FoamedOver: A Dynamic Overset Grid Implementation in OpenFOAM

David Boger   Eric Paterson   Ralph Noack

Penn State University, Applied Research Lab
State College, PA USA

10th Symposium on Overset Composite Grids and Solution Technology
20 - 23 September 2010
NASA Ames Research Center
Moffet Field, California USA

Acknowledgements

- Development of **foamedOver** has been sponsored by: CREATE-Ships, Myles Hurwitz, Project Manager
- Supercomputing resources have been provided by: DOD High–Performance Computing Modernization Program (HPCMP) and the Army Research Laboratory (ARL) DOD Supercomputing Resource Center (DSRC)

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   - DiRTlib
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Objectives

- Develop a library that provides dynamic–overset mesh capability for NavyFOAM (and other naval applications/solvers).
  - NavyFOAM is an OpenFOAM–based incompressible, multiphase, free–surface hydrodynamics solver.
- Adhere to OOP standards of OpenFOAM
- Library design goals:
  - Build on top of Suggar++ and DiRTlib.
  - Instrumentation of solvers with overset capability should be simple.
  - Dynamic–mesh capability for a variety of motion types: table look–up; analytical functions; 6DOF equations of motion.
  - Utilization of the run–time selection mechanism for motion type and algebraic solvers.
  - Simulation control through dictionaries.

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Objectives

Intended Use

- Intended use is naval hydrodynamics: surface ships; submarines; weapons systems.
- CREATE-Ships: Develop CFD tools which can impact design and acquisition
  - Rapid Design Capability: Automation of CFD Process
  - Hull–form optimization and ship motions in ocean waves

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OpenFOAM: Executive Summary

Overview

- OpenFOAM is a free-to-use Open Source numerical simulation software with extensive CFD and multi-physics capabilities.
- Free-to-use means using the software without paying for license and support, including massively parallel computers.
- Software under active development, capabilities mirror those of commercial CFD
- Substantial user base in industry, research labs, and universities
- Possibility of extension to non-traditional, complex or coupled physics
- Physics model implementation through *equation mimicking*

OpenFOAM: Executive Summary

Main components

- Discretization: General-polyhedral finite–volume method. Numerous schemes are available.
- Lagrangian particle tracking.
- Finite Area Method: 2-D FVM on curved surface in 3-D
- Libraries for turblence modeling (RANS, DES, LES); thermophysical properties; combustion; . . .
- Automatic mesh motion, support for topological changes
- Parallelism via domain decomposition. Methods include metis, scotch, simple, and hierarchial

OpenFOAM: Executive Summary

Equation Mimicking

- Flexible handling of arbitrary equations sets
- Natural language of continuum mechanics: partial differential equations
- Example: turbulence kinetic energy equation

$$\frac{\partial k}{\partial t} + \nabla \cdot (\mathbf{U}k) - \nabla \cdot [(\nu + \nu_t)\nabla k] = \nu_t \left[\frac{1}{2}\left(\nabla \mathbf{U} + \nabla \mathbf{U}^T\right)\right]^2 - \frac{\epsilon_0}{k_0} k$$

  - Objective: Represent differential equations in their natural language

```
solve
(
      fvm::ddt(k)
    + fvm::div(phi, k)
    - fvm::laplacian(nu()+nut(), k)
   == nut*magSqr(symm(fvc::grad(U)))
    - fvm::Sp(epsilon/k, k)
);
```

  - Correspondence between implementation and the original equation is clear

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OpenFOAM: Executive Summary

Top–Level Applications and Utilities

- Applications
  - Libraries encapsulate interchangeable models with run-time selection
  - New models provide functionality by adhering to a common interface
  - Custom top-level solvers written for a class of physics, e.g. compressible combusting LES or VOF free-surface flow
  - Code clarity is paramount: existing solvers act as examples for further development or customization

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OpenFOAM: Executive Summary

Top–Level Applications and Utilities, Cont.

