Chimera Grid Method for Coupling of Coastal Ocean Model and Computational Fluid Dynamics Model

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Outline

I. Introduction: Needs and current status
II. Coastal ocean model and CFD model
III. Coupling strategies
IV. Examples of coupling
V. Concluding remarks
I. Introduction: Needs and current status

Multi-scale and Multi-physics Flows: Example problems

A. Deepwater horizontal oil spill
   1) small-scale plume of oil spill: initial mixing, momentum dominant
   2) large scale ocean circulation: floating and dispersion, buoyancy prevalent

B. Coastal surface wave
   1) surge bore: wave, inviscid
   2) underwater vortex flow: mixing & diffusion process
I. Introduction: Needs and current status

Coastal Ocean Flow Modeling, Challenge, and Approach

- Large scales -- Computational Geophysics Dynamics (GFD):
  O(10)km – O (10,000) km
  O(1)hr – O (1) month

6 million elements (grid spacing 20 m --- 20 km)
Two week flow run takes:
  15 days (800 cores)
  7 days (2000 cores)
I. Introduction: Needs and current status

Coastal Ocean Flow Modeling, Challenge, and Approach

- Smaller scales: computational fluid dynamics (CFD):
  \[ O(10) \text{ cm} - O(10) \text{ km} \]
  \[ O(1) \text{ ms} - O(1) \text{ hr} \]

- Challenges: coastal ocean flows are multi-scale, multi-physics, most current models are designed for individual phenomena: circulation, wave, etc.

- Objective: Accurate simulation of coastal ocean flows, especially those at small scales.

  Approaches: Hybrid GFD/CFD, or coupling of GFD/CFD models (with as change in side the two models as less as possible)
II. FVCOM and CFD Model

CFD Model and FVCOM

**CFD model**

\[
\begin{align*}
\Gamma \frac{\partial Q}{\partial t} + J \frac{\partial}{\partial \xi_k} (F^k - F^k_v) + H &= 0, \\
\Gamma &= \text{diag}(0,1,1,1), \\
Q &= (p,u,v,w)^T,
\end{align*}
\]

\[F^k_v = \frac{1}{J} \left(0, g^{ik}_{\xi_k}, g^{ik}_{\xi_i}, g^{ik}_{\xi_i}, g^{ik}_{\xi_i}\right)^T, \quad F^k = \frac{1}{J} \left(1 + \nu_t \right) \left(0, g^{ik}_{\xi_k}, g^{ik}_{\xi_i}, g^{ik}_{\xi_i}, g^{ik}_{\xi_i}\right)^T \quad H = -\frac{T}{Fr^2} e
\]

**FVCOM (hydrostatic assumption, p=\(\gamma h\), ....)**

- External mode (shallow water eqs)
  \[
  \frac{\partial \eta}{\partial t} + \frac{\partial D U_i}{\partial x_i} = 0, \quad \frac{\partial U_i D}{\partial t} + \frac{\partial U_i U_i D}{\partial x_i} = -gD \frac{\partial \eta}{\partial x_i} - \frac{g D}{\rho_0} \left( \int_0^1 \frac{\partial}{\partial x_i} \left(D \int_0^\sigma \rho d\sigma'\right) d\sigma + \frac{\partial D}{\partial x_i} \int_0^0 \rho d\sigma \right)
  \]
  \[+ (-1)^i f U_j D + \frac{\tau_{sx_i} - \tau_{bx_i}}{\rho_0} + D\tilde{F}_i + G_i,
  \]

- Internal mode
  \[
  \frac{\partial \eta}{\partial t} + \frac{\partial D u_i}{\partial x_i} + \frac{\partial \omega}{\partial \sigma} = 0, \quad \frac{\partial u_i D}{\partial t} + \frac{\partial u_i u_i D}{\partial x_i} + \frac{\partial u_i \omega}{\partial \sigma} = -gD \frac{\partial \eta}{\partial x_i} - \frac{g D}{\rho_0} \left( \frac{\partial}{\partial x_i} \left(D \int_0^\sigma \rho d\sigma'\right) + \sigma \frac{\partial D}{\partial x_i} \right)
  \]
  \[+ (-1)^i f u_j + \frac{1}{D \frac{\partial}{\partial \sigma}} \left(K_m \frac{\partial u_i}{\partial \sigma} \right) + D F_i,
  \]

