Looking into the future of wind energy simulation

Gradient-Based Optimisation, Wave Generation & Ciespace platform

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Outline

Objective

- Very little “wind” in this presentation
- Identify (future) challenges apart from ones that have been raised in other talks
- Show some avenues ahead by looking at other fields

Topics

- Gradient-based optimisation
- Wave generation
- Ciespace platform
• Find

\[ \min(J(p)) \]

where \( J \) is the objective functional and \( p \) are free parameters.

• \( J \) is calculated by executing a computational workflow (pre-processing, solver, post-processing) which takes into account the parameters \( p \).

• Classification:
  
  o Single vs. Multi-Objective problem (\( J \) is a vector)
  o Unconstraint vs. constraint problem (additional restrictions on \( J \) and/or \( p \))
  o Parameter vs. Shape or Topology optimisation (geometry is changed)
  o Gradient vs. non-gradient based algorithms (uses \( \frac{\partial J}{\partial p} \))

• Optimization as a discipline is very rich in methods, approaches and algorithms.

• Many external tools exist (Dakota, modeFrontier, LMS Optimus)
Different Approaches

General approaches to optimization

- Non-gradient based algorithms
  - Simplex, Brent’s and Powell’s methods
  - Genetic algorithms
  - Surrogate and reduced order model algorithms

- Gradient based algorithms
  - Steepest descent
  - Newton’s method
  - Conjugate gradient
  - Sequential quadratic programming (SQP)

- Gradient calculation
  - Finite differences, incomplete gradient, reduced order model for gradients, etc.
  - Continuous adjoint and tangent equations
  - Discrete adjoint and tangent equations
  - Automatic differentiation
Non-gradient Based optimization

• Non-gradient based optimization is based on the evaluation of gradients of objective functional in which OpenFOAM is responsible for providing the current state

• Usually several states are saved in order to deduce the behavior of the function being minimized

• This knowledge is used to retain and discard the states in an effort to find the optimal point

• Typical problem with non-gradient based algorithms is so called “curse of dimensionality” - too many parameters require excessive number of non-linear function evaluations thus making the algorithms very expensive

• In shape optimization effective geometrical parameterization is crucial in controlling the cost of the optimization algorithm
Gradient Based optimization

- Gradient based optimization algorithms rely on the analytical and semi-analytical tools of gradient evaluation in order to guide optimization algorithms.
- Gradients can be obtained in several ways: Numerically, Automatic differentiation, Analytically (continuous - discrete, tangent - adjoint).
- If the original PDE equations are differentiated with respect to the optimization parameter, the resulting equations form a continuous approach to gradient evaluation.
- Two approaches in analytical differentiation of PDEs and gradient evaluations:
  - Continuous tangent equations
  - Continuous adjoint equations
- Continuous approach is ideal for OpenFOAM as software framework allows rapid implementation of PDEs.
Continuous Adjoint

- Construct the Lagrange functional from the weak form of Navier-Stokes equations and the cost function:

\[ L(x, u, p) = J(x, u, p) + \int_t \int_\Omega F(x, u, p)U^*(x, u)d\Omega dt \]  

(1)

- Continuous adjoint equations are obtained by using the duality principles on continuous tangent equation

- In the case of the incompressible laminar Navier-Stokes equations, continuous adjoint equations are as follows:

\[-\nabla \cdot u^* = 0\]

\[-u \nabla \cdot u^* - \nabla (u^*) \cdot u - \nu \nabla \nabla u^* = -\nabla p^*\]

- This system of equations describes the propagation of the derivatives from outputs to inputs in the system - It finds the source of a specific anomaly

- It does NOT model physical quantities - It models the sensitivity of a property to these quantities

- Efficiently computes sensitivity of a model with a large number of sensitivity parameters.
Catalyst System

Optimisation of a Catalyst (Inlet Part) with Porous Media: Body-Fitted Mesh

- Forward and adjoint solution: pressure and velocity
Optimisation of a Catalyst (Inlet Part) with Porous Media: Body-Fitted Mesh

- Shape derivative and convergence history
Optimisation of Connecting Piping

- Forward and adjoint solution: pressure and velocity
Optimisation of Connecting Piping

- Forward and adjoint solution: shape derivative and convergence history
Immersed Boundary Catalyst System

Optimisation of a Catalyst (Inlet Part) with Porous Media: Immersed Boundary

- Mesh setup, immersed boundary and live subset
Optimisation of a Catalyst (Inlet Part) with Porous Media: Immersed Boundary