- Utilities
  - Pre-processing, data manipulation, mesh-to-mesh mapping etc.
  - Mesh import and export, mesh generation and manipulation
  - Parallel processing tools: decomposition and reconstruction
  - Post processor hook-up (Paraview) and data export (EnSight, Tecplot, Fieldview)
  - Solution analysis, PyFoam
- Customized Data Extraction and Analysis
  - User-defined on-the-fly data extraction: function objects
- This is just a “standard set”: *Users write their own applications using the library*

OpenFOAM at Penn State

- PSU OpenFOAM community has significantly grown to include faculty and students from:
  - Applied Research Laboratory
  - Mechanical Engineering
  - Bioengineering
  - Nuclear Engineering
  - Aerospace Engineering
  - Research Computing and Cyberinfrastructure

- Application areas include:
  - Naval hydrodynamics
  - Fluid–structure interaction
  - Wind– and hydro–turbines
  - Atmospheric turbulence and LES
  - Explosives detection
  - Cardio–vascular hemodynamics and blood pumps
  - Electron beam-physical vapor deposition
  - Nuclear–reactor dynamics
  - Rotorcraft icing
  - CFD education

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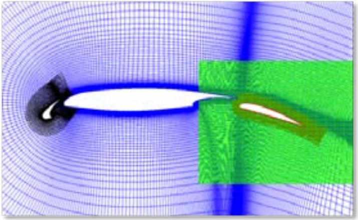
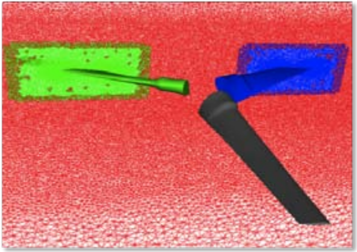
Suggar++[1]

- Overset grid assembly software
- Performs hole-cutting, donor search, overlap minimization
- Static or dynamic (moving body) assemblies
- Structured and **unstructured** grids
- Node-centered and **cell-centered** flow solvers
- Stand-alone executable (static) or library calls for dynamic grids (libsuggar.so)





[1] Ralph W. Noack, David A. Boger, Robert F. Kunz, and Pablo M. Carrica, "Suggar++: An Improved General Overset Grid Assembly Capability," AIAA Paper 2009-3992

DiRTlib[2]

DiRTlib is a solver-neutral library that simplifies the addition of an overset capability to a flow solver by encapsulating the required operations

- Acquire interpolation stencils via file I/O or direct communication with libSuggar++

```
drt_get_dci()
```

- Provides higher-level methods to transfer field data from donors to receptors and interpolate

```
drt_generate_transmit_apply()
```

- Provides lower-level access to donor member indices and weights to help build implicit global matrix

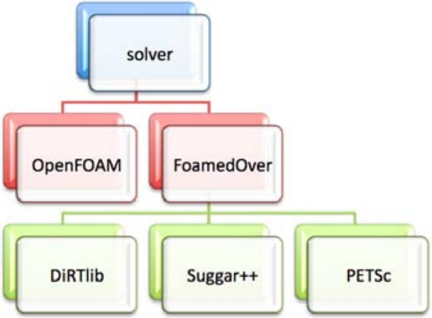
```
drt_get_donor_members_donor_weights()
```

[2] Ralph W. Noack, “DiRTlib: A Library to Add an Overset Capability to Your Flow Solver” AIAA 2005-5116

foamedOver

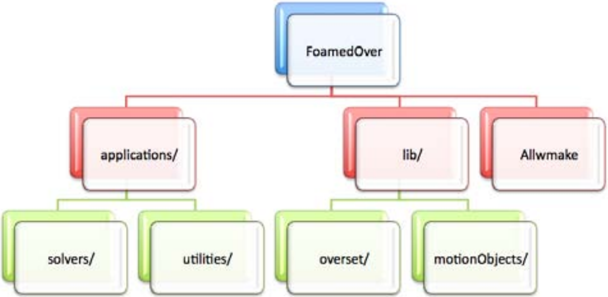
FoamedOver is an interface between OpenFOAM and other specialized libraries

- DiRTlib – Library to facilitate the addition of overset capability to any flow solver
- Suggar++ – Overset grid assembly software
- PETSc – Library of data structures and routines for the parallel solution of large systems of linear and non-linear equations



foamedOver

FoamedOver is a collection of custom classes, solvers, and applications.



foamedOver

FoamedOver is a **stand-alone library** that provides a dynamic overset grid capability to any OpenFOAM solver

- No changes are required to the OpenFOAM library itself
- Any OpenFOAM solver is made overset-capable by the insertion of a half-dozen lines of code . . .
- . . . and the use of custom run-time selectable objects

```
# include "oversetObject.H"
# include "createOverset.H"

  U *= cellMask;
  overset.updateFringeValues(U);
```

```
dynamicFvMesh oversetFvMesh;

mesh.update()
```

