CFD and wave and current induced loads on offshore wind turbines

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SPH predictions by CNR-Insean
Relevant offshore wind turbines

Relevant hydrodynamic problems are similar as for other offshore structures
Problems of Practical Interest

Slowly-varying (Slow-drift) motions:
Moored offshore platforms

Resonance caused by second-order wave-body interaction effects
Wave-drift and viscous damping
Springing of TLP

- Resonance caused by second-order wave-body interaction effects in operating conditions
- Viscous damping

Caused by 3rd and 4th-order wave-body interaction effects in survival conditions in deep water

Ringing in shallow water due to plunging breaking waves

Damping is secondary

Transient ringing response of monotowers and TLPs
Global and local effects

Wetdeck slamming

Wave run up and slamming
Accidental load: Breaking wave impact on platform column

Experiments

Steep and breaking deep-water waves.
Scale 1:40 & 1:125

Correspond to extreme events in severe storms ($H_s=18\text{m}, T_p=17\text{s}$)

The resulting shear forces can cause structural failure of a concrete structure
Breaking wave forces in shallow water

- Calculations show that the forces from the plunging breaking waves are governing the responses of the structure and the foundations.

Truss support structure for wind turbines on the ThorntonBank, Belgian Coast. Design by Reinertsen A/S.

Truss structure in shallow water

Water depth = 15.4m, $H_b \approx 17 - 18$ m
Mathieu-type instability

Time-dependent change of waterplane area shape and position

Damping is important

Model test with scaled 202.5m draft Spar in 8.5m wave amplitude and 22.5s wave period

Maximum response:
Heave amplitude=20m
Pitch amplitude=20°

Time-dependent difference between centers of gravity and buoyancy

Haslum
Vortex Induced Motions (VIM) and Vibrations (VIV)

T3120 V=1.4m/s Striked riser

T2120 V=1.4m/s Naked riser
Marine installation operations using a floating vessel/jack-up

Resonance and viscous damping

Lin Li, T. Moan
Access to offshore wind turbines

Minimize relative motion between ship and wind turbine support structure by automatic control

Wave run up at the structure matters

Use of high-speed Surface Effect Ship
Tools

- Experiments
- CFD Methods
- Analytical Solutions
- Approximate Computational Tools
Tools

- Complex models
- Complex geometries
- Visualization
- Global & local estimates

CFD Methods
(Navier-Stokes solvers)

- Reliability
- Costs

Peric, CFD Workshop, Trondheim (2007)
Survey by International Towing Tank Conference (ITTC) (2011)

What are the difficulties and limitations of CFD to achieve wider use and acceptance to marine hydrodynamic problems?

The accuracy of CFD is a main problem (Industries and universities)

Grid generation is a major problem (Model basins)

CFD Methods
(Navier-Stokes solvers)
Main Features of a CFD Solver

1. Modelling
2. Discretization
3. Reliability analysis
1) Modelling

- Define the problem
Define the Problem

- Water
- Air
- Body
- Space: \( P \)
- Time: \( t \)
- Computational Domain, \( \Omega \)
1) Modelling

- Define the problem
- Define the fluid/flow properties
Define Fluid/Flow Properties

Examples:

- Compressible or incompressible fluid?

- Air

- Water
Compressibility is secondary for water, but may be important for air
Define Fluid/Flow Properties

Examples:

- Viscous or inviscid fluid?
Define Fluid/Flow Properties

Examples:

- *Laminar or turbulent flow?*

Path of a fluid particle in laminar flow

Mean path of a fluid particle in turbulent flow
Turbulence involves low space-time scales. Proper modelling is still an open question.
Viscous effects must be considered when flow separation occurs.

Occurs for structures with "small" cross-sectional area.
Turbulent flow is secondary with flow separation from sharp corners.
1) Modelling

- Define the problem
- Define the fluid/flow properties
- Identify the variables of the problem
Identify the variables of the Problem

- Assume no air pockets
- Air irrelevant for water evolution
- Incompressible fluid
1) Modelling

- Define the problem
- Define the fluid/flow properties
- Identify the variables of the problem
- Find the equations
**Governing Equations**

They are given by fluid conservation properties:

1) Conservation of fluid mass

2) Conservation of fluid momentum
   → Navier-Stokes equations
Conservation of fluid mass: (Incompressible Fluid)

→ Volume = constant
→ Zero net flux
**Initial Conditions**

- Unsteady problem

\[(u, p) \text{ at } t = 0\]
Boundary Conditions

Body

Wetted hull

Free surface

Water

Control surface
1) Modelling

Modelling implies assumptions and they may be wrong.
2) Discretization

$h : \text{discretization size}$
Basic Assumptions

Forms of the Governing Eqs

Field Equations

Grid Methods (FVM/FDM/FEM)

Gridless Methods

Navier-Stokes Methods

Field Methods

Boundary-Fitted Grids

Moving particles (SPH, MPS)

Fixed Nodes (RKPM)

Potential Flow Methods

BEM, HPC

Solution 'view point'

Immersed' in the Comput. Domain

Body 'naturally' tracked

Body

Gas-liquid Interface

Interface capturing (VOF, LS, MAC, CIP)

Interface tracking

Eulerian

Lagrangian

Eulerian

Lagrangian

Body modeled numerically

Grid methods: inside body problem, body capturing..