Curvilinear coordinates

Overset grids

2nd-order artificial compressible method

Ref: Sotiropoulos, et al. JCP, 1991

Tang, et al., JCP, 2003


Triangle mesh and

\(\sigma\) coordinate

2nd-order finite volume method

Mode splitting solution

Ref: Chen, et. al., JAOT, 2003

Lai, et al., JGR, 2010

…….
II. FVCOM and CFD Model

Overset Method of CFD Model

Implicit interface conditions implemented using Schwarz alternative iteration

A mass conservative interpolation MFBI (e.g., Tang, et al., JCP, 2003)

\[
\sum_j \bar{F}_{3/2,j}^1 (U_p^A, U_q^A) \Delta \Gamma_j' = \sum_j \bar{F}_{3/2,j}^1 (U_p^B, U_q^B) \Delta \Gamma_j',
\]
III. Coupling Strategies

Outline of Coupling

CFD/FVCOM coupling:

--- Domain decomposition, overlapping regions, and Schwarz alternative iteration
--- Coupling between CFD and internal mode of FVCOM: exchange of solution for u, v, w
--- Tri-linear interpolation, FVCOM $\rightarrow$ CFD: one point (c) or two point interpolation (c & d)

CFD $\rightarrow$ FVCOM: all points in the blanked region

One – point interpolation ---- natural, conventional (FVCOM, CFD 2nd order)
Two – point interpolation ---- unusual, seems abundant / unnecessary,
an approximation of derivatives, ... ?

Focus of this presentation: 1) Feasibility and solution quality of approach
2) Interface algorithm, e.g., performance of one- and two-point interpolation
IV. Examples of CFD/FVCOM coupling

Thermal Discharge in Steady Curved Channel Flow

Mesh:
- coupling – FVCOM: 115,000 nodes each layer, 11 layers
- CFD: 220,000 nodes

Diffuser:
- Diameter of ports: 0.17 m
- Discharge plume: 3.9 m/s, 32 °C
- Ambient flow: 20.5 °C
IV. Examples of CFD/FVCOM coupling

Computed Solutions

Discrepancy in contours

Two-point interpolation

Total velocity Total velocity Temperature

Temperature
IV. Examples of CFD/FVCOM coupling

Unsteady Sill Flow

Configuration

Convergence section

Horizontal mesh

Vertical mesh
IV. Examples of CFD/FVCOM coupling

Computed Solution in Horizontal Plane

CFD FVCOM

CFD/FVCOM at convergence section

CFD/FVCOM at divergence section

CFD/FVCOM at convergence section
IV. Examples of CFD/FVCOM coupling

Computed Solution in Vertical Plane

CFD

FVCOM

CFD/FVCOM at divergence section

CFD/FVCOM at convergence section
IV. Examples of CFD/FVCOM coupling

Coastal flow at Sea Mount

FVCOM mesh

FVCOM/CFD mesh

Sea mount

mesh sea mount
IV. Examples of CFD/FVCOM coupling

Solution in horizontal Plane

Flood tide

Ebb tide

FVCOM/CFD solution

CFD solution
IV. Examples of CFD/FVCOM coupling

Solution in Vertical Plane

Flood tide

Ebb tide
IV. Examples of CFD/FVCOM coupling

Comparison of Two- and One Point Interpolation

Two-pt interpolation
More details, Smoother solu transition

One-pt interpolation

Velocity of flood tide

Velocity of ebb tide
IV. Examples of CFD/FVCOM coupling

Thermal Discharge in Coastal Environment

Diffuser mesh

Diffuser configuration

Discharge temperature: 32 °C
Ambient temperature: 25 °C
IV. Examples of CFD/FVCOM coupling

Computed Velocity Field

- Flood tide
- Ebb tide

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\[(U^2 + V^2 + W^2)^{1/2}\] (m/s)

- 

\[(U^2 + V^2 + W^2)^{1/2}\] (m/s)
IV. Examples of CFD/FVCOM coupling

3D Thermal Plume (Movie)

Flood tide

Ebb tide

Time = 0.05hrs

Velocity 0.5 (m/s)

Temperature (°C)

20.52 20.54 20.56

3D plume movie
IV. Examples of CFD/FVCOM coupling

Comparison of Two- and One Point Interpolation

Two point interpolation
Stronger temperature field

One point interpolation

Temperature field at ebb tide

Cluster of contours
IV. Concluding remarks

Discussions

Questions

1) Why one- and two-point interpolations perform differently, hint and analysis?

2) Governing equations of two models are different, they may tend to different solutions as grid spacing goes to zero. Then, how we define interface conditions?

3) Schemes of the two models are different, how to minimize nonphysical solutions at the interfaces?

4) How to integrate the two models so the system work efficiently?

5) …..
IV. Concluding remarks

Conclusions

Conclusion and Future work

1) Overset grid techniques are powerful in resolving multi-scale and multi-physics problems
2) A systematic investigation on accurate and stable model interface algorithms is necessary
3) Challenges: coupling between different sets of PDE and flow models

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References