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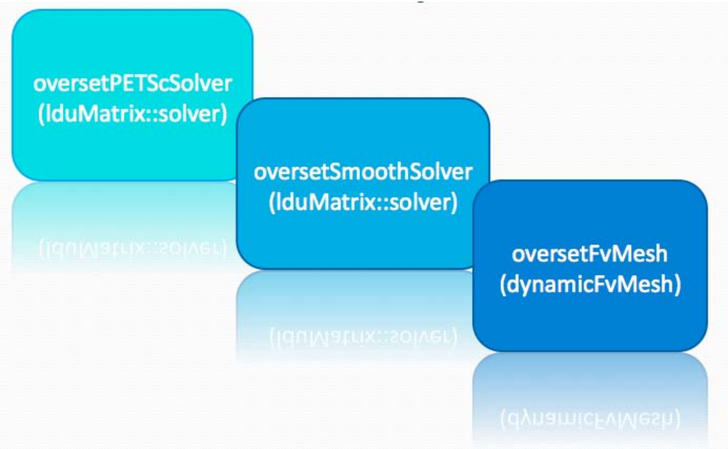
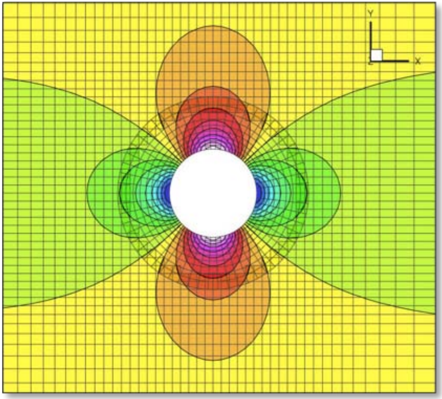
Run–Time Selectable Objects



Code verification on static meshes

Potential Foam

- cylinder
- steady
- potential flow



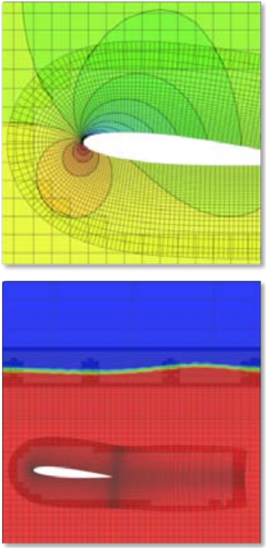
Overset dictionary for static meshes

constant/oversetDict

```
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

isOverset         yes;
readFromDisk      yes;
isDynamicOverset no;
dciFileName       ``SUGGAR/output++.dci'';
clipInterpolation yes;

bodies ();

// ************************************************************************** //
```

Code verification on static meshes

interFoam



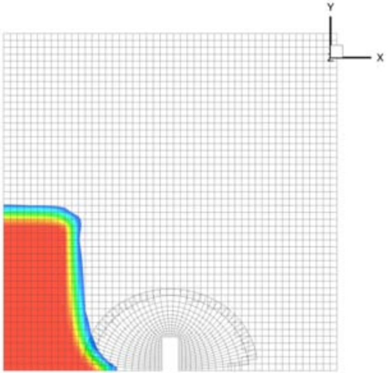
- submerged hydrofoil[a]
- steady
- incompressible multiphase

[a] J. Duncan, "The Breaking and Non-Breaking Wave Resistance of a Two-Dimensional Hydrofoil," *J. Fluid Mech*, 126:507–520, 1983.

Code verification on static meshes

interFoam

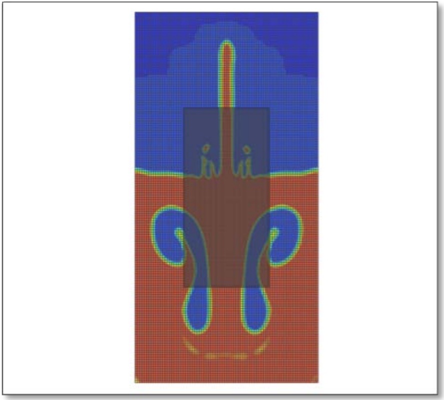
- extension of damBreak tutorial
- unsteady
- incompressible multiphase



figures/damBreak.avi

Code verification on static meshes

compressibleInterFoam

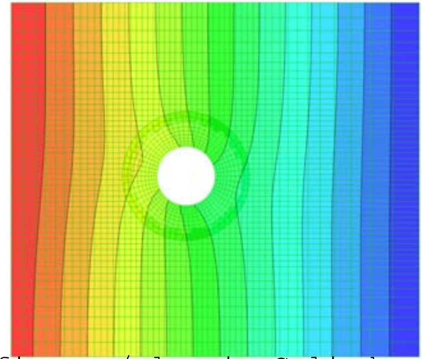


- extension of depthCharge tutorial
- unsteady
- compressible multiphase

Code verification on dynamic meshes

Unsteady potential flow

- cylinder
- **prescribed** mesh motion
- unsteady
- unsteady potentail flow is a series of steady solutions


figures/plungingCylinder-p.