- Forward and adjoint solution: pressure and velocity
Immersed Boundary Catalyst System

Optimisation of a Catalyst (Inlet Part) with Porous Media: Immersed Boundary

- Convergence history

![Convergence history graph]

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Summary

Continuous Adjoint

- Full implementation including adjoint turbulence
- Resolved Convergence Problems with Continuous Adjoint equations for Navier-Stokes: rapid convergence for all cases and optimisation objectives
- Stabilisation is achieved at **numerics level**: careful discretisation, handling of cross-component coupling and reformulation of the boundary condition handling
- Stable across all mesh types: hex, tet, polyhedral; even Immersed Boundary!!!
Modelling of Free Surface Flows: Review of Equations

- Immiscible condition combines momentum equations: no inter-penetrating continua, no phase drag terms

- Phase continuity equation with volume fraction variable $\alpha$: derived from mass conservation for a phase
  \[
  \frac{\partial \alpha}{\partial t} + \nabla \cdot (u\alpha) = 0
  \]

- Combined momentum equation
  \[
  \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) - \nabla \sigma = -\nabla p + \rho f
  \]

- Volumetric continuity equation, to be reformulated in terms of pressure
  \[
  \nabla \cdot u = 0
  \]

- Discretisation issues arising from the above will be investigated and practices available in OpenFOAM reviewed in detail
Analytical Wave Forms

- Calculation of response to wave loading requires a wave train to be introduced into the domain with minimal distortion
- Wave theory derives combinations of free surface elevation and velocity field that satisfy (simplified forms of) the free surface flow equation set
  - Potential current (not really a wave)
  - Solitary wave
  - Regular waves
    - Linear wave (first order Stokes wave)
    - First order Stokes standing wave
    - Second order Stokes wave
    - Fifth order Stokes wave
    - Cnoidal wave
  - Irregular waves: Bretschneider sea state wave spectrum
    - Superposition of linear waves to reproduce random behaviour with given modal frequency and significant height
    - Number of sampling bands depends on application: typically 5 to 200
Wave Boundary Conditions

Wave Boundary Conditions

- Under controlled circumstances and with sufficient mesh resolution, prescription of waves is performed at inlet boundary patches
- Special numerical treatment required: flow goes in-and-out, specification of free surface elevation is not trivial
- Current implementation does not allow for sub-cell resolution of incoming wave
- Consistency in $\alpha$ and $U$ boundary condition is paramount!

Implemented Wave Boundary Conditions

- Water table boundary: constant free surface level on a moving mesh
- Linear wave
- Linear wave, with forward speed (eg. ship on waves)
- Bretschneider sea state wave spectrum

Numerical Beach

- For patch-imposed incoming wave boundary conditions, a patch-based numerical beach is used: distance calculated as distance-to-patch

Other Forms: Wave Generation via moving wall conditions
Wave Boundary Conditions

Example: Wave Boundary Condition

- Regular linear wave with zero mean velocity

Regular linear wave: boundary condition treatment
H. Jasak, Wikki Ltd. Feb/2013
Wave Boundary Conditions

Example: Wave Boundary Condition

- Regular linear wave at forward speed of 5 m/s
Wave Boundary Conditions

Example: Wave Boundary Condition

- Irregular Bretschneider sea state spectrum at forward speed of 5 m/s
- Significant height = 3.3 m; modal frequency = 0.64 Hz, n bands = 10
Wave Relaxation Zones

- Under some circumstances, wave boundary conditions are inappropriate:
  - Far field mesh is coarse: sub-cell wave resolution required
  - Moving and pitching inlet boundary: no longer possible to impose a 1-D vertical solution
  - High fidelity required: introduce wave train with minimum distortion
  - Cases with badly posed flow conditions, e.g. ship at forward speed in following seas
  - Numerical beach relaxation in cases with forwards speed

- **Jacobsen approach: DTU Copenhagen**
  - Wave forms obtained under simplified conditions satisfy the governing equation set
  - It is therefore possible to blend numerical solution in the bulk with analytical wave prescription in relaxation regions
  - Analytical wave trains are now specified in the volume, as opposed to only on boundary surface

- Algorithmic improvement: implicit (matrix-level) blending instead of field blending
Wave Relaxation Zones: Example of Setup

- Define computational domain of interest, with room for relaxation zones at inlet/outlet
- Relaxation zone is defined as a primitive shape, eg. rectangle or cylinder
- Each relaxation zone defines a wave theory model, where wave field (elevation and velocity) is obtained from analytical wave forms
- Across the relaxation zone, analytical and numerical solution is blended, based on a weighting function from relaxation zones
- In the bulk, weighting function equals zero and CFD solution is obtained
Wave Relaxation Zones

