Tackling Complex Flow Problems via Numerical Simulation
From Jumping Fish & Heart Valves to River Flooding and Wind Energy

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Mitigating impacts of climate change:
Extreme flooding

Harnessing renewable energy from wind, tides and waves

Fluid mechanics challenges in energy, environment, biology and health

How has hydrodynamics shaped fish evolution?

Anthropogenic effects in urban air quality

Hemodynamics and heart disease
The Pillars of Scientific Inquiry

THEORY

Continuity Equation
\[ \nabla \cdot \mathbf{V} = 0 \]

Momentum Equations
\[ \frac{D \mathbf{V}}{D t} = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{V} \]

OBSERVATION

SIMULATION

DATA-DRIVEN KNOWLEDGE
Exponentially Growing Computing Power

1. The accelerating pace of change...
   - Agricultural Revolution: 8,000 years
   - Industrial Revolution: 120 years
   - My first research computer: VAX 11/780

2. ...and exponential growth in computing power...
   - Computer technology, shown here climbing dramatically by powers of 10, is now progressing more each hour than it did in its entire first 90 years

3. ...will lead to the Singularity
   - Apple II: At a price of $1,298, the compact machine was one of the first massively popular personal computers
   - UNIVAC I: The first commercially marketed computer, used to tabulate the U.S. Census, occupied 943 cu. ft.
   - Power Mac G4: The first personal computer to deliver more than 1 billion floating-point operations per second

TIME

2045
- Surpasses brainpower of human in 2023
- Surpasses brainpower of mouse in 2015
Most flows in nature are turbulent

Size of relevant eddies can range from $O(10^3 \text{m})$ to $O(10^{-4} \text{m})$

Large Eddy Simulation (LES) vs Direct Numerical Simulation (DNS)
Multi-Physics Phenomena & Arbitrary Geometric Complexity
Virtual Flow Simulator®: Large Eddy Simulation of turbulence in real-life flows

- Sharp Interface Immersed Boundary
- Wall model to reconstruct velocity field at IB nodes
- 2nd order central differencing on a hybrid staggered/non-staggered grid
- Fractional-step algorithm: Jacobian-free Krylov solvers with Algebraic Multigrid
- Turbulence simulation and modeling:
  - Direct Numerical Simulation (DNS)
  - Large Eddy Simulation (LES)
- Fluid-structure interaction (Borazjani et al., JCP, 2008; Gilmanov et al., J. Comp. Phys 2015)
- Level sets for free-surface modeling (Kang & Sotiropoulos, J. Hydr. Eng., 2015)
- Coupled hydro-morphodynamics for sediment transport (Khosronejad & Sotiropoulos JFM 2014)

http://safl-cfd-lab.github.io/VFS-Wind/
Hydrodynamics and Fish Evolution


Anguilliform

Carangiform
What if a Mackerel could swim like an Eel or an Eel swim like a Mackerel?

*Borazjani & Sotiropoulos, J. Exp. Biology, 2009, 2012*

Lamprey body
Re=∞ (Inviscid)  St~0.3

Anguilliform Kinematics
Carangiform Kinematics

The camera is fixed on the slower (top) lamrpey.
The distance is scaled by half for better visualization.
Hydrodynamics of Archer fish jumping out of water

With Alex Techet (MIT) & Leah Meldenson (Harvey Mud)
Comparison of simulations with measurements

Comparison of the propulsive jets and the instantaneous out-of-plane vorticity contours between LES and PIV measurements. PIV time series correspond to 1 body length jump and LES calculations to 2.3 body length jump of the same specimen.
Water exit dynamics of jumping archer fish

With Alex Techet (MIT) & Leah Meldenson (Harvey Mud)
Image-guided patient-specific simulations of aortic valves

From MRI to high-resolution computational modeling
The hemodynamics of aortic valves: Tricuspid vs. bicuspid valves

Bicuspic aortic valve (BAV) occurs in ~1-2% of the population

BAV patients show increased prevalence of aortopathies
Genetics or hemodynamics?

