the flow field may be useful:

Velocity Field U = U(Potential) + U(Rotational)

Outer 3-D Potential Flow Field

Inner 2-D Navier-Stokes Flow --> 2-D U(Rotational)

Examples:

(1) Sectional viscous flows over high aspect ratio bodies which generate a 3-D far wake. (eg. Rotor blade, Cylinder VIV, Flutter)

(2) Vortex shedding from the edge of a body in purely oscillatory flow (eg a ship rolling in waves).

General Equations

$$v = v_R + \nabla \phi$$

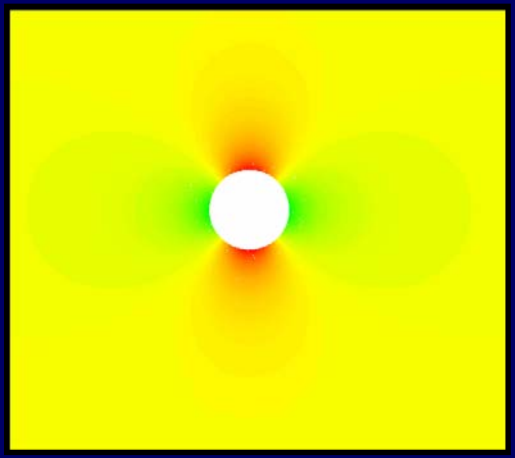
$$\begin{aligned}
\nabla \cdot v_R &= 0 \\
\frac{\partial v_R}{\partial t} + (v \cdot \nabla) v &= -\nabla p_{residual} + \nu \nabla^2 v_R \\
p_{residual} &= p + \frac{\partial \phi}{\partial t}
\end{aligned}$$

Cylinder in Steady Current (Re=100)

C_d = 1.33, St = 0.167

$$\phi = U_\infty \cos\theta \left(r + \frac{D^2}{4r} \right)$$

$\nabla \phi$



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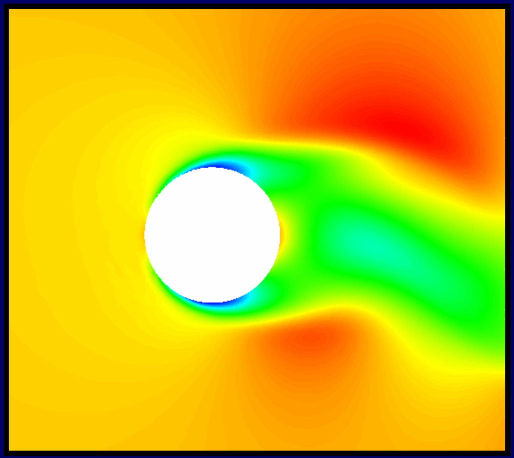

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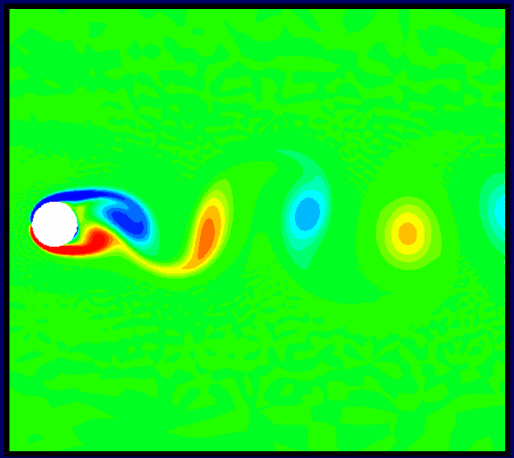
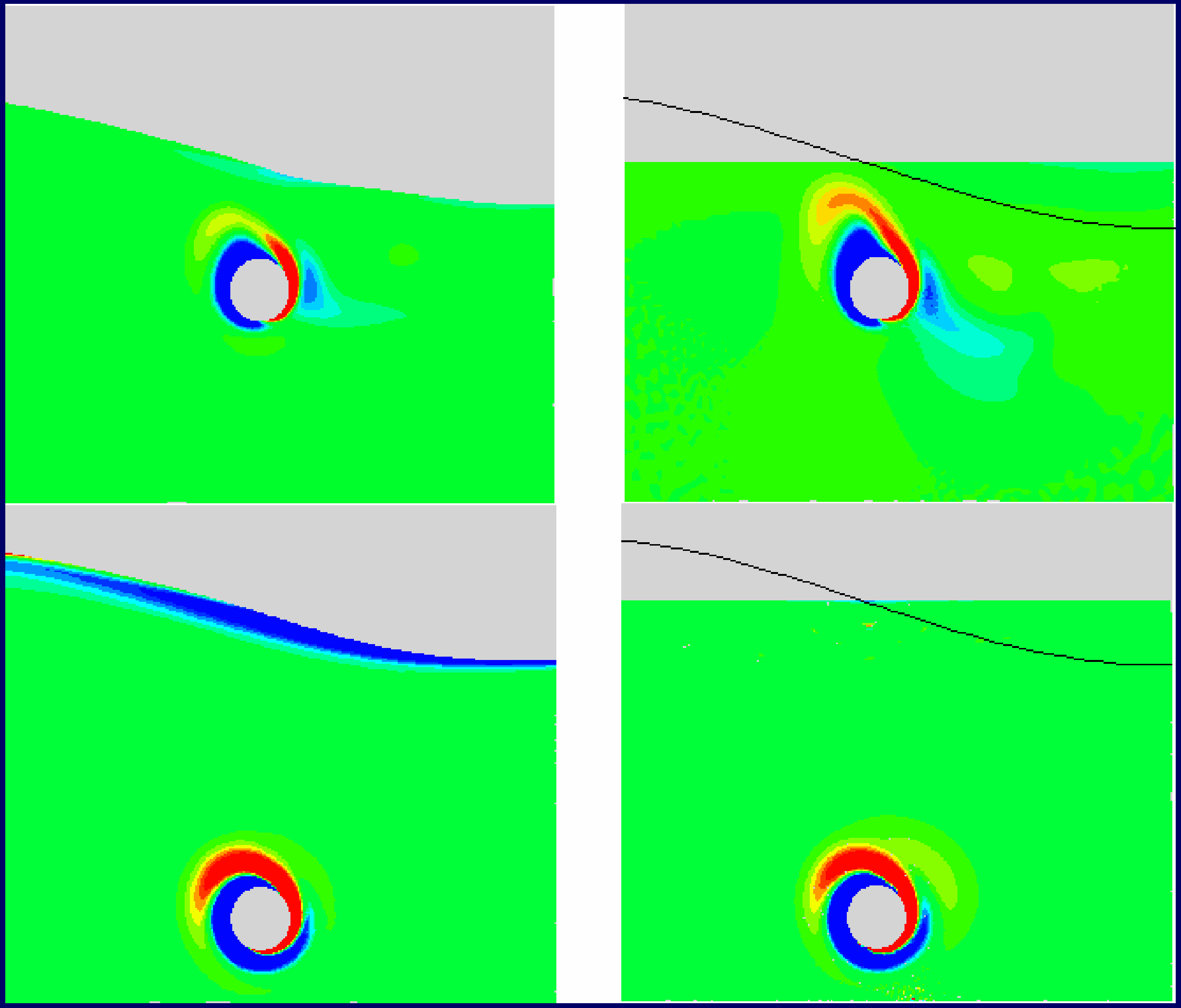


Fully Immersed Circular Cylinder beneath Regular Waves

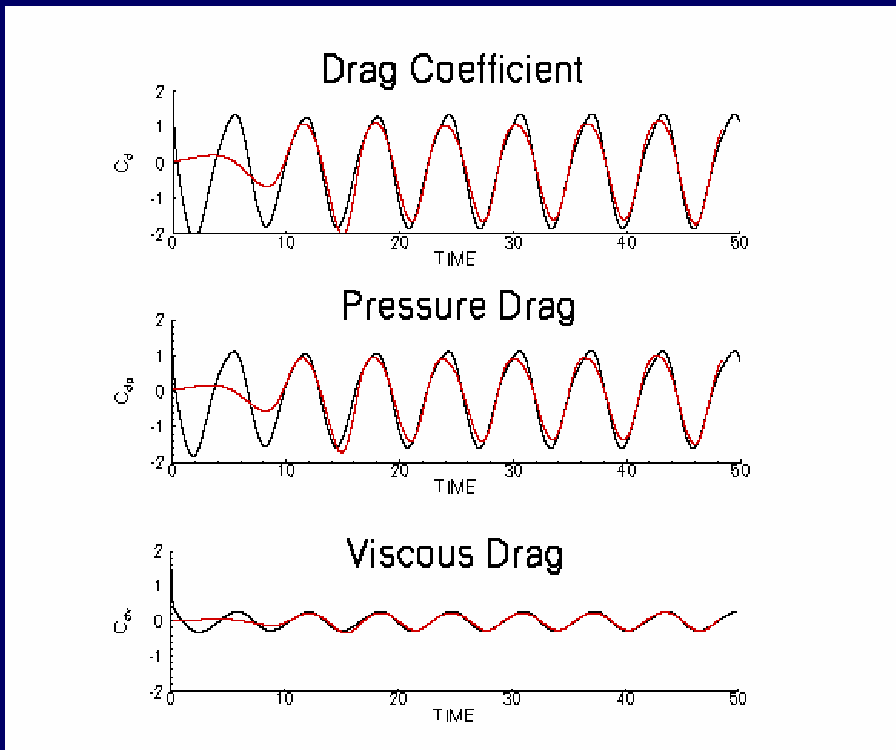
(Kc=6.28, Fn=0.56, Re ~ 100)

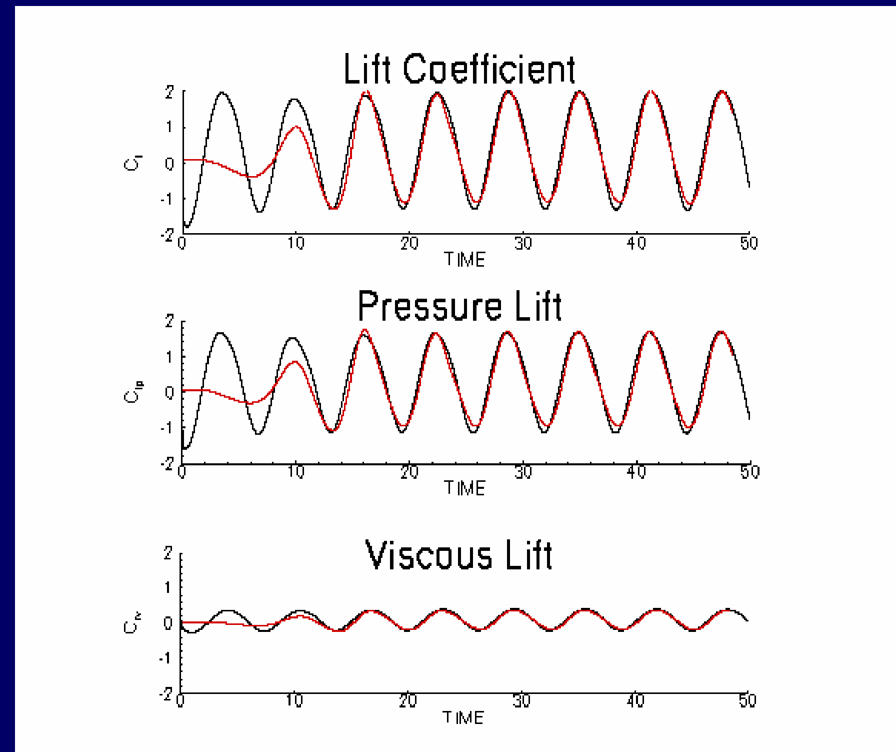


Non-linear solver

Potential/Rotational

Inner/Outer Coupled versus Full Non-Linear





Full Nonlinear Solver

Coupled Solver

A comparison of the drag and lift coefficients between the rotational solver and the full nonlinear code for a horizontal cylinder beneath waves, centred at a depth 2 diameters beneath the undisturbed free surface. (Kc~6.3; Fr~0.3; Re~100)

Turbulence Modelling (LES)