Dictionaries for dynamic mesh motion

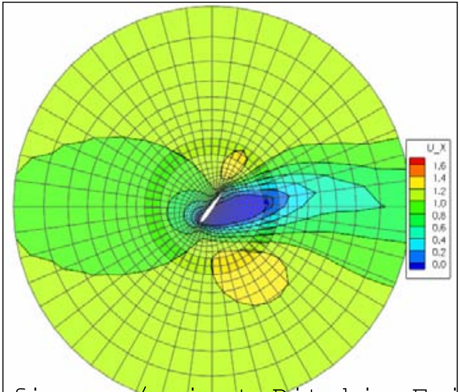
constant/dynamicMeshDict and constant/oversetDict

```
%----------------------------------------------------------------
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

dynamicFvMesh   oversetFvMesh;

// ************************************************************************ //
```

```
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //
isOverset        yes;
readFromDisk     no;
isDynamicOverset yes;
useLibSuggar     yes;
motionType       multibody;

bodies
(
  projectile
  {
      oversetMotion  specifiedTrajectoryOversetMotion;
      translationTable "constant/translations";
      rotationTable "constant/rotations";
  }
);
// ************************************************************************ //
```

Code verification on dynamic meshes

icoDyMFoam



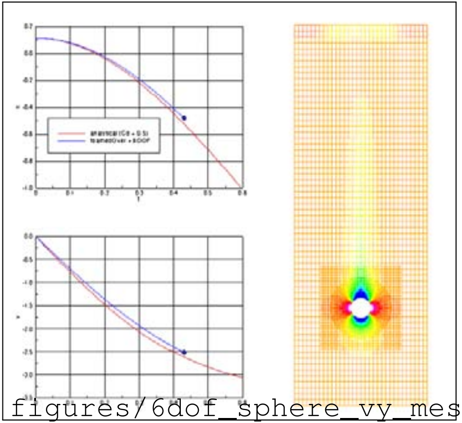
figures/animatePitchingFoil.avi

- pitching foil
- **prescribed** mesh motion
- incompressible, laminar, mulitphase flow

Code verification on dynamic meshes

interDyMFoam with 6DOF

- falling cylinder
- **6DOF** mesh motion
- incompressible, multiphase, laminar flow
- Compare to simplified analytical solution for free-falling body with constant CD



Overset dictionary for dynamic meshes with 6DOF motion

constant/oversetDict

```
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

isOverset        yes;
readFromDisk     no;
isDynamicOverset yes;
useLibSuggar     yes;
motionType       multibody;

bodies
(
  ship
  {
     oversetMotion sixDofOversetMotion;
  }
);

// ************************************************************************* //
```

Body dictionary for sixDofOversetMotion

0/ship

```
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

mass                m               [1 0 0 0 0 0 0]      0.500;
momentOfInertia     J               [1 2 0 0 0 0 0]      (10 10 10);

equilibriumPosition x               [0 1 0 0 0 0 0]      (0 0.1144 0);
linearSpring        k               [1 0 -2 0 0 0 0]     (0 0 0);
linearDamping       d               [1 0 -1 0 0 0 0]     (0 0 0);

// Xabs = Xeq + Xrel
Xrel                Xrel            [0 1 0 0 0 0 0]      (0 0 0);
U                   U               [0 1 -1 0 0 0 0]     (0 0 0);
Uold                Uold            [0 1 -1 0 0 0 0]     (0 0 0);

rotationVector                      (0 0 1);
rotationAngle       rotationAngle   [0 0 0 0 0 0 0]      0;
omega               rotUrel         [0 0 -1 0 0 0 0]     (0 0 0);

force               f               [1 1 -2 0 0 0 0]     (0 0 0);
moment              m               [1 2 -2 0 0 0 0]     (0 0 0);

forceRelative       fRel            [1 1 -2 0 0 0 0]     (0 0 0);
momentRelative      mRel            [1 2 -2 0 0 0 0]     (0 0 0);

// ************************************************************************** //
```

