Simulations of Coastal Ocean Flows Using Chimera Grids

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12th Symposium on Overset Grid Symposium
Georgia Tech, Oct. 6-9, 2014

Supported by NSF (CMMI #1334551), PSCUNY
Outline

I. Introduction: Needs and current status
II. Modeling framework
III. Coupling strategies
IV. Application examples
V. Concluding remarks
I. Introduction: Needs and current status

Coastal Flows: Example Problems

Bridge carrying US-90 damaged during Hurricane Katrina (Douglass et al. 2006)

A destroyed section of boardwalk at Long Beach, NY (Photo by Bruce Bennett/Getty Images)
A modeling question:
How can we make a high fidelity, detailed simulation of such phenomena, considering actual settings, forcing, etc.?

Other problems: oil spill, ...
I. Introduction: Needs and current status

Current Status, Challenge, and Approach

- Large-scales: geophysical fluid dynamics (GFD): $O(10) - O(10,000)$ km, $O(1)$ min – $O(1)$ month
- Smaller scales: fully 3D fluid dynamics (F3DFD): $O(10)$ cm – $O(10)$ km, $O(1)$ ms – $O(1)$ hr
- Challenges: coastal ocean flows are multi-scale, multi-physics, most current models are designed for individual phenomena: circulation, wave, etc.
- Objective: high-fidelity, detailed simulation of coastal ocean flows, especially those at small scales.
- Approaches: Hybrid GFD/F3DFD (with change in the two models as less as possible)
- References of this presentation:
  - Tang, Wu, and Qu, JCP 2014
  - Tang, Qu, Wu, and Zhang, DD22, Lugano, Switzerland, 2013.
  - Tang and Wu, IEMSS, Ottawa, Canada, 2010
  - Tang, Comput. & Fluids, 2006
  - Tang, Jones, and Sotiropoulos, JCP 2003
II. Modelling framework

**Fully 3D Fluid Dynamics and Coastal Ocean Model**

\[ \nabla \cdot \mathbf{u} = 0, \]
\[ \mathbf{u}_t + \nabla \cdot \mathbf{u}\mathbf{u} = -\frac{1}{\rho_0} \nabla p + \nabla \cdot ((\nu + \nu_t)\nabla \mathbf{u}) - g(1 - \alpha (T - T_0) - \beta (C - C_0)) \mathbf{k}, \]
\[ T_t + \nabla \cdot (\mathbf{u} T) = \nabla \cdot \left( \left( \frac{\nu}{Pr} + \frac{\nu_t}{Pr_t} \right) \nabla T \right). \]

SIFOM -- solver for incompressible flow on overset meshes (Tang et al. 2003; Ge and Sotiropoulos 2005, ...)

Gravity & buoyancy

External mode

\[ \eta_t + \nabla_H \cdot (\mathbf{vD}) = 0, \]
\[ (\mathbf{vD})_t + \nabla_H \cdot (\mathbf{vD}D) = -g D \nabla_H \eta + \frac{\tau_s - \tau_b}{\rho_0} + \mathbf{G}. \]

Internal mode

\[ \eta_t + \nabla_H \cdot (\mathbf{vD}) + \omega_\sigma = 0, \]
\[ (\mathbf{vD})_t + \nabla_H \cdot (\mathbf{vD}D) + (\mathbf{v}\omega)_\sigma = -g D \nabla_H \eta + \nabla_H \cdot (\kappa \mathbf{e}) + \frac{1}{D} (\lambda \mathbf{v}_\sigma)_\sigma \]
\[ - \frac{g D}{\rho_0} \left( \nabla_H \left( D \int_\sigma^0 \rho d\sigma' \right) + \sigma \rho \nabla_H D \right) + \mathbf{H}, \]
\[ (\mathbf{T})_t + \nabla_H \cdot (\mathbf{T}D) + (\mathbf{T}\omega)_\sigma = \nabla_H \cdot (\theta \nabla_H T) + \frac{1}{D} (\vartheta T_\sigma)_\sigma + \mathbf{I}. \]
II. Modelling framework

Outline of Coupling

SIFOM/FVCOM coupling:

--- Domain decomposition, Chimera grids, overlapping regions, and Schwarz alternative iteration
--- Coupling between SIFOM and FVCOM: exchange of solution for $\eta$, $u$, $v$, $w$
--- Tri-linear interpolation, FVCOM $\Rightarrow$ SIFOM, SIFOM $\Rightarrow$ FVCOM

Focus of this presentation: 1) Treatments of coupling
2) Demonstration of feasibility and performance
III. Coupling strategies

Test1 --- Flow over Sill

Configuration of channel and sill

\[
\begin{align*}
-1500 & < x < 2000, \\
y & = \pm 200(1 - 0.8 e^{-4 \times 10^{-6} x^2}), \quad x < 0; \quad y = \pm 40, \quad x > 0, \\
z & = -150 + \frac{140}{1 + (x/500)^4}, \quad x < 0; \quad z = -120 + \frac{110}{1 + (x/500)^4}, \quad x > 0,
\end{align*}
\]