- LES Momentum Equation

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu + \nu_s \left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) \right]$$

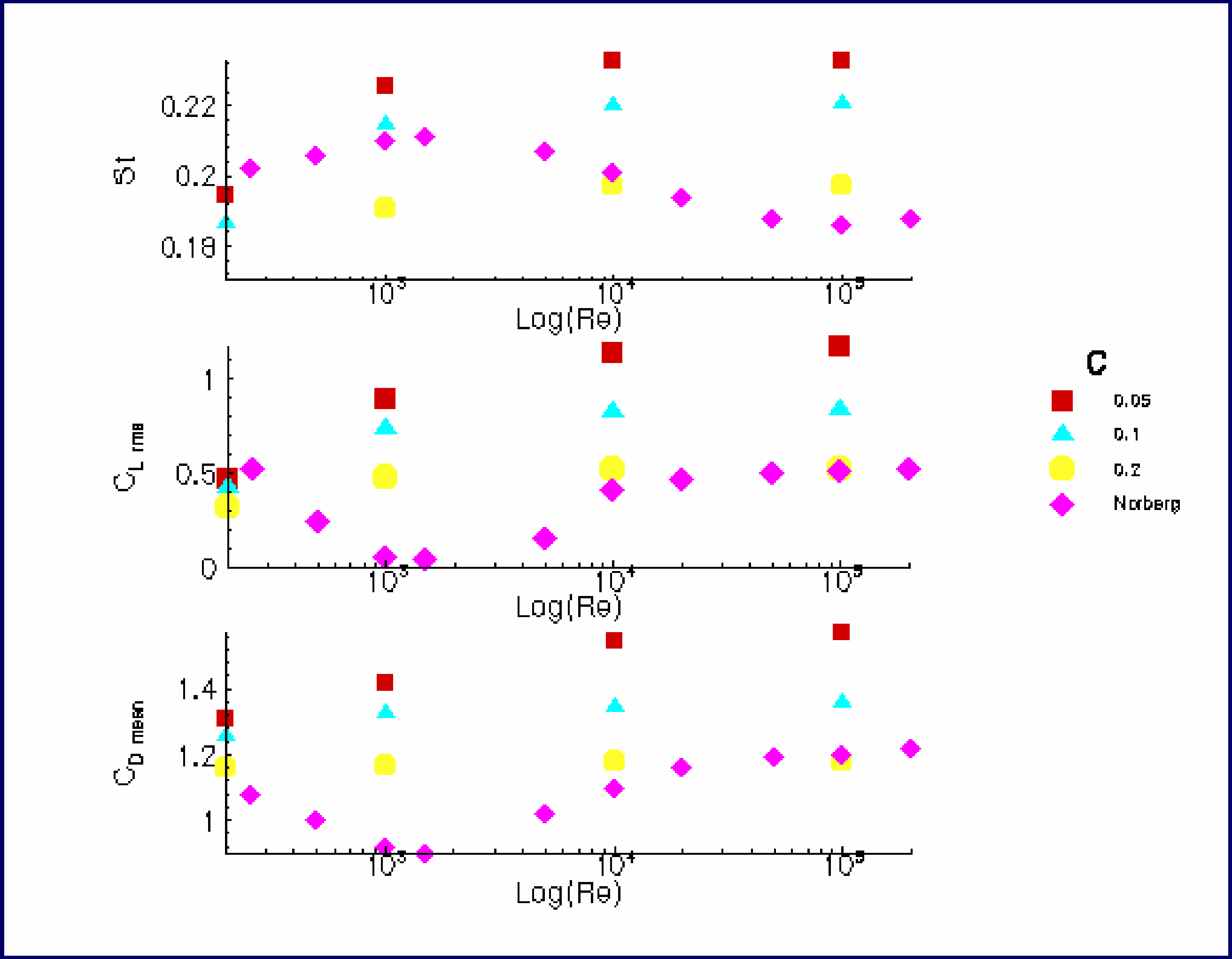
- Smagorinsky Model

$$\nu_s = l_s^2 \left| \overline{S} \right| = (C_S \Delta)^2 \sqrt{2 S_{ij} S_{ij}}$$

- Variable viscosity, ν_{var}

$$\nu + \nu_s = \overline{\nu} + \nu_{\text{var}}$$

Turbulence Modelling (LES)



Strouhal Number, Lift and Drag Coefficients, for flow past a cylinder using LES model, where we see the effect of varying the calibration constant C. Comparisons are made with experiment (C.Norberg JFS Vol15)

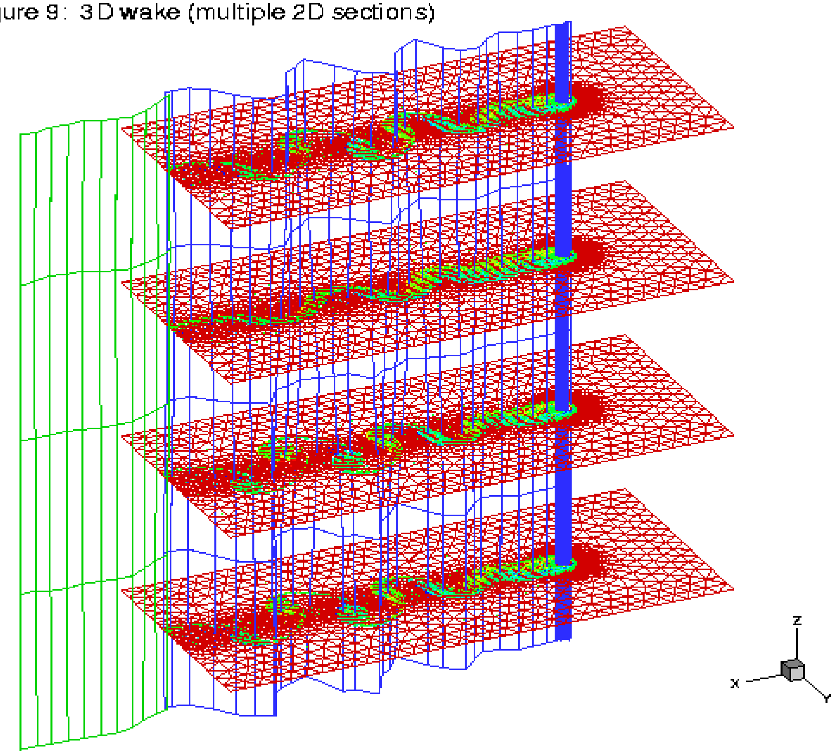
1) Navier Stokes Sectional (Incompressible) Flow + 3-D Vortex Lattice wake

- Inner multi-section flows computed using Mixed Lagrangian (vortex particle) - Eulerian (fixed mesh) scheme. (Viscous, fine resolution, unstructured mesh).
- Inner vorticity provides upstream boundary conditions for outer 3-D Vortex Lattice method. (Inviscid, coarse discretisation, grid-free).
- Outer vortex lattice provides outer boundary conditions for inner flow fields.

Inner Sectional Viscous Flows (VIVIC).
Outer 3-D Vortex Lattice (Potential) Flow Field.

Quasi 3D Numerical Simulation of the Flow about a Circular Cylinder,
using a Velocity-Vorticity formulation of the Navier-Stokes equations.
Reynolds Number = 100 : Time Step = 0.01

Figure 9: 3D wake (multiple 2D sections)



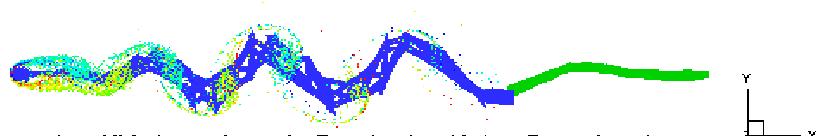
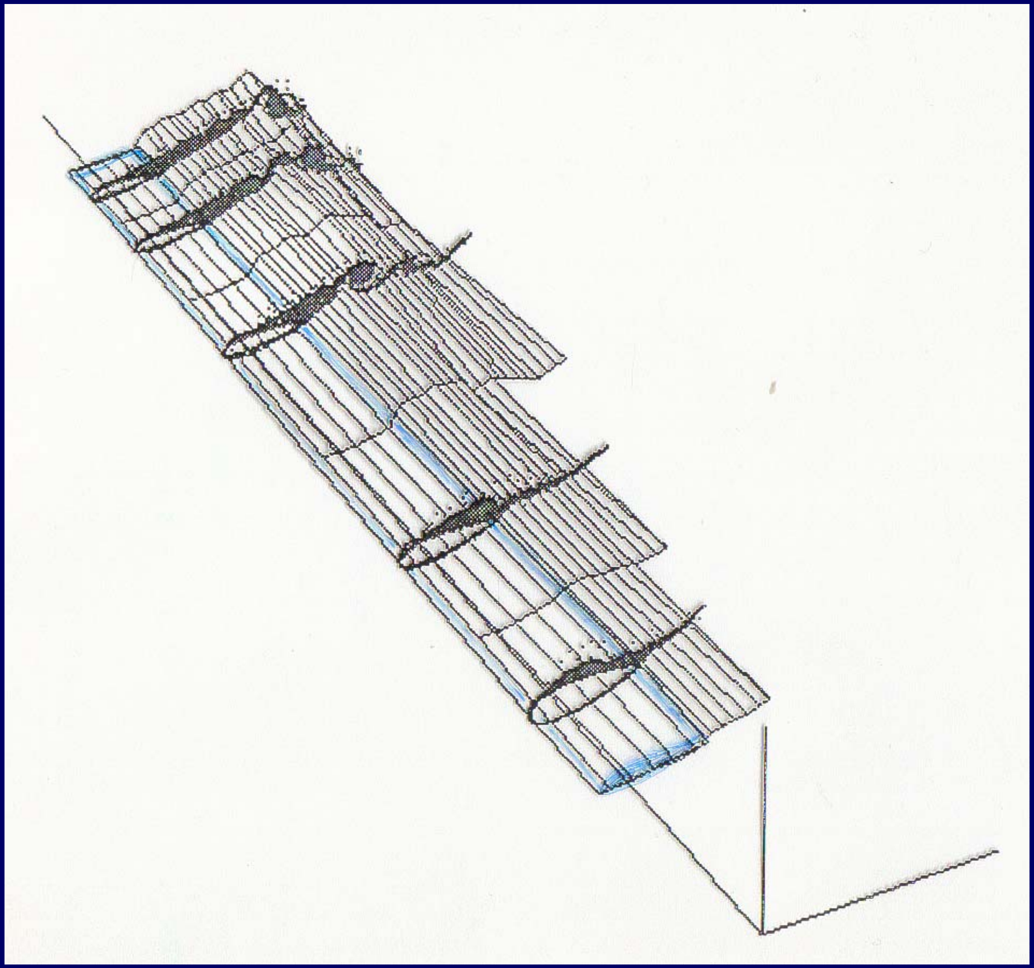
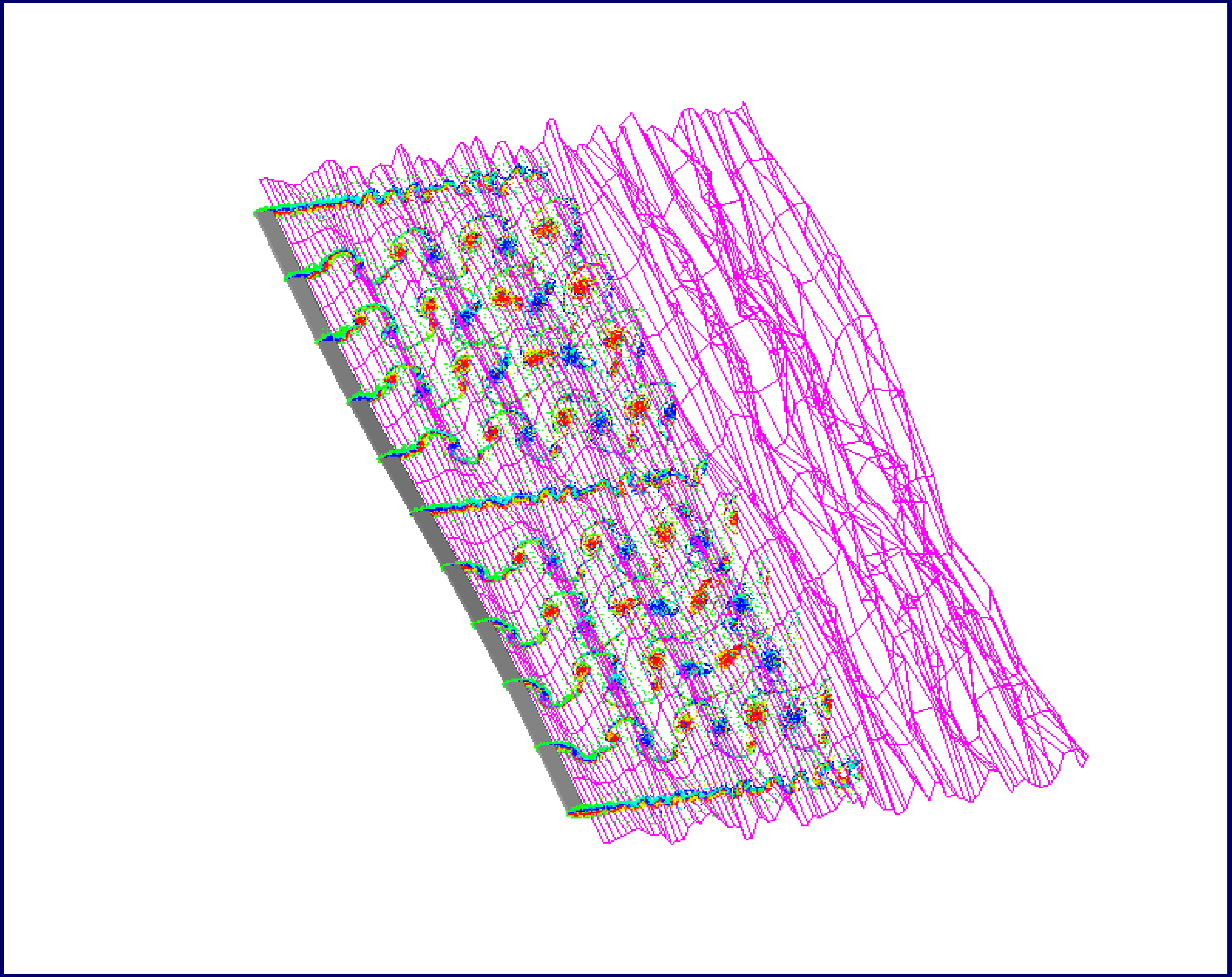