Bissell, et al.
Circ. Cardiovasc. Imaging 2013
Instantaneous streamlines
Comparison with 4D MRI

Bicuspid aortic valve

Bissell, et al.
Circ. Cardiovasc. Imaging 2013

Gilmanov & Sotiropoulos
Theo. & Comp. Fluid Dyn. 2015
“The largest remaining opportunities to reduce the cost of energy will come from substantial gains in understanding complex wind plant aerodynamics.” EERE DOE.
The Horns Rev Offshore wind farm
Denmark, North Sea
Tip vortices in the wind tunnel

NASA Ames wind tunnel
A Utility-Scale (2.5MW) “Wind Tunnel”

Super Large Scale PIV (SLPIV) using natural snow as tracer implemented at the University of Minnesota 2.5MW EOLOS turbine (Rosemount, MN)

Hong et al., Nature Comm., 2014.
Complex flows in the near wake: Tip vortices
Numerical simulation
Tip speed ratio = 9; Inflow turbulence; Stably stratified atmosphere

$u/U_b$: 0.2 0.4 0.6 0.8 1 1.2
Vorticity magnitude as surrogate for snow voids

Experiment

Simulation
Coherent dynamics in the rotor tip shear layer of utility-scale wind turbines

Yang et al., J. Fluid Mechanics, 2016

Positive and negative iso-surfaces of azimuthal vorticity
Wind farms in complex terrain
Site-specific simulations of wind farms in complex terrain
LES of a utility-scale wind farm in complex terrain
Yang, Pakula & Sotiropoulos, Applied Energy, 2018

Field measurements vs Simulation
Error bars: RMS of power fluctuations

Measured vs computed mean and RMS fluctuations of power

$P$: averaged power of each group; $P_{G1}$: averaged power of G1 group
Fluid-structure interaction simulation of floating structures interacting with complex, large-scale ocean waves and atmospheric turbulence

Calderer et al., J. Comp. Physics, 2018
Control co-design of offshore wind farms
Individual vs collective pitch control
Individual Pitch Control can reduce blade bending loads
Site specific simulations of turbulence in waterways
Khosronejad et al., J. Geophysical Research 2016

Eagle Creek, MN
Surveyed stream bathymetry
Background mesh
Data-driven site-specific simulations of turbulence and solute transport in waterways

Large-eddy simulation of solute transport in Eagle Creek, MN
Sand waves in waterways

• How do they originate?

• What is their impact on infrastructure?
Sand waves in a laboratory flume

Venditti, Church & Bennett, J. of Geophysical Research, 2005
LES of turbulent flow over a mobile sand bed

Transition to 3D pattern

Merging process

Venditti & Chruch (2005)

$0 < t < 3600 \text{ sec}$

30 cm deep

Sediment layer
Coupled hydro-morphodynamic LES of barchan dunes in a turbulent open channel flow

Vorticity magnitude iso-surfaces over evolving barchans

Physical time is accelerated by 200 times
Data-informed simulations of extreme flooding in the Upper Mississippi River


- **Objective:** Finding maximum scour depth under extreme flood conditions of 100 and 500 year-floods

- **Source of geometrical data:** LiDAR; Sonar onboard a boat; Laser scanner

- **Sources of flow field data for model validations:** Acoustic Doppler Current Profiler (ADCP) onboard a boat
High-resolution digital terrain model by fusing a variety of data sets
Validation with field measurements under base-flow condition
Hydrodynamics & morphodynamics of a 100-year flood event

Simulating bridge foundation scour at field scale
Simulation-based optimization of tidal energy
The Verdant Power Roosevelt Island Tidal Energy Project
Chawdhary et al., Water Resources Research, 2018

Hydrodynamic interactions of the Verdant TriFrame™
Turbine-flow-sediment interactions

Performance and resilience of hydrokinetic turbine arrays under large migrating fluvial bedforms

Musa, Hill, Sotiropoulos & Guala, *Nature Energy*, 2018
Fluid mechanics in the era of extreme computing: Cyber-physical systems of natural environments

**Local scale**: Real-time data from embedded and autonomous robotic sensors

**Ecosystem scale**: Data from satellites and airborne lidars

**Data-driven HPC simulation of ecosystems**: Hazard mitigation, water quality, energy harvesting, restoration & sustainability, etc.

**Site-specific reduced order models for engineering design & decision support**: Big-data from measurements and high-fidelity models, Machine learning

**Ecosystem scale**: Data from satellites and airborne lidars

**Local scale**: Real-time data from embedded and autonomous robotic sensors
Thank you!