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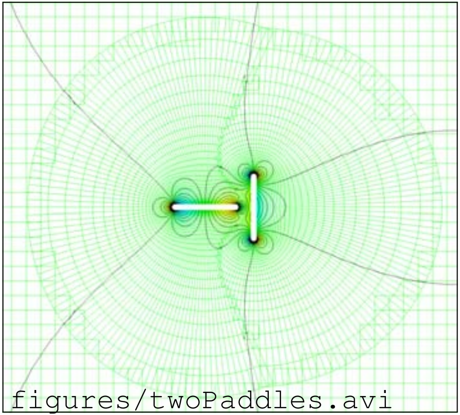
Code verification on dynamic meshes

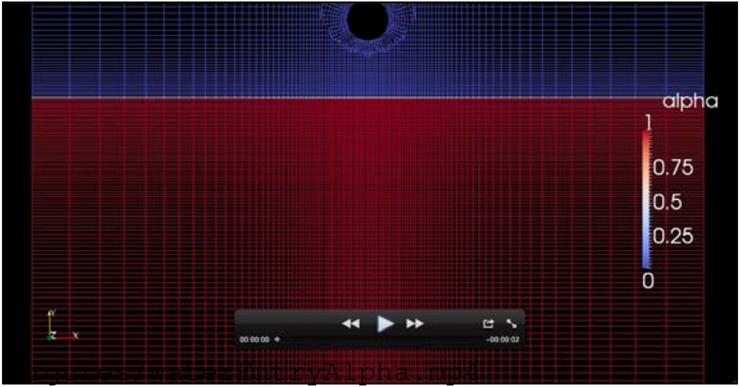
Complex mesh motion: interlacing paddles



- interlacing rotating paddles
- motion would be very difficult to resolve with GGI, RBF, or Laplacian dynamicFvMesh methods.

Code verification on dynamic meshes

Water entry of projectiles

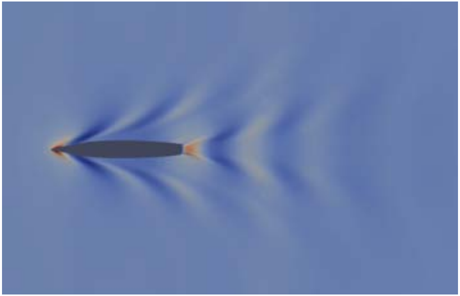


Validation for intended–use applications

Model 5415: an international benchmark for a naval surface combatant

- Gothenburg 2010 A Workshop on CFD in Ship Hydrodynamics, Dec 8-10, 2010
- 49th AIAA Aerospace Sciences Meeting, 4-7 January 2011
  - Steady resistance
  - Dynamic sinkage and trim (2DOF)
  - Ships in waves (diffraction problem)
  - Roll damping with bilge keels(1DOF)

Steady wave field at Fr = 0.28



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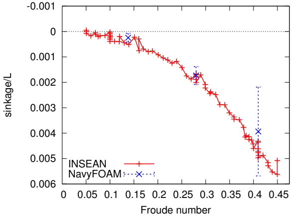
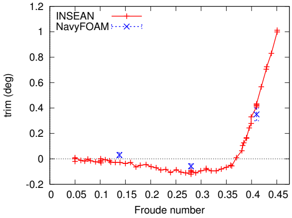
Comparison to experiment: dynamic sinkage and trim vs. speed





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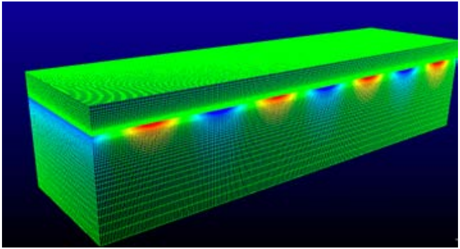
Background mesh with ambient waves



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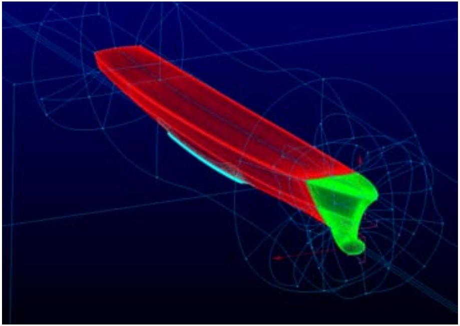
Overset mesh for roll damping simulations



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Summary

- **foamedOver** is a collection of custom classes, solvers, and applications which adhere to OpenFOAM object–oriented programming practices, and which utilizes the existing tools Suggar++, DiRTlib, and PETSc.
- It is a **stand-alone library** that provides a dynamic overset grid capability to any OpenFOAM solver.
- **motionObjects** have been developed which permit table-lookup, analytical, and 6DOF motions.

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