Figure 10: XY plane view of 3D wake (multiple 2D sections)

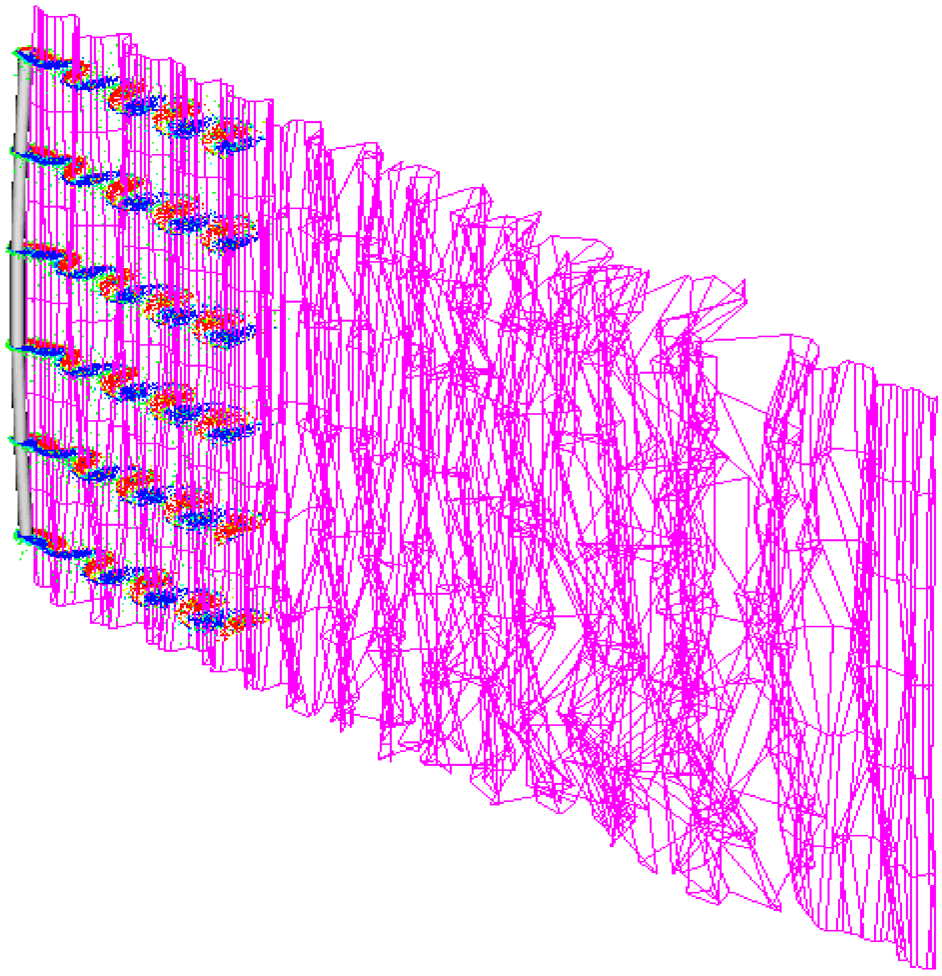
Inner Sectional Viscous Flows (VIVIC).
Outer 3-D Vortex Lattice (Potential) Flow Field.
Application to Wind-Turbine Rotor Flow.



Inner Sectional Viscous Flows (VIVIC).
Outer 3-D Vortex Lattice (Potential) Flow Field.
Application to very high aspect ratio flexible aerofoil (Bridge Deck)

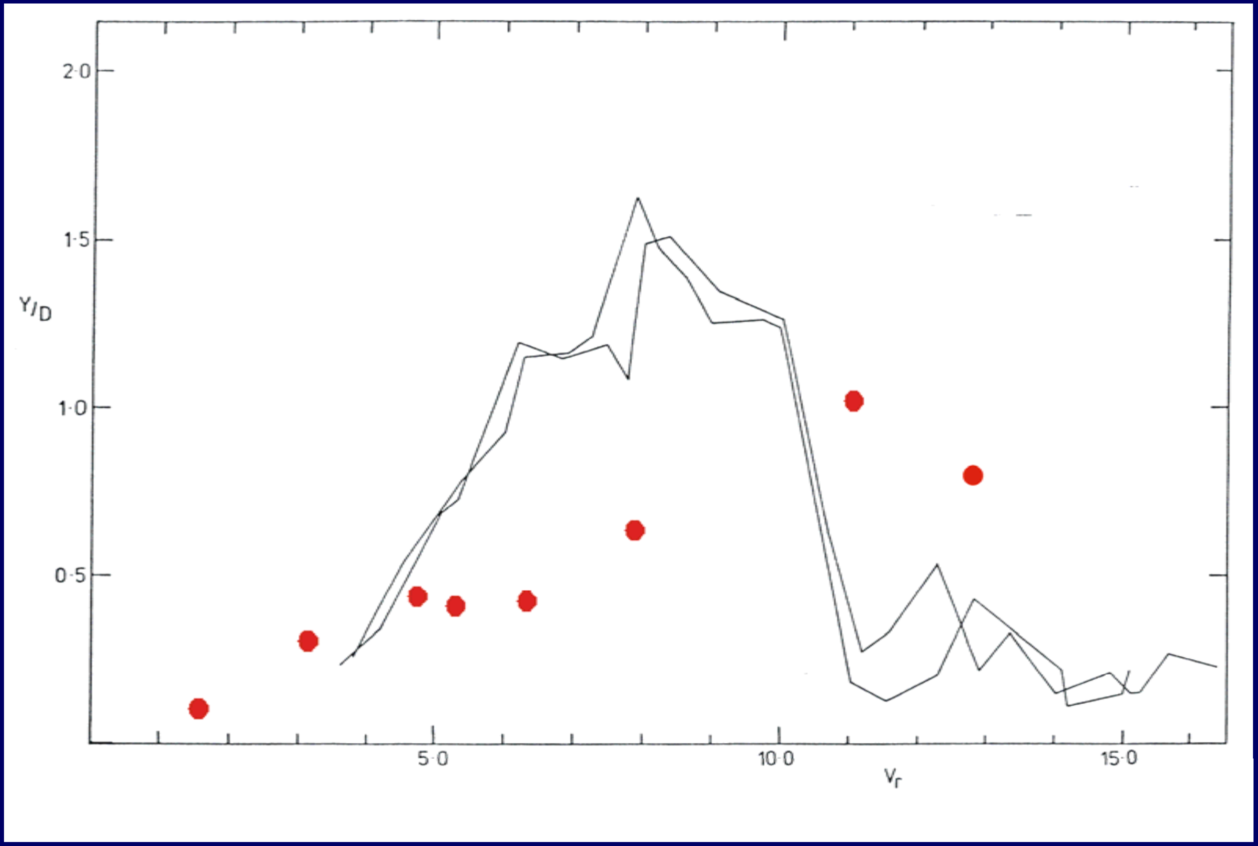


Inner Sectional Viscous Flows (VIVIC).
Outer 3-D Vortex Lattice (Potential) Flow Field.
Application to long flexible (Riser) pipe in cross-flow.

