Coupled Simulation of Flow and Body Motion Using Overset Grids

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DFBI-Model in STAR-CCM+, I

- DFBI-model allows coupled simulation of flow around a rigid body and body motion due to external and flow-induced forces.

- Equations of motion for the body (up to 6 degrees of freedom) are solved using 2\textsuperscript{nd}-order discretization and implicit coupling with flow equations:

\[
m \frac{d\mathbf{v}}{dt} = \mathbf{f}
\]

\[
M \frac{d\mathbf{\omega}}{dt} + \mathbf{\omega} \times M\mathbf{\omega} = \mathbf{n}
\]

\[
\mathbf{f} = f_r \left( f_p + f_\tau + f_g + \sum f_{ext} \right)
\]

\[
\mathbf{n} = f_r \left( \mathbf{n}_p + \mathbf{n}_\tau + \sum \mathbf{n}_{ext} \right)
\]
DFBI-Model in STAR-CCM+, II

• Special versions:
  – 1 DoF Rotational motion
  – 1 DoF Linear motion

• External effects:
  – External forces and moments (constant or variable)
  – Damping forces and moments
  – Spring couplings
  – Catenary couplings
Implicit coupling scheme:

- Update flow-induced forces on body after each outer iteration;
- Update body position and grid in flow domain after each outer iteration.

Body can also deform…

Grid is usually morphed to account for deformation…

Overset grid is most suitable to account for body motion…
Automatic superposition of motions:
- Vessel moving with respect to a fixed reference frame;
- Propeller moving with respect to vessel;
- Blades moving with respect to propeller…
Overset Grids Method in STAR-CCM+, I

- Control volumes are labelled as:
  - **Active** cells, or
  - **Passive** cells.

- In active cells, regular discretized equations are solved.

- In passive cells, no equation is solved – they are temporarily or permanently de-activated.

- Active cells along interface to passive cells refer to **donor** cells at another grid instead of the passive neighbours on the same grid...

- The first layer of passive cells next to active cells are called **acceptor** cells...
Currently, triangular (2D) or tetrahedral (3D) interpolation elements are used, with either distance-weighted or linear interpolation... Other (higher-order) interpolations will come...

\[ N_1, N_2, N_3 \text{ – Neighbors from the same grid; } \]

\[ N_4, N_5, N_6 \text{ – Neighbors from the overlapping grid. } \]
Overset Grids Method in STAR-CCM+, III

- No explicit interpolation of solution is performed...
- Solution is computed on all grids simultaneously – grids are implicitly coupled through the linear equation system matrix...
Overset grids usually involve:

- One background mesh, adapted to environment (can be fixed or moving);
- One or more overset grids attached to bodies and overlapping the background mesh and/or each other.

Each grid represents a separate region.

Both background and overset mesh(es) can be generated in the usual way (or imported) as in the case of a single region.

Each grid can also deform (e.g. in a coupled fluid-structure interaction simulation).

Overset grid can fall out of solution domain (cut-out by boundary surface).
In the overlapping zone, cells should be of comparable size in both meshes (recommendation):

- Interpolation errors in the coupling equation should be of the same order as when computing convective and diffusive fluxes (interpolation over half a cell);
- The coarser of the two coupled meshes determines the error level.

Between two body walls, at least 4 cells on both background and overset grid are needed to couple them (requirement).

The overset grid should not move more than one cell per time step in the overlapping zone (recommendation).
Working with Overset Grids

- No compromises on usability:
  - Any grid type can be used
  - Most physics models can be applied
  - Processing pipeline (meshing, solving, analysing) unaffected
  - Minimum on additional set-up steps:
    - New region interface (with interface options)
    - New boundary condition

- Using STAR-CCM+ infrastructure for interfaces

- New **intersector-module** was added (it searches for donors, defines interpolation factors, cuts holes etc.) – the solver is almost unaffected…
Advantages of Overset Grids for DFBI

• One set of grids allows many simulations for different set-ups (easy parametric studies, less effort for grid generation and less data to store).

• Grid quality is not affected by body motion or changed body position.

• Arbitrary motions are possible (including $360^\circ$ rotation and large linear displacements).
Simulation of motion of a container ship in Stokes waves propagating from right to left: initial vessel orientation 30° (upper) and -30° (lower) relative to the direction of wave propagation.
Simulation of motion of a container ship in Stokes waves propagating from right to left: initial vessel orientation 30° (upper) and -30° (lower) relative to the direction of wave propagation.
Simulation of Lifeboat Launching

Simulation by H.J. Morch, CFD Marine; Experiment by Norsafe AS
Lifeboat Launching Into Waves, I

- Initial wave position varied by 20 m (drop from 32 m height).
- Following wave (180°)
- Wavelength ca. 220 m, wave height 13.5 m, water depth 33.5 m
- The questions to be answered:
  - When is the load on the structure the highest?
  - When are accelerations the highest?
Pressure at one monitoring point for different wave hit points, 180°
umoè performed analysis of collapse of air bubble on aft bulkhead of lifeboats; the pressure loads were very close to full-scale tests (3-4%) for both drop heights considered. It was very important to account for air compressibility...
Simulation of Lifeboat Launching, II

Wave propagates from left to right

Wave propagates from right to left
Patrol Vessel, I

VIRTUAL TOWING TANK

Hull Id.: PB141
Speed: V = 30 kn
Sea state: Calm water
Solution Time 0 (s)
Iteration 0
Patrol Vessel, II

Comparison of predicted and measured resistance of patrol vessel
Comparison of predicted and measured trim and sinkage of the patrol vessel
Two vessels with crossing paths:
This kind of simulation would be difficult to perform without overset grids (sliding grids cannot be used; morphing would require frequent re-meshing)
Modern ship hulls form with different bilge keels
3 years research project to reduce roll motion
Simulations performed by two universities and Germanischer Lloyd using STAR-CCM+
Experiments by SVA Potsdam
Simulation of store separation using DFBI (6 DoF); for details see Deryl Snyder’s presentation…
Simulation of missile launch using DFBI (1 DoF); for details see Deryl Snyder’s presentation…
Future Developments

• New motion model, allowing for a combination of prescribed (in-plane) and free degrees of freedom.

• Further development of overset grid technology:
  – Multiple overset grids, overlapping each other
  – More physics models with overset grids (Lagrangian multiphase, Discrete-Element Method…)
  – Contact modeling (porosity or deactivation of cells in gaps)

• Adaptive dynamic grid refinement and coarsening:
  – To accommodate requirements by overset grids
  – To track free surface or other fronts
  – Controlled by error estimate…
Overset-Overset

Example of overset grids overlapping each other (feature under development).
Overset-Lagrangian

Example of overset grids in combination with Lagrangian multiphase flow model (overset grids move and fall partly outside solution domain; particles are not affected by internal grid motion).