Special Topics

Free-Surface Flows
& Grid Motion Methods

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Introduction

- A major event in marine hydrodynamics
  - Mostly gravity waves due to balancing action between gravitational and inertial forces
- Must satisfy the kinematic and dynamic BCs
  - Kinematic BC: No flow through interface
  - Dynamic BC: Force is continuous across interface
    - Usually contribution from air is neglected
    - Zero shear
    - Normal stress equal to atmospheric pressure

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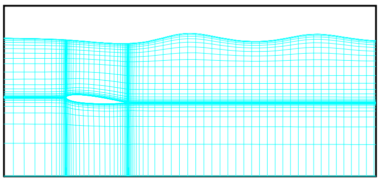
Numerical Methods

- Boundary element methods
  - Potential flow
  - Efficient for far-field and ocean waves where viscous effects are negligible
- Euler equations
  - Inviscid flow
  - Can handle realistic geometries
  - Cannot address viscous/inviscid interaction
- Navier-Stokes equations
  - Complete equations except for turbulence modeling
  - Can handle free-surface turbulence and viscous effects on waves

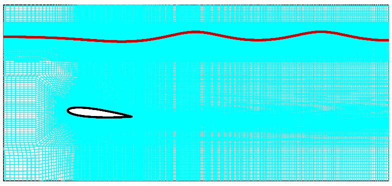
Free-Surface Solution Methods

- Interface tracking methods
  - Track interface by satisfying kinematic BC, then conform mesh
  - Solve for Euler or NS equations with dynamic BC on interface
  - Pros
    - Accurate & sharp interface shape
    - Computationally less demanding
  - Cons
    - Cannot handle highly distorted or breaking waves
    - Difficult mesh conforming
    - Degrading mesh quality when geometry is complex near interface



Free-Surface Solution Methods – Cont.

- Interface capturing methods
  - Capture interface in domain by solving hyperbolic equation for volume fraction or distance function
  - One set of governing equations with different fluid properties for different phases
  - Pros
    - Can handle highly distorted or breaking waves
    - No need for mesh conforming
    - Mesh quality maintained
  - Cons
    - Interface sharpness dependent on mesh resolution
    - Computationally intensive



Interface Capturing Methods

- VOF method
  - Physics based and simple to implement
  - Accurate enough to capture essential flow features
  - Possible to handle mass and heat transfer through interface
- Level-set method
  - Basically similar implementation to VOF
  - Based on a hyperbolic equation solution a distance function from the interface
  - Re-initialization of the distance and proper treatment of the interface region are a key to success.

Volume of Fluid (VOF) Method

- Background
  - Two or more fluids/phases are not interpenetrating
  - In each cell, the volume fractions of all phases sum to unity
  - The fields for all variables and properties are shared by the phases and represent volume-averaged values, as long as the volume fraction of each of the phases is known at each location.
  - Based on the local volume fraction of the q-th fluid, α_q, the appropriate variables and properties are assigned to each cell within the domain.
  - Tracking of the interfaces between the phases is accomplished by the solution of a continuity equation for α_q.

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VOF Method – Cont.

- Equations
  - For q-th phase,

$$\frac{\partial \alpha_q}{\partial t} + \vec{v} \cdot \nabla \alpha_q = 0$$

  - For primary phase,

$$\sum_{q=1}^{n} \alpha_q = 1$$

  - Single momentum equation solved throughout the domain
  - Momentum equation depends on volume fractions of all phases through fluid properties in each control volume

$$\rho = \sum_{q=1}^{n} \alpha_q \rho_q$$

  - Turbulence variables are shared by phases throughout the field.