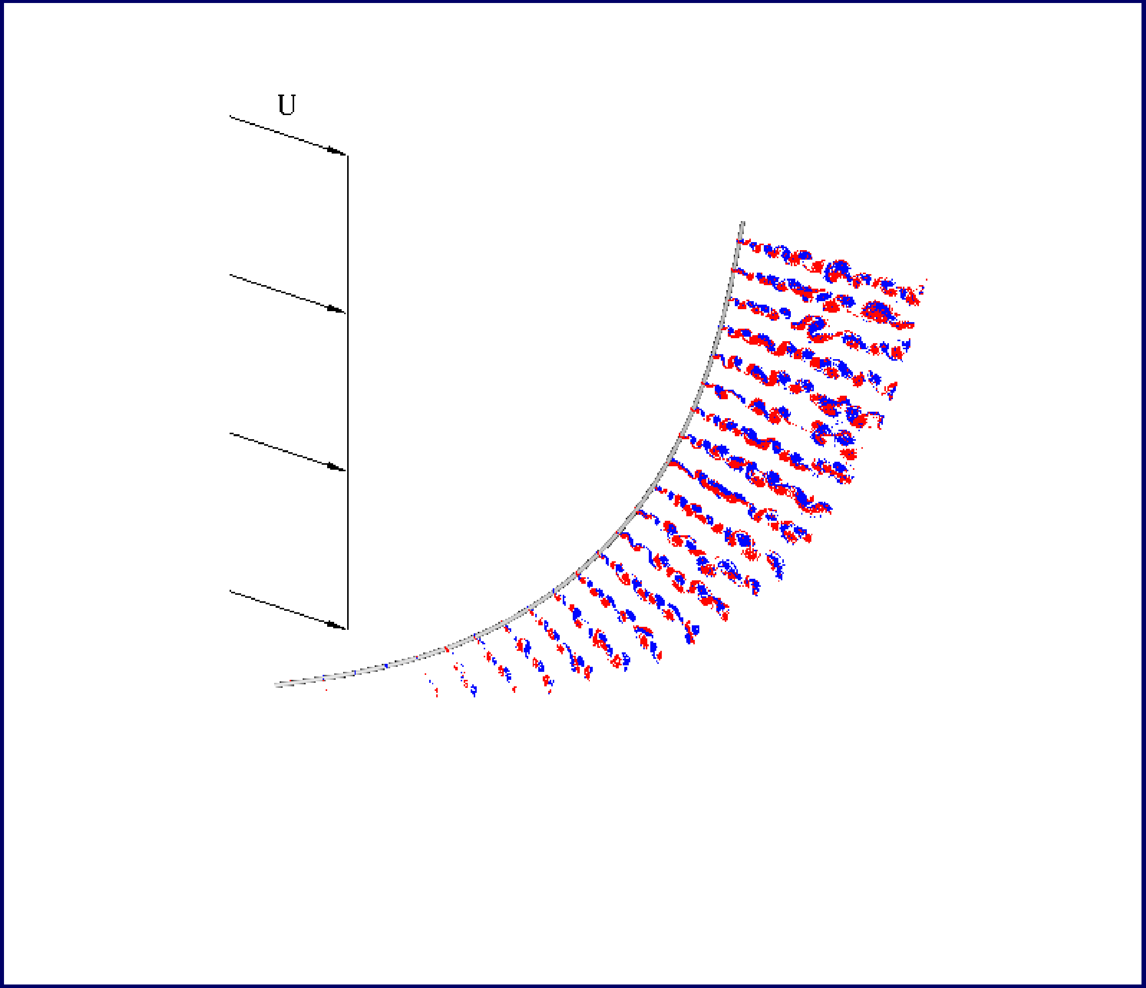


TOP TENSIONED (RISER) PIPE

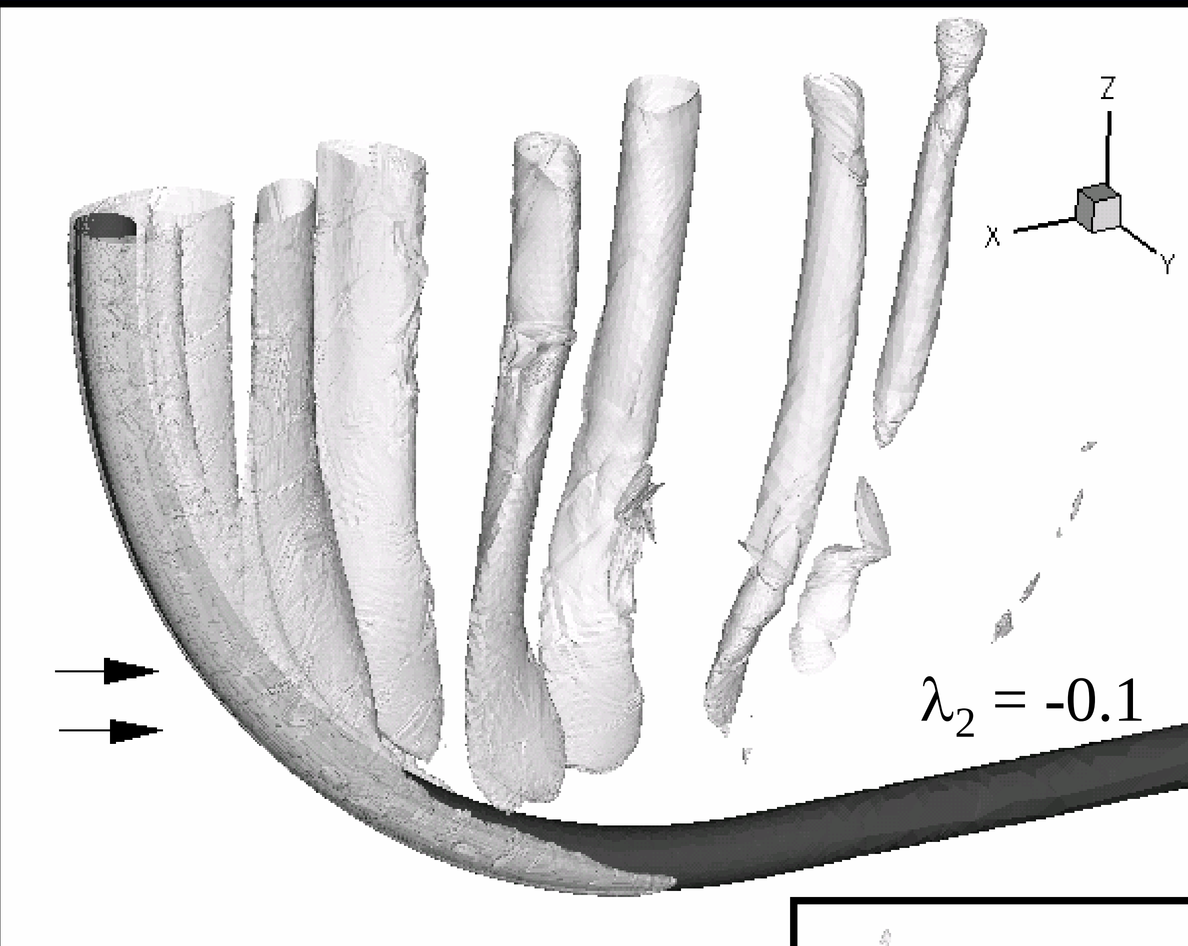
Comparison of Numerical Prediction with Experiment (Lamb, 1988, BHRA)

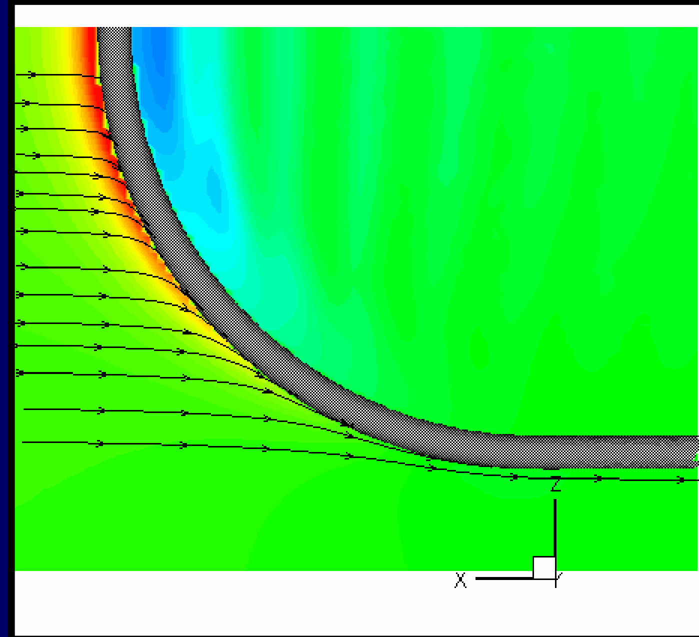


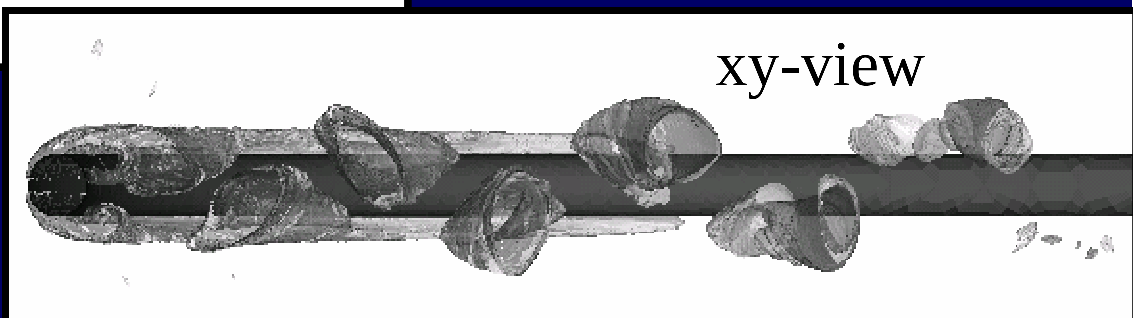
Inner Sectional Viscous Flows (VIVIC).
Outer 3-D Vortex Lattice (Potential) Flow Field.
Application to curved (catenary riser) pipe.