Gridless methods: body force/ particles, ghost particles..
Incompressible inviscid water with irrotational motion

Equations with unknowns on the boundary

Computational Domain

Boundary Element Methods

Equations with unknowns in the domain

Computational Domain

Field Methods

Potential Flow Methods
Harmonic Polynomial Cell (HPC) method

Features:
- Water divided by cells
- Within each cell, the physical variables are expressed by harmonic polynomials;

Benefits:
- Efficient (sparse matrix)
- Accurate (higher order)
- Easy to implement

3D wave-body interaction

Yanlin Shao
Solution ‘Point of View’

‘Lagrangian’: The solution is found through moving grid/particles.
Solution ‘Point of View’

‘Eulerian’: The solution is found at fixed locations.
Solution ‘Point of View’

‘Eulerian’: The solution is found at fixed locations.

When ‘Eulerian’ strategy is used for the field equations an additional technique is required to predict free-surface evolution.
Strategies for Free-Surface Evolution

Lagrangian strategy

Eulerian strategy
Free-surface Evolution VoF Method

$H_p$: The quantity $f$ is the fraction of water volume
Free-surface capturing methods (Level Set, VOF, Colour functions)

Initial artificial change between water and air must remain small
CFD Scenarios

Field Equations

- Potential Flow Methods
  - BEM, HPC
- Hybrid Methods
- Navier-Stokes Methods
  - Field Methods

Interfaces

- Grid Methods
  - Eulerian: interface capturing (VOF, LS, MAC, CIP)
  - Hybrid Methods
    - Eulerian
    - Lagrangian
  - Fixed Grids
    - Boundary-Fitted Grids
  - Gridless Methods
    - Eulerian
    - Lagrangian

Grid Methods

- (FVM/FDM/FEM)

Interfaces

- Time evolution

Body

Air-Water Interface
Hybrid method

Coupled potential flow (linear) and local viscous solutions with flow separation with significant reduction of computational speed

Vortex shedding causes damping of resonant motions
Hybrid method

Linear or weakly nonlinear potential-flow solver

Navier-Stokes solver

Efficiency

Accuracy

Breaking

Fragmentation

Air entrainment

Viscosity
CFD and CeSOS

- BEM (Boundary Element Method)
- HPC (Harmonic Polynomial Cell)
- SPH (Smoothed Particle Hydrodynamics)
- FDM (Finite Difference Method) + Level Set
- CIP (Constrained Interpolation Profile): FDM with CIP used during advection step. Combined with colour functions
- OpenFoam (FVM+VOF)
- Maxwell-Boltzmann method and use of GPU
- Hybrid methods for locally separated flow (HPC, FVM)
- Hybrid methods for green water on deck
Reliability Analysis

1) Verification: “Solving the equations right?”

The check of 1) means comparing with other benchmark numerical tests and analytical solutions using the same model.

2) Validation: “Solving the right equations?”

The check of 2) means comparing with model tests.

Experiments have also errors

Error analysis is needed in both experiments and computations
Is this correct?
Numerical wave tank

Numerical damping can cause too quick decay of waves on a coarse grid.

Numerical dispersion can cause too large error in the dispersion relation between wave length and wave speed.
Wave focusing due to uneven seafloor

HPC results agree well with experiments
Verification and validation of ringing loads
Comparisons with numerical (Ferrant) and experimental (Huseby & Grue) results

Time-domain nonlinear wave forces on a cylinder with exact free-surface conditions by the HPC method

Yanlin Shao
Ringing of monotower in survival condition

Steep local waves propagating on the two sides of the cylinder

The waves start on the upstream hull side when there is a wave trough
Ringing of monotower in survival condition

The two steep propagating waves will later collide

Big splash
Water entry of circular cylinders

Relevant for impact loads on vertical cylinders due to steep waves

Wienke & Oumeraci
Non-viscous flow separation on a curved surface by BEM
Convergence studies for water entry of circular cylinder with commercial CFD code based on FVM and VOF

The effect of the time step size $dt$ on the slamming force coefficient $C_s = \frac{F_s}{\left(\rho RV^2\right)}$

Experiments:
$C_s = 5.15 / (1 + 9.5Vt / R) + 0.275Vt / R$

Neither the force nor the force impulse converge

CIP code developments at CeSOS:
X. Zhu: Converged force impulse
T. Vestbøstad: Satisfactory force
Verification and validation of numerical predictions of local slamming

- "Simple" case
- Difficult benchmark tests:
  - Small local deadrise angles
  - Ventilation
- Experimental errors (bias and precision errors)
- Bias examples: 3D flow, oscillatory rig motions, elastic rope forces

Viscous effects can be neglected and potential flow assumed

Temarel (2009) Viscous effects can be neglected and potential flow assumed
Difficult benchmark test
Water entry of wedge with deadrise angle
7.5 degrees and constant velocity $V$

Slamming predictions by commercial code (FVM+VOF)

$$\frac{p - p_0}{0.5 \rho V^2}$$

$\frac{z}{Vt}$

Commercial code ×

Human errors?
Summary

- There exists a broad variety of CFD methods
- Computational time is of concern for wave and current induced loads
- Physical simplifications by potential flow and hybrid methods reduce computational time
- Reliability of CFD results
- All physical problems such as turbulence is not fully understood
- Convergence
- Verification and validation
Some Useful CFD References

Brebbia C. A. many books on “Boundary Elements”, WIT Press.