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General Requirements

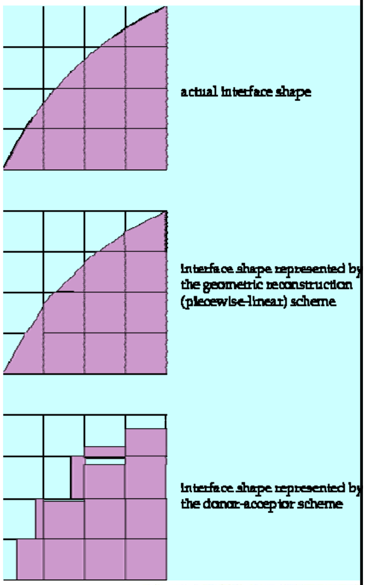
- Turbulence model
  - For most cases, the realizable k-ε and SST k-ω models perform very well.
  - Sometimes more sophisticated turbulence models, e.g., Reynolds stress transport model, help get more accurate and sharper free-surface.
- Unsteady/Steady
  - Unsteady solver is more stable even for steady flow solutions, in most cases.
  - Use maximum possible time step size for steady solution.
  - Use the problem specific or most meaningful time step size for unsteady solution.
  - NITA may be helpful, when time accurate solution is needed.

Time Step Size

- For unsteady flows, how to set the appropriate time step size, Δt?
  - Run at least one time step with very small Δt. If solution does not diverge and looks reasonable, save the data file.
  - Set ‘max iteration per time step’ to one and provide a much larger Δt, i.e., several orders of magnitude larger. You should get an error message.
  - Take the number between parentheses, i.e., 346, in the example *“Error: Too many (346) VOF sub-time steps.…”* and divide Δt with this number. This is the VOF sub-iteration Δt required.
  - The physical Δt is of the same order of magnitude to 100 times this sub-iteration Δt.
  - Repeat this calibration periodically.

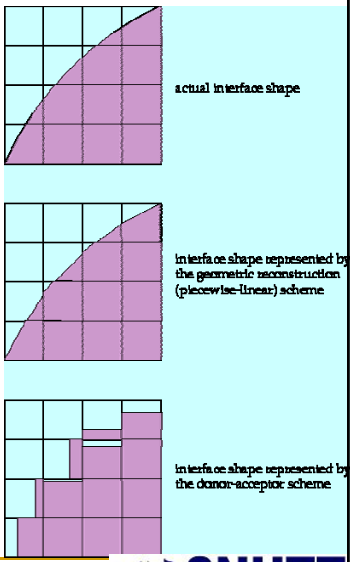
Face Fluxes Near Interfaces

- Donor-acceptor (DA)
  - Standard scheme for VOF
  - Only available in quad/hex cells
  - Determine flux direction based on
  - Pure upwind or downwind
  - Flux amount limited to available/empty volumes in donor/acceptor cells
  - Explicit scheme



Face Fluxes Near Interfaces – Cont.

- Geometric reconstruction (GR)
  - Determine interface shape and location based on $\nabla\alpha_q$ and α_q
  - Determine advecting flux with interface shape and face center velocity
  - Balance flux amount based on α_q
  - Explicit scheme



Face Fluxes Near Interfaces – Cont.

- High resolution interface capturing (HRIC)
  - Determine interface based on
  - Estimate local CFL that represents the time required to empty one cell
  - Determine upwind/downwind blending based on the above plus α_q
  - Both implicit and explicit possible
- For naval applications
  - HRIC and GR perform BEST

Grid Motion Methods

- Stretching/springing
  - Stretch existing cells with connectivity unchanged
  - Degrading cell quality
- Remeshing
  - Add or delete cells in regions expanded or squeezed, respectively
  - Difficult maintaining mesh resolution
- Layering
  - Add or delete layers of cells
  - Must have defined path

Grid Motion Methods

- Sliding interfaces
  - Two or more sub-domains rotate or translate w.r.t. each other
  - Mesh quality maintained
  - Interpolation across interface
- Overset grids
  - Two or more levels of sub-domain meshes on top of background mesh
  - Large dependency on interpolation accuracy between meshes
  - Fast algorithm required to identifying and blanking cells
- Immersed boundary methods
  - Body and its motion represented as body force
  - Relatively inaccurate
  - Difficult turbulent boundary layer treatment