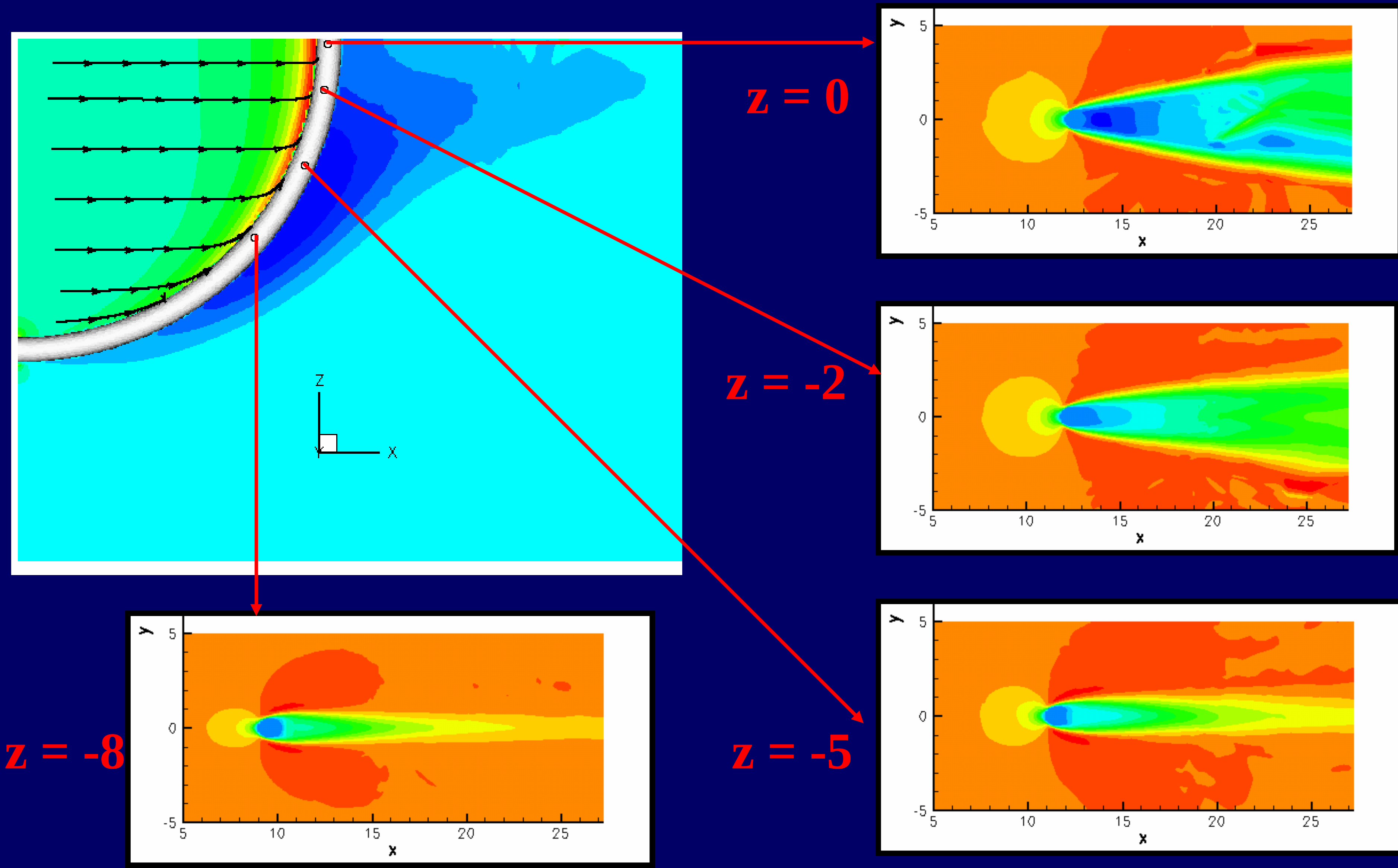
Vortex cores in the wake







Centreplane streamlines and *u*-velocity contours

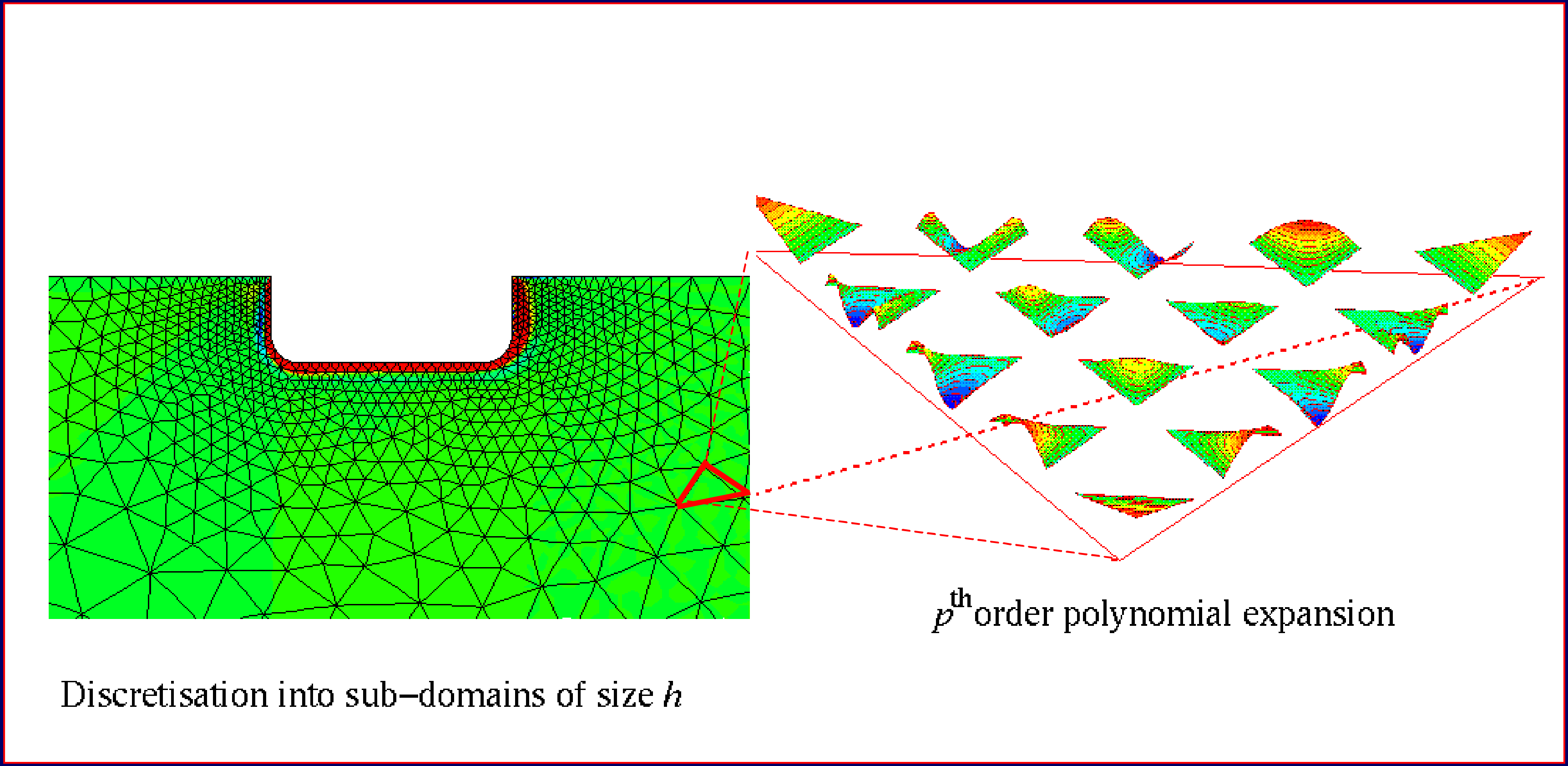


2) Embedding of Rotational (Viscous) Flow Solver in Potential (Inviscid) Wave Field around a Body (Helmholtz Decomposition).

- 1) Potential flow field calculated by standard 3-dimensional method (eg linearised, frequency domain, panel code).
- 2) Rotational flow component computed on 2-D sections in the time domain, correcting the no-slip condition on the body surface but not applying outer boundary conditions for wave propagation.
- [3) If required, calculation of wave radiation by rotational flow component and iteration through (2) and (3).]

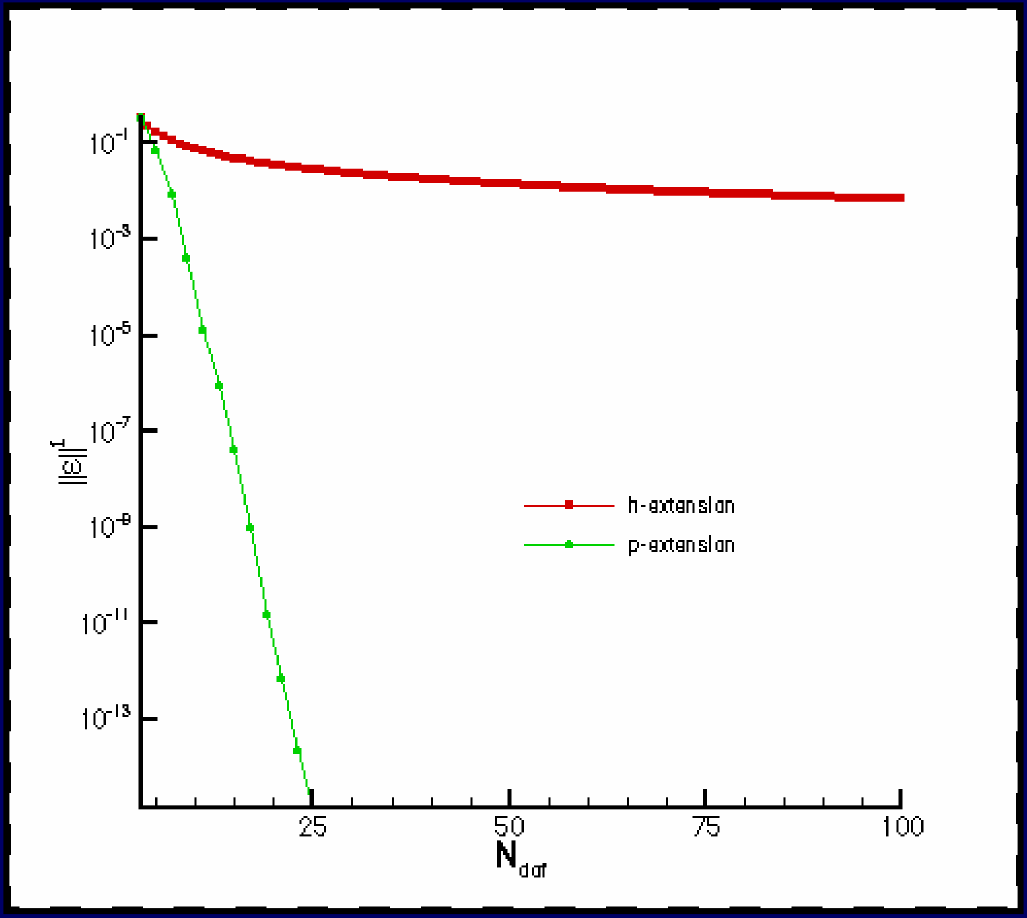
Numerical Technique:

Spectral/*hp* element methods



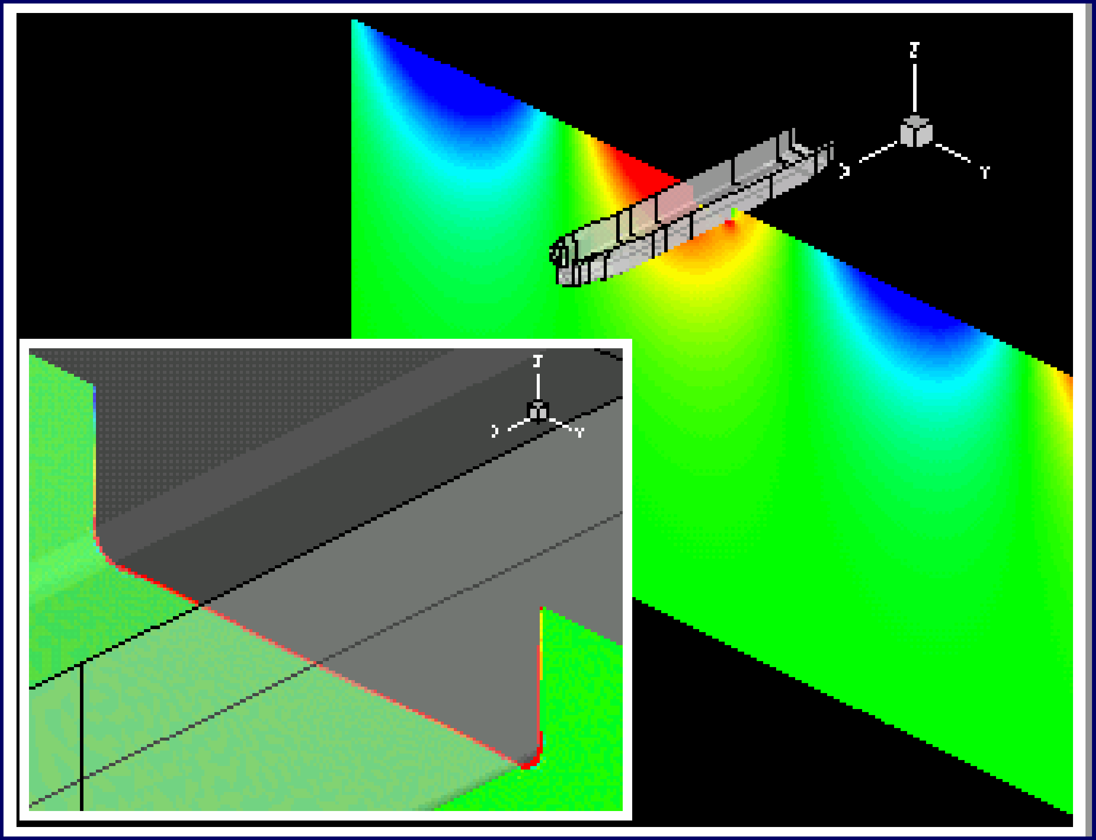
- **High order accuracy**
- **Unstructured meshing (GiD)**

Spatial Convergence



$$\log \varepsilon \propto p$$

Coupled Strip Theory / 3D Potential applied to Floating Hulls

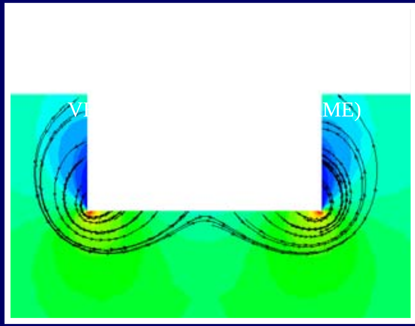


Body Motion

Potential Body BC:

(inertial frame)

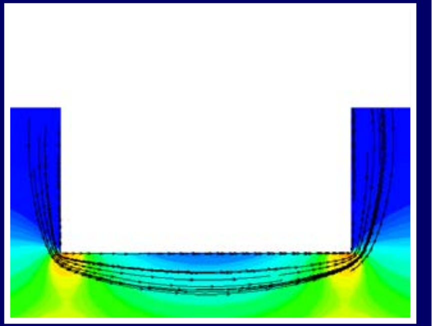
$$\frac{\partial \phi}{\partial n} = \dot{d} \cdot n + \left[\dot{\Omega} \times x \right] \cdot n$$



Transformation of Potential

(inertial to body)

$$\nabla \phi - \dot{d} - \dot{\Omega} \times x$$



Potential Body BC:

(body frame)

$$\frac{\partial \phi}{\partial n} = 0$$

Governing Equation

(body frame)

$$\frac{\partial v_R}{\partial t} + (v \cdot \nabla) v = -\nabla p_{residual} + \nu \nabla^2 v_R + G(v, v_R, t)$$

Coupled Roll Sway Response of Rectangular-Section Hull in Beam Seas

Experiments: *D.T. Brown, R. Eatock Taylor & M.H. Patel, JFM (1983), vol 129, pp.385-407*

