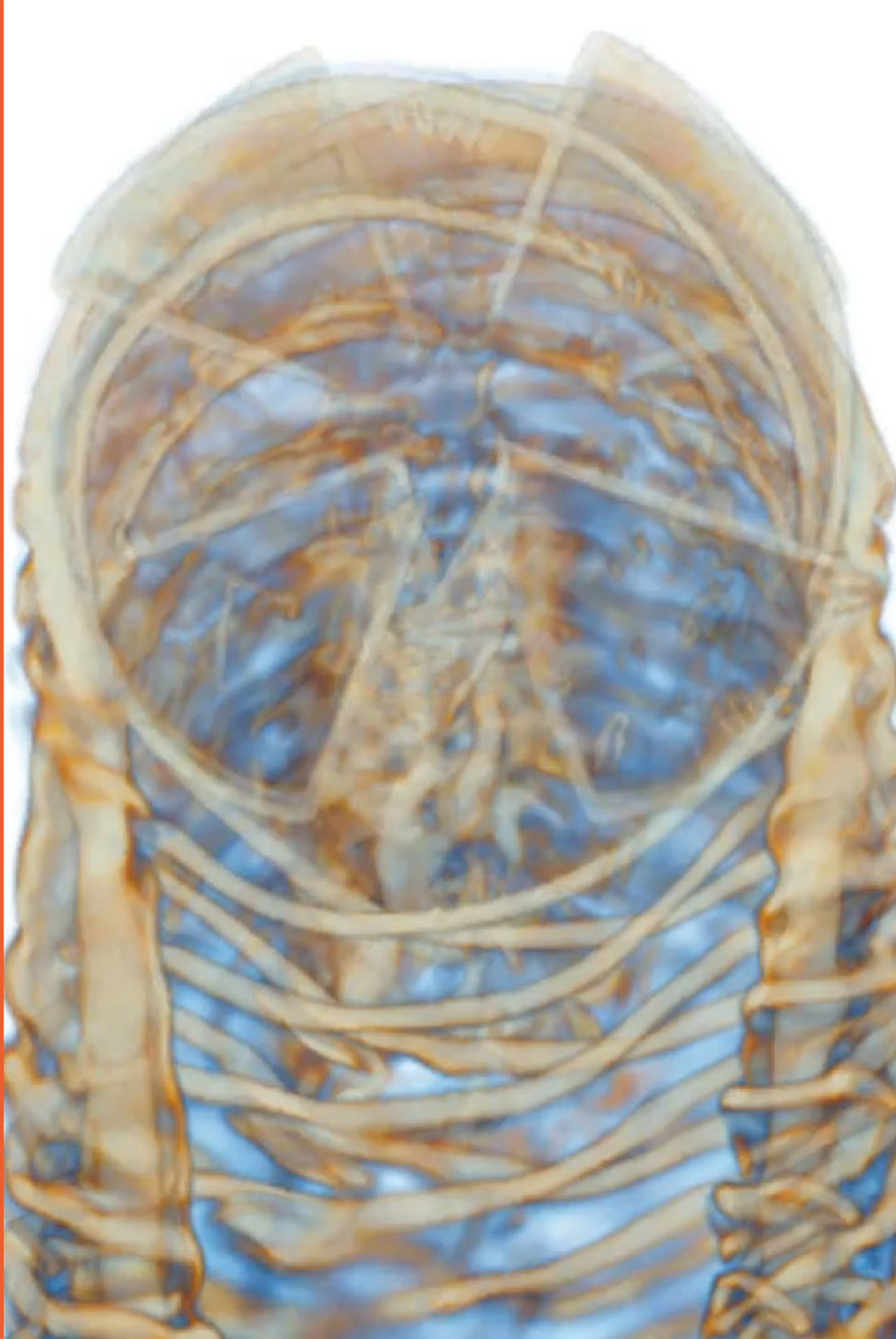
High Speed Aerodynamics
The University of Sydney

Presenter

A/Prof Ben Thornber



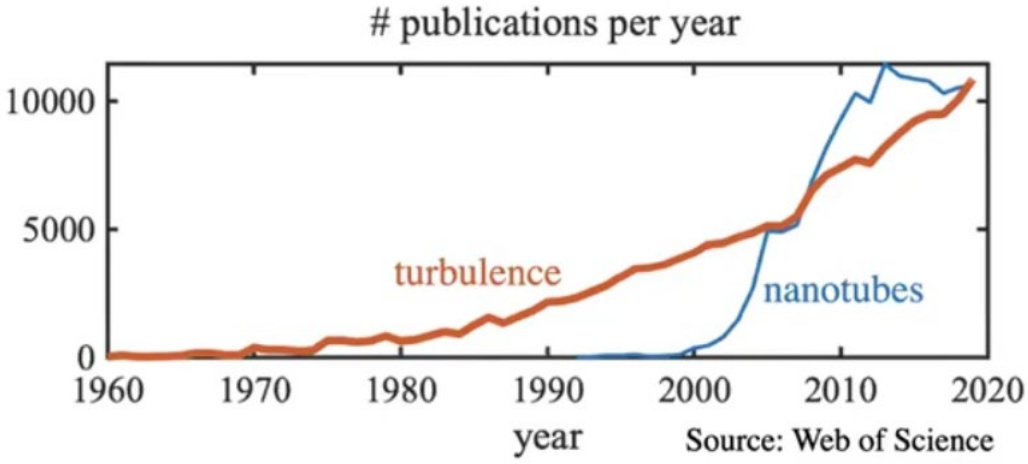
THE UNIVERSITY OF SYDNEY

Introduction

1. Quick Flavour of the problem and why we care
2. Our contributions and potential opportunities
   1. Advanced numerical methods
   2. Understanding of dependence of flow on initial conditions
   3. New governing models
3. Thoughts