Example: Wave Generator and Potential Current

- Inlet wave relaxation zone: regular Stokes waves with soft ramp time
- Outlet relaxation zone: potential current, fixed water table
Summary

- Naval Hydro Pack is equipped with wave maker boundary conditions
  - Patch-based conditions
  - Relaxation zone conditions
- Number of wave forms available for run-time selection
- Relaxation zone conditions provide sub-cell wave resolution: possibility of generating waves on a coarse (far field) mesh
- Wave boundary conditions integrated with navalFoam solvers, with support for dynamic mesh motion
Today’s Engineering Environment

More competitive than ever, and not getting any easier…

- R&D is global
- Resources are Scarce
- Design complexity is increasing
- Quality demands growing
- Product lifecycles growing shorter
Generations of Computing Paradigms

1960s-early 1980s
Gov’t and Big Aero

Late 1970s-late 1980s
Large Enterprises

Late 1980’s-current day
SMB’s

Current day and beyond
Anyone...
Q: Cloud computing and the open source movement have made significant inroads in the software engineering, enterprise marketing, and consumer spaces, why not mechanical engineering…?

A: Until now there didn’t exist the confluence of technology, market acceptance, and thought leadership Ciespace brings to bear.
Who is Ciespace?

Mission
“To accelerate the rate of innovation and dramatically reduce the cost of digital prototyping”

55% of Ciespace employees hold graduate degrees in engineering related fields

5 Patents related to geometry and mesh generation

1st To market with an end to end cloud based CAE solution and first open platform CAE provider
Ciespace for Wind Turbines

- Start with raw CAD. Simplify and merge bodies
- Extract fluid volume and create MRF region
- Mesh – tet dom; 10M nodes
- Rich post-processing capabilities
- End to end CFD Workflow
  - No software installation
  - Simplifies running OpenFOAM®
  - Powerful meshing and geometry
  - Collaboration built in
- Solve using 2.1.1, 1.6, or your own custom solver!
Cloud Services Layer

An Open Cloud Native Platform for 3D Engineering

Accessibility  Access to Ciespace is as simple as logging in from a browser, anywhere in the world, at any time, from any device.

Scalability  Having access to the right resources, when you need them, affordably.

Security  A three tiered security strategy ensuring that your data is accessible only to you or those you explicitly grant access.

The Ciespace platform delivers against the 5 key cloud characteristics (On-Demand Self-Service, Broad Network Access, Resource Pooling, Rapid Elasticity, Measured Service) with an architecture flexible to suit private or public cloud deployments.
Management Layer

Supporting the rapid, iterative design

Data Analytics  Being able to easily see what projects were worked on by whom, how much solution time and user time each took, and any details about past projects

Workflow Management  Project, CAE workflow, and task tracking and assignment are all addressed in the management layer.

Collaboration  Engineering collaboration drives improved quality and compresses design review cycle time. Leverage knowledge and expertise; collaborate with clients and customers.

Real Time Collaboration  One or more engineers can view the same project, interact with the same model, pass control from one to another, whiteboard, chat, and annotate – over distances of thousands of miles…
**Application Layer**

Best of breed capabilities to build from…

**Geometry Engine** The geometry application component in Ciespace is the interface between the CAE workflows and the CAD data.

**Mesh Engine** The core meshing technology of the Ciespace meshing engine relies on the patented IP of the physics based bubble meshing algorithm.

**Solver Engine** As with the other components in application layer, the solver engine is architected in such a way as to support plugging in different solvers to address the unique physics necessary to solve.

**Visualization Engine** The Ciespace visualization engine can read most of the common CAE application output formats and generate 2D and 3D plotting for results visualization.

**Leveraging OpenFOAM®** OpenFOAM
Ciespace includes both the 2.1 and 1.6 versions of OpenFOAM®; the most popular open source CAE solver used by industry leading organizations worldwide.

**Supported Mesh Types**
- Fully automated Tetrahedral, Conformal and non-conformal hex dominant, 2D wedge + hex meshing capability

**Ability to handle huge datasets**
Remote visualization makes rendering possible even on the thinnest of clients without transferring large raw datasets over the network.
Ciespace CFD

Engineering Empowered
• An Open Cloud Platform for Engineering Design & Analysis

Ciespace is

Efficient
Collaborative
Open
Agile

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See a demo on Vimeo