Basic Hull Properties

Length = 2.4m

Beam = 0.8m

Height = 0.34m

Draft = 0.105m

Roll moment of inertia = 11.95 kg m^2

Roll Natural frequency = 5.8 rad/s

Expt Run Parameters

Random Sea Data

3 significant wave heights

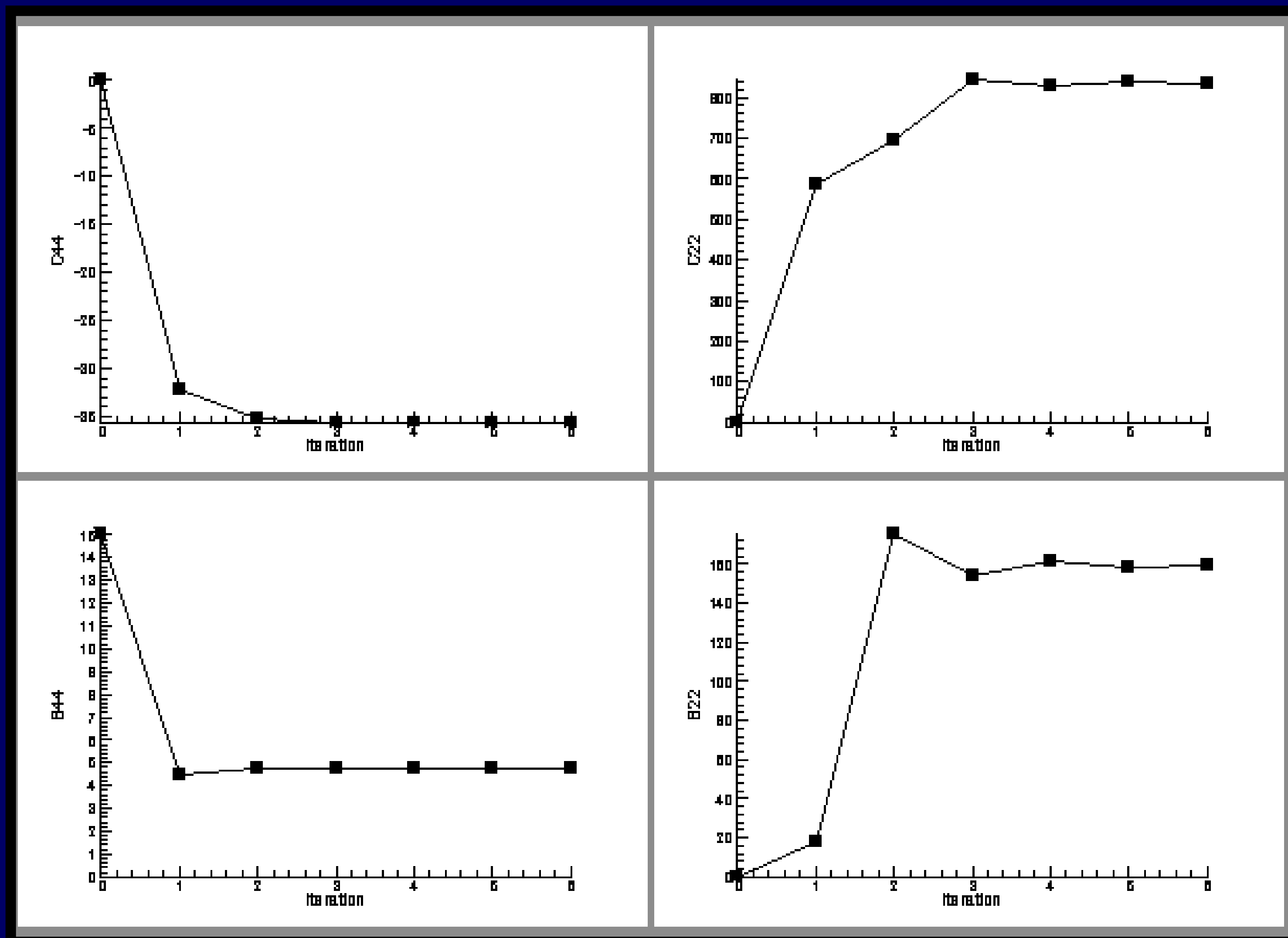
- 3.0, 2.4, 1.9 cm

2 bilge profiles

- Sharp
- Rounded (r=40mm)

Coupled Roll Sway Response of a Rectangular Hull in Beam Seas

Convergence of Damping and Stiffness Coefficients (Sharp Bilge)



Coupled Roll Sway Response of a Rectangular Hull in Beam Seas

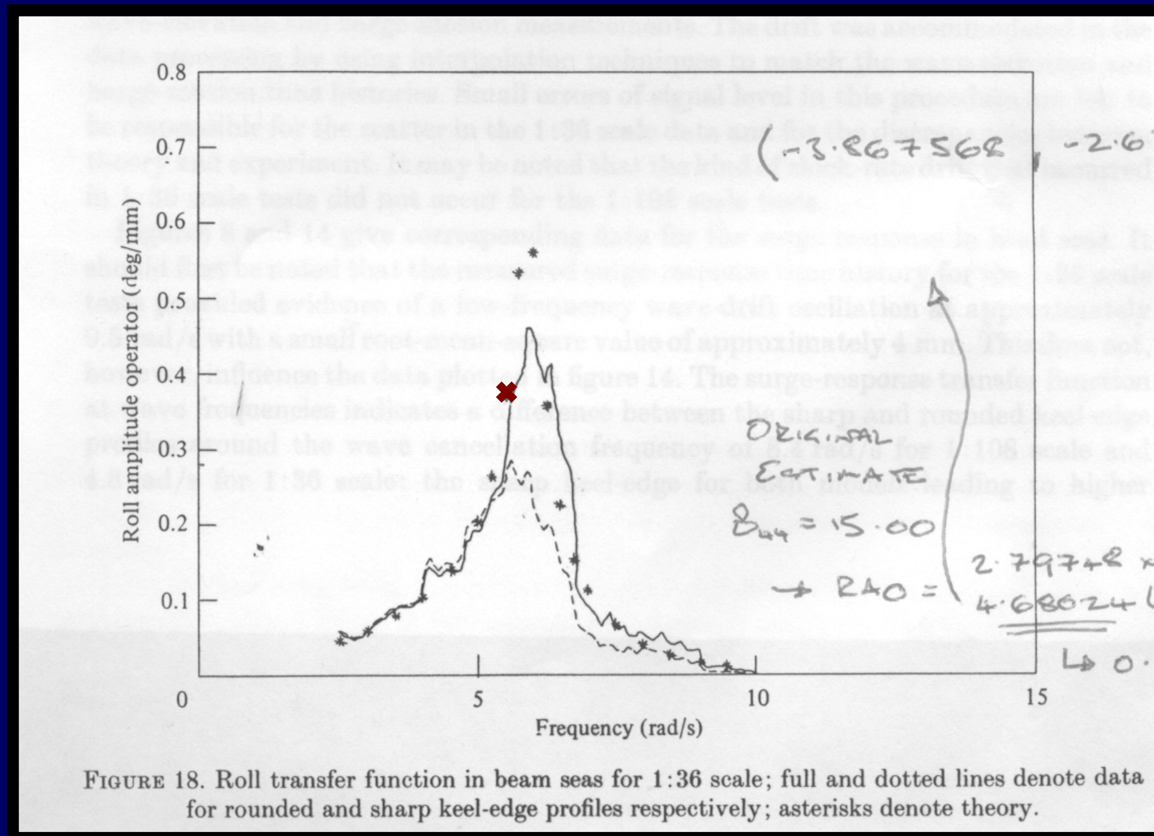


FIGURE 18. Roll transfer function in beam seas for 1:36 scale; full and dotted lines denote data for rounded and sharp keel-edge profiles respectively; asterisks denote theory.

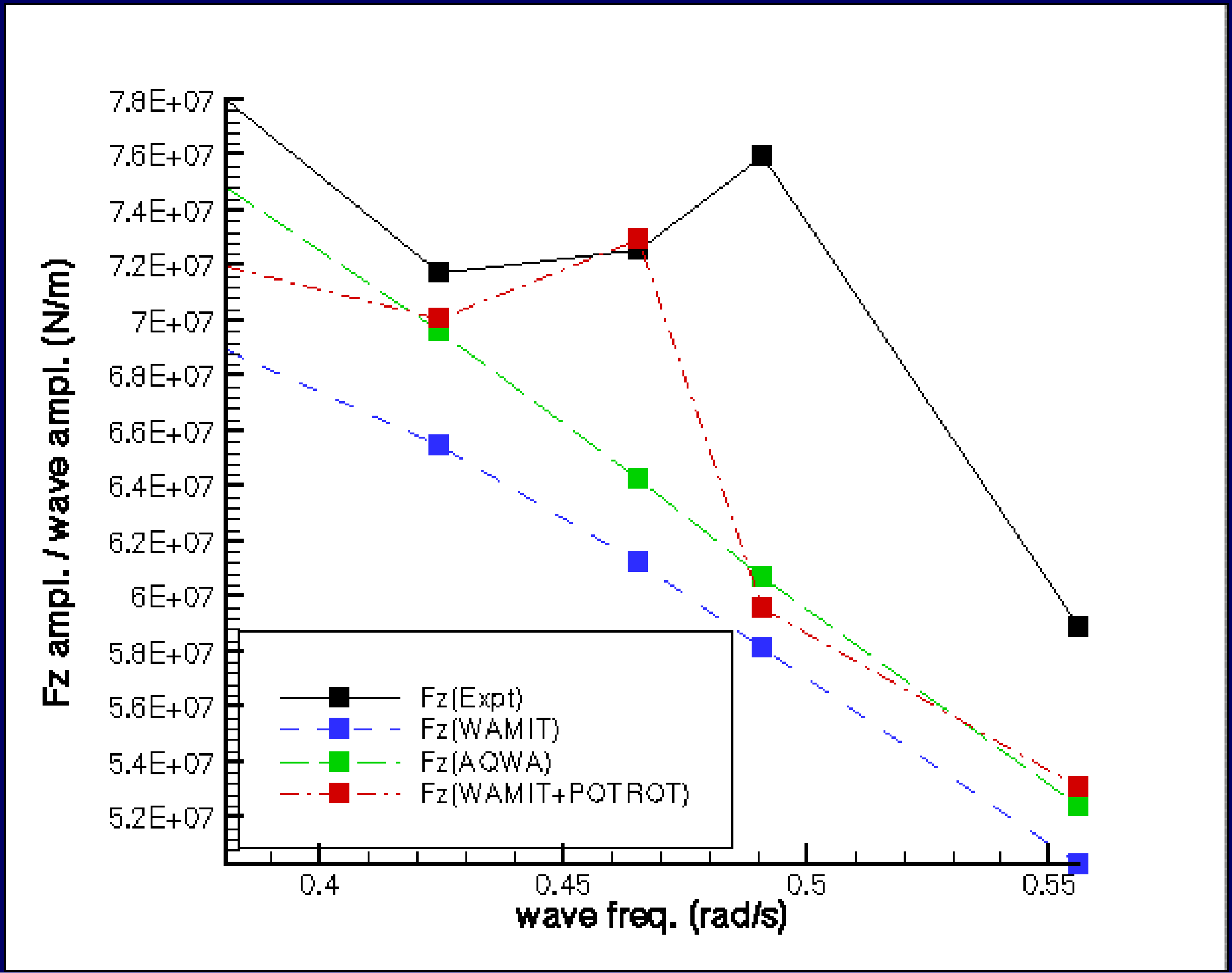
RAO expt (deg/mm) ~ 0.27 (Sharp), 0.46 (Rounded)

RAO calc (deg/mm) ~ 0.412 (Sharp) - (Computed for Re. = 0.02 x Re(Expt)