Introduction

"It is estimated that more than 25% of the energy used by industry globally is spent either moving fluids or moving objects through fluids."



International Energy Agency, Key World Energy Statistics (IEA, Paris, 2012), available from http://www.iea.org/publications/freepublications/publication/kwes.pdf

Introduction - Complexity

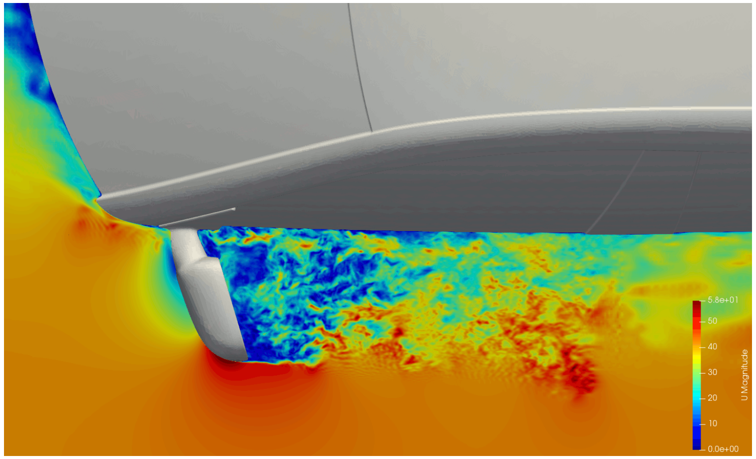
Large scales of a turbulent flow ℓ are correlated over an integral length ~1/4 of the object size

Small scales depend on viscosity, $$\frac{\ell}{\eta_K} \approx Re^{3/4}$$

For a car wing mirror, Re ~275k

$\ell \approx 0.04m, \eta \approx 3.3\mu m$

Smallest scales are 12000x smaller than largest



Aircraft Re ~ 10^8, Submarines ~10^9, $\frac{\ell}{\eta} \approx 10^6$

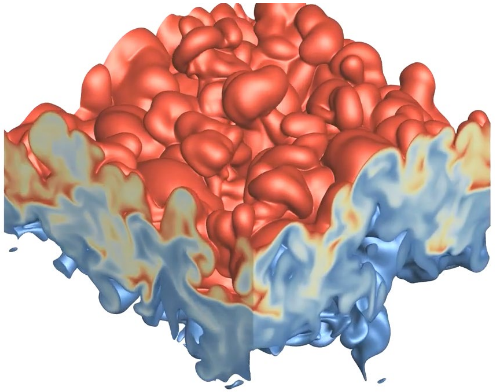
Introduction - Numerics

Imagine solving all scales Direct Numerical Simulation (DNS):

- To resolve a vortex, you need ~ 8 cells in each direction
- To resolve the large scale, you need at least 10 ℓ
- Turbulence is 3D
- Grid resolution is thus (wing mirror):

  Number of points ~$(12000 \times 8 \times 10)^3 \sim 10^{17}$

Current state of the art ~ 10^{10}



Title: DNS of Richtmyer-Meshkov Instability
Created by: M. Groom (USYD)

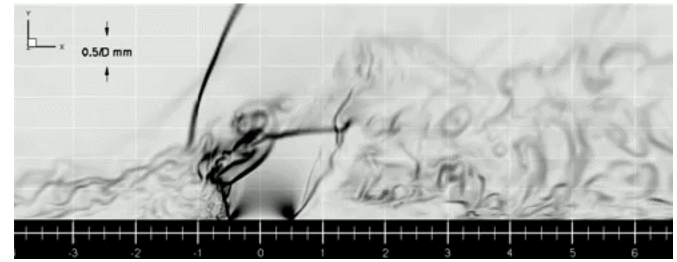
Gap of 10^7, roughly 25 years of Moore's law.

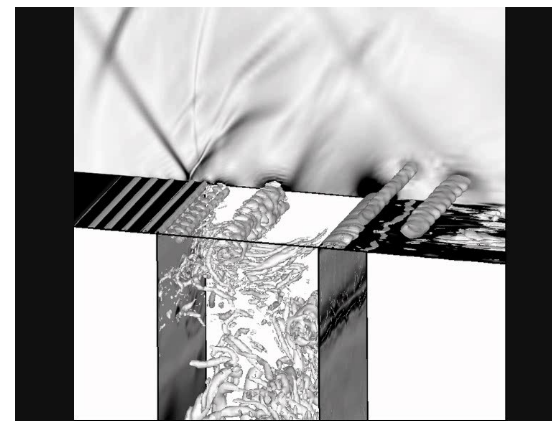
A DNS of an A380 on a PetaFlop machine would run for 30 years.