IC & BC

\[
\begin{align*}
u, v, w &= 0, \quad t = 0, \\
\eta u &= 0.9175(1 - e^{-0.01t}), \quad x = -1500; \quad \eta = 0, \quad x = 2000.
\end{align*}
\]
III. Coupling strategies

Test2 --- Thermal Discharge Flow

<table>
<thead>
<tr>
<th>Ambient parameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity, $U_d$ (m/s)</td>
<td>0.05</td>
</tr>
<tr>
<td>Temperature, $T_d$ (°C)</td>
<td>20.5</td>
</tr>
<tr>
<td>Channel depth, $H$ (m)</td>
<td>12.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effluent parameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity, $U_d$ (m/s)</td>
<td>3.92</td>
</tr>
<tr>
<td>Temperature, $T_d$ (°C)</td>
<td>32.0</td>
</tr>
<tr>
<td>Port diameter, $d$ (m)</td>
<td>0.175</td>
</tr>
<tr>
<td>Port length, $L_d$ (m)</td>
<td>0.91</td>
</tr>
<tr>
<td>Port angle, $\alpha$ (degree)</td>
<td>30°</td>
</tr>
<tr>
<td>Pipe diameter, $D$ (m)</td>
<td>1.32</td>
</tr>
</tbody>
</table>
III. Coupling strategies

Treatment of Hydrostatic Pressure

SIFOM and SIFOM1 perform differently. Why?

SIFOM1-FVOCM

Differential-integral equation

\[
\mathbf{u}_t + \nabla \cdot \mathbf{u} \mathbf{u} = -\frac{1}{\rho_0} \nabla p_d + \nabla \cdot ((\nu + \nu_t) \nabla \mathbf{u}) - g \nabla_H \left( \eta - \int_0^\eta \left( \alpha(T - T_0) + \beta(C - C_0) \right) d\zeta \right),
\]

\[
-\frac{1}{\rho_0} \nabla_z p_h = g \left( 1 - \alpha(T - T_0) - \beta(C - C_0) \right) k.
\]
III. Coupling strategies

Treatment of Buoyancy

\[ p = p_h + p_d', \quad \frac{1}{\rho_0} \nabla z p_h = g k, \]

\[ \mathbf{u}_t + \nabla \cdot \mathbf{u} \mathbf{u} = -\frac{1}{\rho_0} \nabla p'_d + \nabla \cdot ((\nu + \nu_t) \nabla \mathbf{u}) - g \nabla H \eta + g (\alpha (T - T_0) - \beta (C - C_0)) k. \]

SIFOM1

SIFOM2

No buoyancy

0.4 million nodes
CPU time comparison

<table>
<thead>
<tr>
<th>Model</th>
<th>CPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFOM 1</td>
<td>300%</td>
</tr>
<tr>
<td>SIFOM 2</td>
<td>100%</td>
</tr>
</tbody>
</table>
III. Coupling strategies

Treatment of Buoyancy

\[ p = p_h' + p_d', \quad -\frac{1}{\rho_0} \nabla_z p_h' = g \mathbf{k}, \]

\[ u_t + \nabla \cdot uu = -\frac{1}{\rho_0} \nabla p_d' + \nabla \cdot (\nu + \nu_t) \nabla u - g \nabla_H \eta + g(\alpha(T - T_0) - \beta(C - C_0)) \mathbf{k}. \]

<table>
<thead>
<tr>
<th></th>
<th>SIFOM1</th>
<th>SIFOM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFOM-FVCOM</td>
<td>123%</td>
<td>100%</td>
</tr>
</tbody>
</table>

SIFOM: 0.4 million nodes
FVCOM: 70k elements

CPU time

SIFOM1-FVCOM
SIFOM2-FVCOM
No buoyancy
III. Coupling strategies

Simulations and Convergence Test

T=10,000 s

T=100 s

<table>
<thead>
<tr>
<th>Accuracy order k</th>
<th>p</th>
<th>η</th>
<th>u</th>
<th>v</th>
<th>w</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFOM model</td>
<td>0.96</td>
<td></td>
<td>1.75</td>
<td>2.12</td>
<td>1.63</td>
</tr>
<tr>
<td>FVCOM</td>
<td>1.08</td>
<td></td>
<td>1.53</td>
<td>2.73</td>
<td>1.68</td>
</tr>
</tbody>
</table>
IV. Application examples

Flow past Bridge Peers in Channel

Peer configuration

mesh

Simulation
IV. Application examples

Comparison with Measurement

Velocity profiles at different locations
IV. Application examples

Flow Past Coastal Bridge – Model Setup

Meshes of FVCOM and CFD model
IV. Application examples

Simulated Flows

Flood tide                             Ebb tide

(a)                                     (b)

(c)                                     (d)

Velocity (m/s)

0.0  0.2  0.4  0.6  0.8  1.0

Velocity magnitude (m/s)
V. Concluding remarks

Discussions

Conclusion:
1) Chimera grid method is promising in coupling fully 3D fluid dynamics and coastal ocean models, which is challenging; it integrates different governing equations, distinct numerical systems, and dissimilar meshes.
2) SIFOM-FVCOM works well, and it can be applied to actual problems.

Future work:
1) More validation and experiment of the modeling system
2) Better model interface algorithms
3) Improve computational efficiency of the system
4) ……

Question?

Thanks!