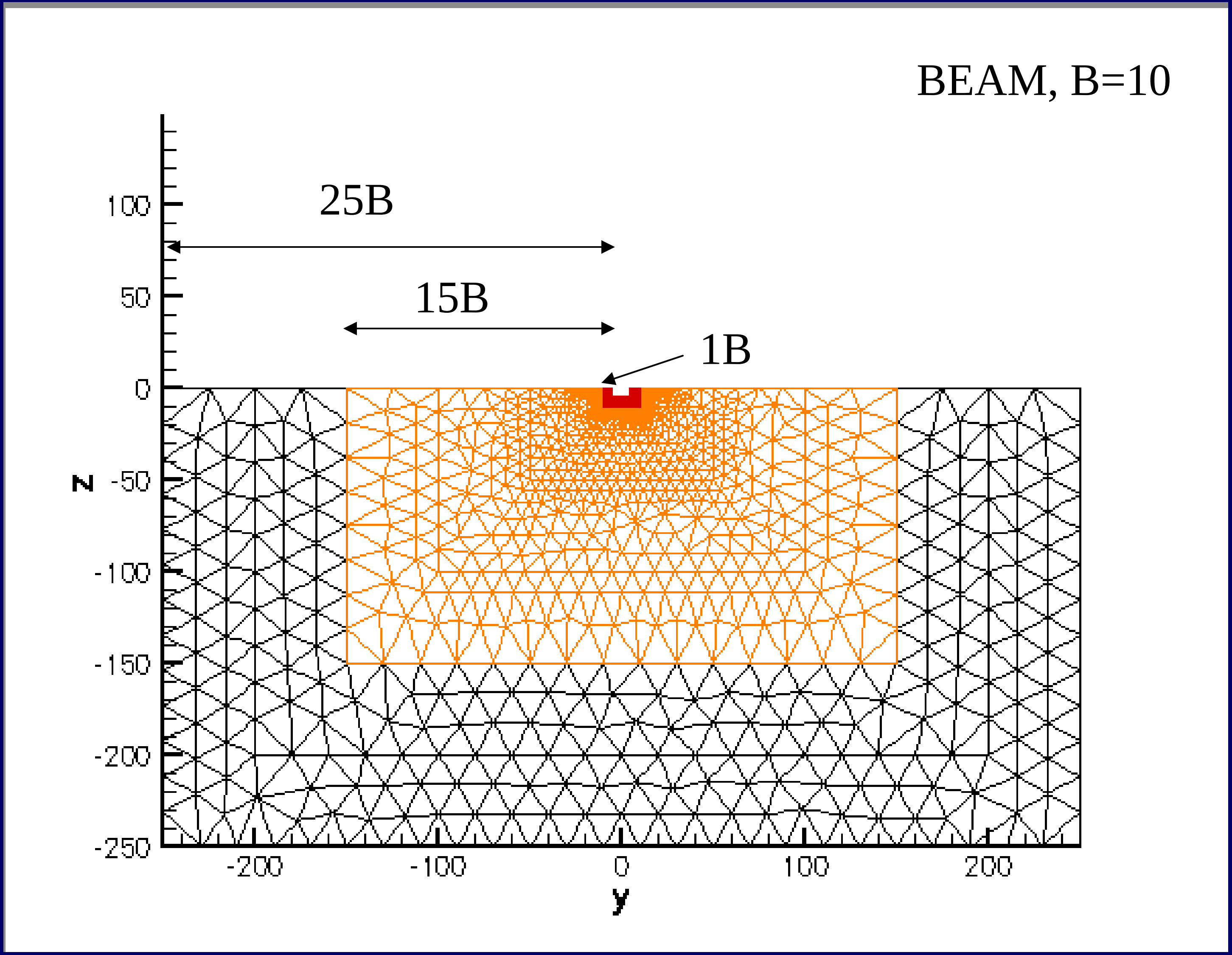
Higher Re. computation now being carried out using quadrilateral meshing of the surface which is more stable than triangular meshing used here.

HEAVE DAMPING (Computation versus Experiment - MARIN)

$$Fz = (Fz_{P_{residual}} + Fz_{Shear}) \times L + Fz_{Diffraction}$$

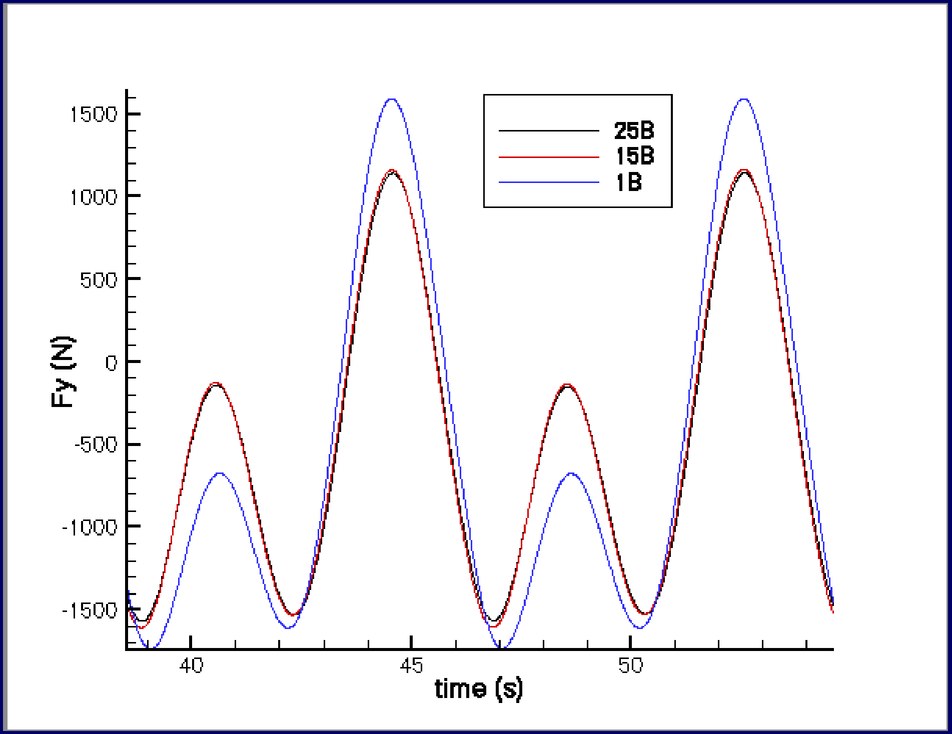


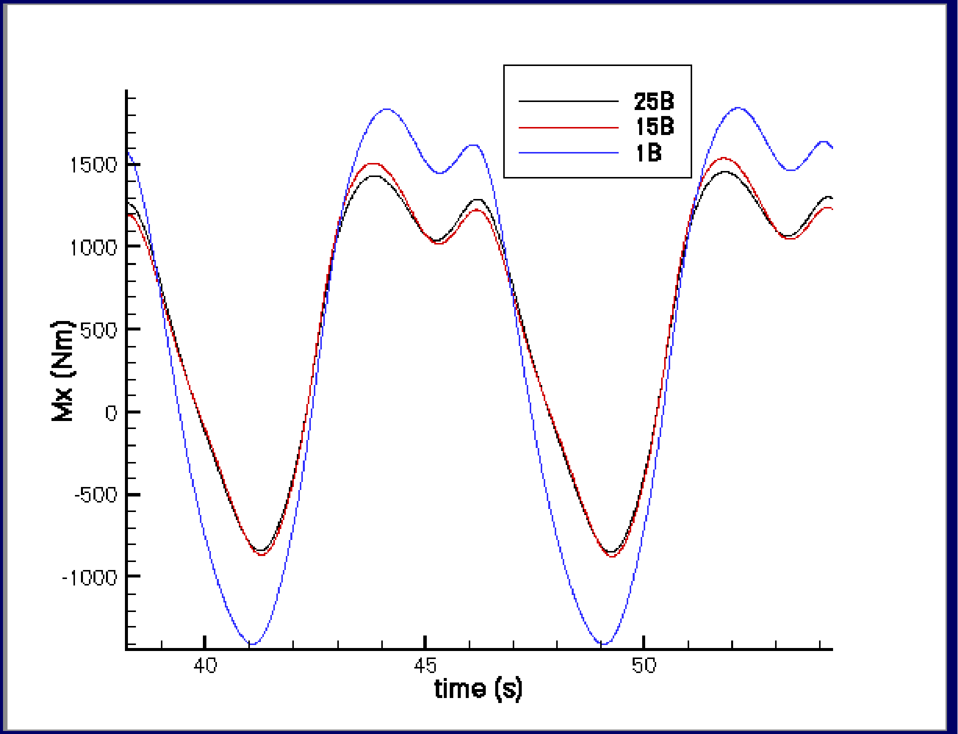
Domain Size / Mesh Size / Computation Speed



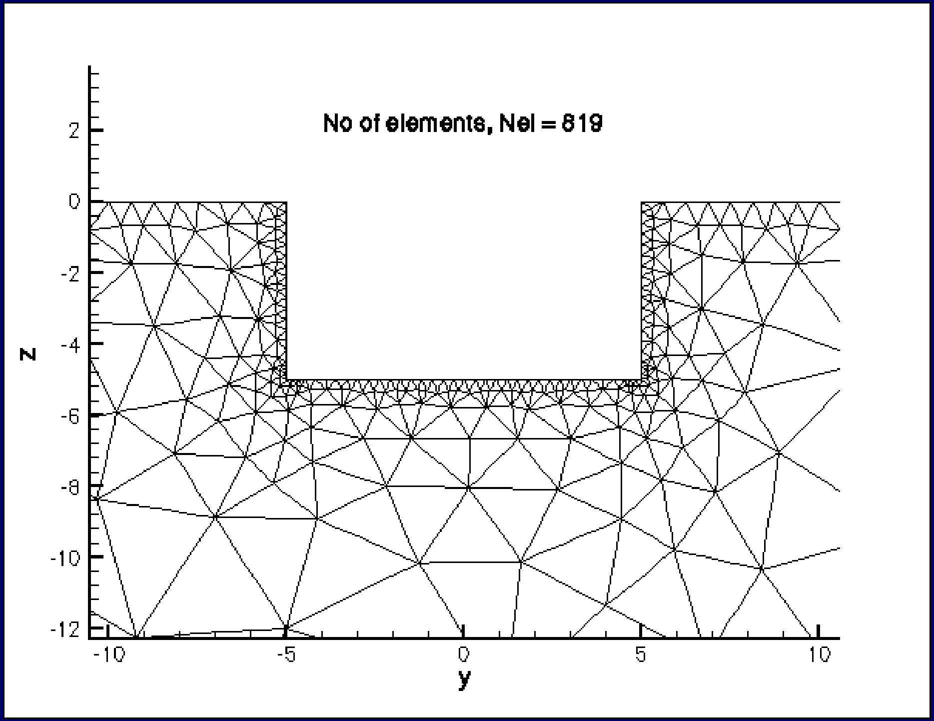
Domain Size / Mesh Size / Computation Speed

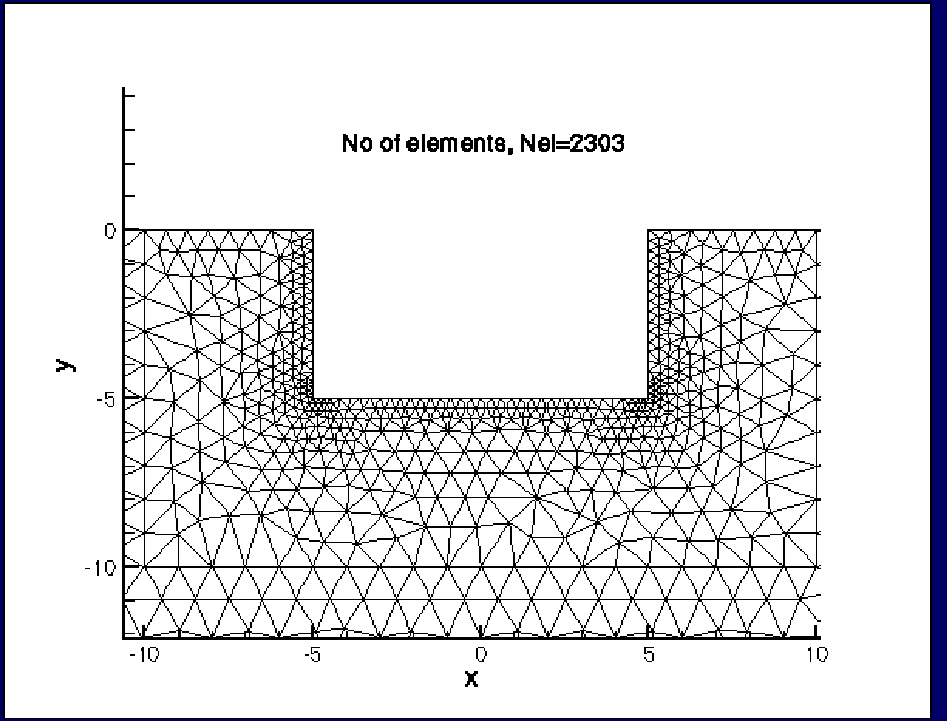
Force/Moment Plots





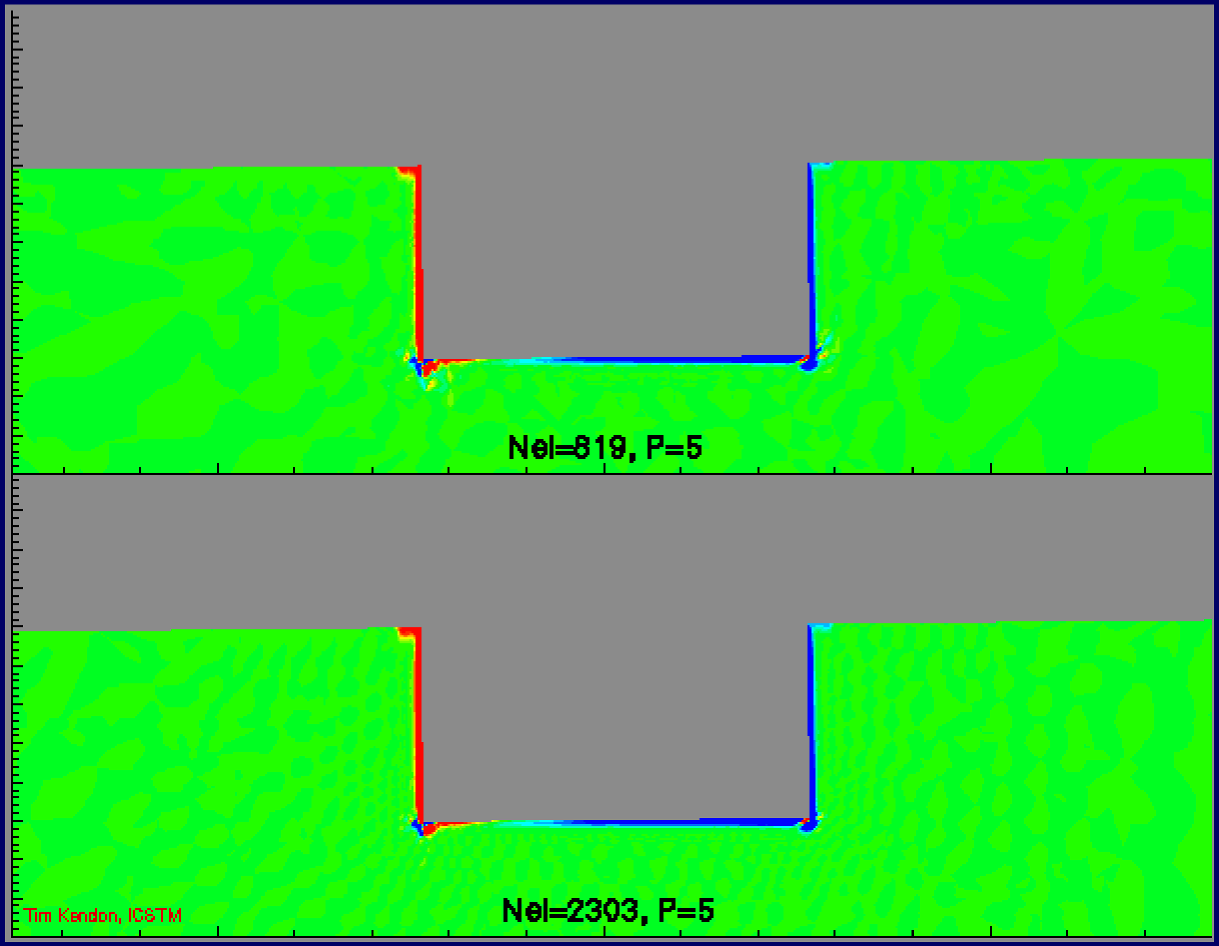
Domain Size / Mesh Size / Computation Speed





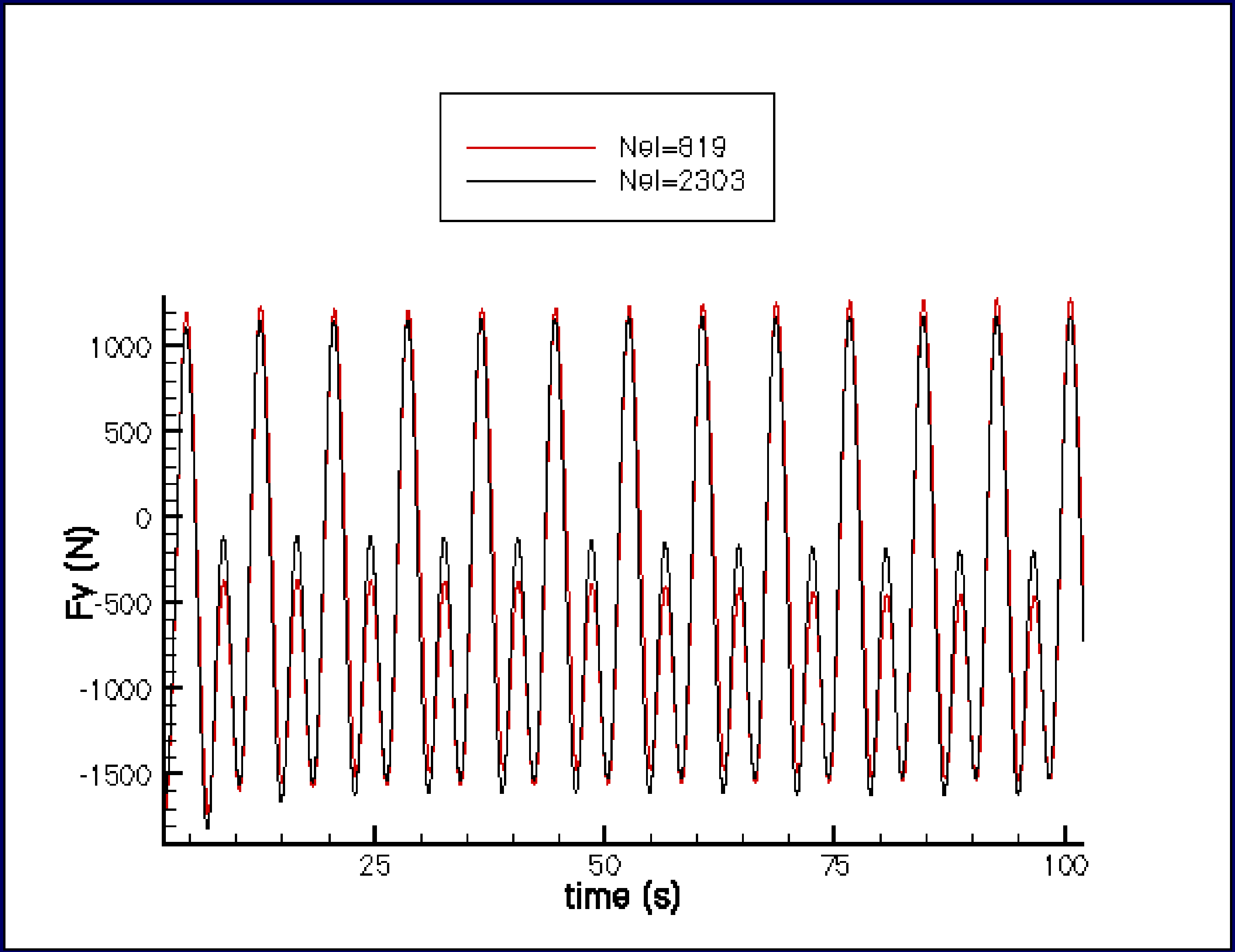
Domain Size / Mesh Expansion Rate / Computational Speed

Vorticity Contours



Domain Size / Mesh Size / Computation Speed

Sway Force



Domain Size / Mesh Size / Computation Speed

Runtime ~ 1hr 10 minutes for the 813 element mesh on a 750Mhz Processor

Number of flow cycles computed = 12

[Visual convergence from plots after 1 cycle]

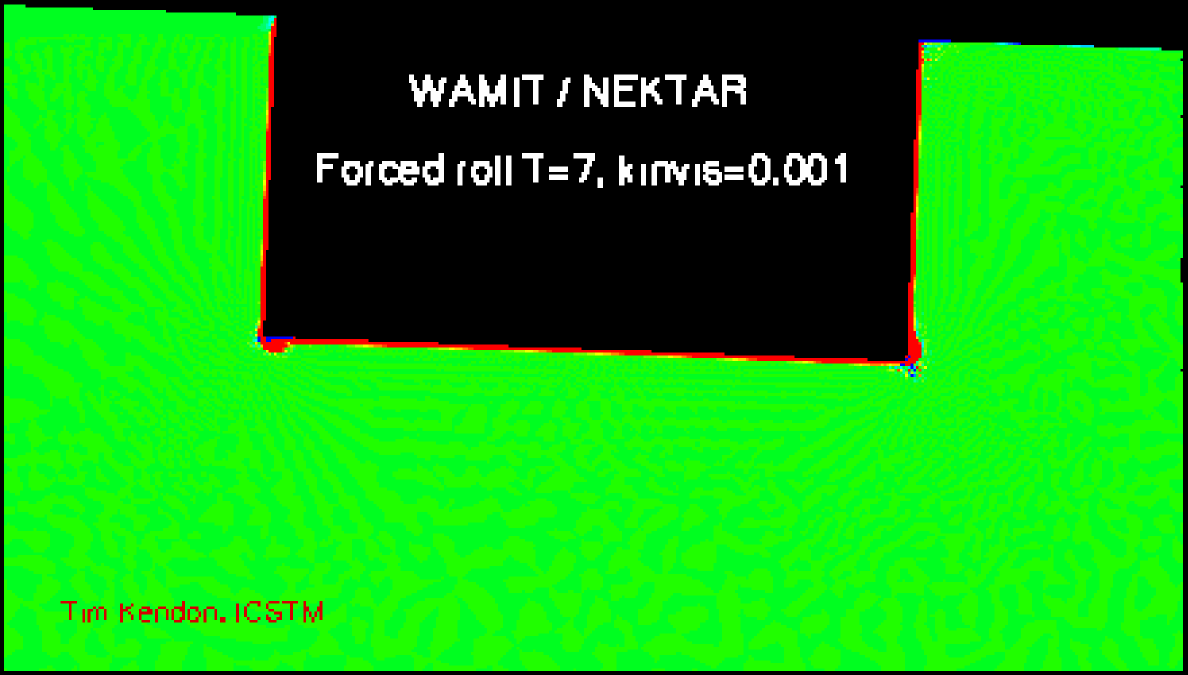
Computational cost scales with number of elements

Higher Reynolds number flows need finer elements. Typically need 5/6 cycles to be sure of asymptotic coefficient values. For RAO convergence shown earlier run times ~ 3 hours on 750MHz for one iteration. Engineering convergence after 2 iterations.

Use of hybrid meshing (quadrilaterals around surface, triangles far-field) for Reynolds number $O(10^4)$.

CONCLUSIONS

- 1. Embedding two-dimensional (sectional) Navier-Stokes fields within an inviscid treatment of the outer flow offers an efficient way of computing unsteady viscous flow past high aspect ratio bodies with weak spanwise variation of the wake.
- 2. Similarly embedding local 2-D rotational flow fields within a standard 3-D wave potential flow field of a body offers a very computationally efficient way of incorporating effects of local separations (vortex shedding driven by purely oscillatory flows about straight edges is often slender) for floating bodies in waves.
- 3. The solution procedure is approximate (cf. boundary layer or lifting line theory). Further correction terms can be obtained from a continued iteration procedure, but the first order solution will usually provide engineering accuracy.


WAMIT / NEKTAR
Forced roll T=7, kinvis=0.001
Tim Kendon, ICSTM