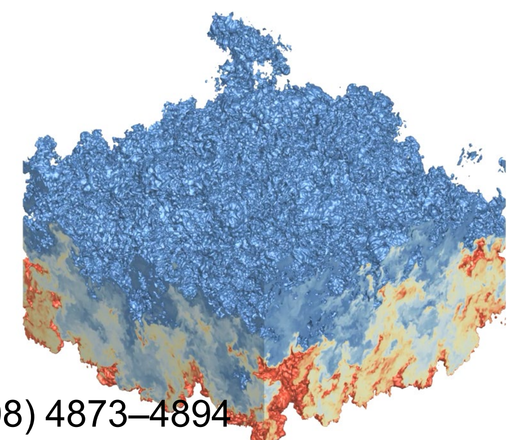
We must both improve governing models, algorithms or adopt new approaches

Video: [1]Groom & Thornber, J. Fluid Mech. (2021), vol. 908, A31.

Introduction to Research Group







Advance governing models, numerical methods and understanding of high-speed flows

1. Advancement in numerical methods
   - Develop new methods for high-speed unsteady turbulent flow
   - Adopted and implemented in many codes worldwide: DLR's Tau (used by Airbus), Los Alamos National Labs, UK AWE, French CEA, Goethe University, Penn State, RWTH Aachen, Lund, Tsinghua…
2. Unsteady computations
   - A world-leading research group in compressible turbulent mixing
   - Aeroacoustics in compressible flows
   - LES and RANS Model development for compressible unsteady flows

Thornber et al, Journal of Computational Physics 227 (2008) 4873–4894
Thornber & Drikakis, AIAA J., Vol. 46, No. 10, October 2008
Rana, et al, Physics of Fluids, 23, 046103 2011

Research Problem (1) Governing Models

Improved governing models can give order of magnitude improvements – we derived a new governing model for gas mixtures doing exactly this[2].

Most commonly, computational effort is reduced by modelling the small scales, picking the energy equation (the worst case!):

$$\frac{\partial \widehat{\rho E}}{\partial t}+\frac{\partial \tilde{u}_i(\widehat{\rho E}+\bar{p})}{\partial x_i}+\frac{\partial \hat{q}_j}{\partial x_j}-\frac{\partial}{\partial x_j}(\hat{\sigma}_{ij}\tilde{u}_i)=\underbrace{\frac{\partial}{\partial x_i}\overline{\left(\rho\sum_{k=1}^{N}h_{s,k}Y_kJ_k\right)}}_{R_1}+\underbrace{\overline{\dot{w}_T}}_{R_2}-B_1-B_2-B_3+B_4+B_5+B_6-B_7,$$

$$B_1=\frac{\partial}{\partial x_i}(\bar{\rho}\widetilde{e_s u_i}-\overline{\rho e_s}\tilde{u}_i),\quad B_2=\overline{p\frac{\partial u_i}{\partial x_i}}-\bar{p}\frac{\partial \tilde{u}_i}{\partial x_i},\quad B_3=\frac{\partial}{\partial x_i}(\tau_{ij}\tilde{u}_i),$$

$$B_4=\tau_{ij}\frac{\partial \tilde{u}_i}{\partial x_i},\quad B_5+B_6=\frac{\partial}{\partial x_j}(\overline{\sigma_{ij}u_i}-\hat{\sigma}_{ij}\tilde{u}_i),\quad B_7=\frac{\partial}{\partial x_i}(\bar{q}_i-\hat{q}_i).$$

The overbar represents filtered quantities (similar to Matt's presentation)

High speed flows suffer from a tighter coupling of physics and numerics

Sheer complexity, lack of experimental or computational data which can provide sufficient validation

[2]Thornber et al., Journal of Computational Physics 372 (2018) 256–280

Research Problem (1) Governing Models

1. Our approach to modelling to date is mostly classical, with some small exceptions:

$$\frac{\partial \overline{U}}{\partial t} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x} + \nu \frac{\partial^2 \overline{U}}{\partial y^2} + \frac{\partial}{\partial y}\left(\nu_T \frac{\partial \overline{U}}{\partial y}\right)$$

Modelled ν_t using a Bayesian Inversion and Regression tree map (different Re) for a channel flow[3]. Others are further down this path using ML with symbolic regression and gene expression programming

2. State space estimators (Illingworth et al, J. Fluid Mech. (2018), vol. 842, pp. 146-162):

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{d}(t),$$
$$\boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t),$$

$\boldsymbol{x} = \begin{bmatrix}\hat{\boldsymbol{w}} & \hat{\boldsymbol{\eta}}\end{bmatrix}^{\mathrm{T}}$; $\boldsymbol{y} = \begin{bmatrix}\hat{\boldsymbol{u}} & \hat{\boldsymbol{v}} & \hat{\boldsymbol{w}}\end{bmatrix}^{\mathrm{T}}$; and $\boldsymbol{d} = \begin{bmatrix}\hat{\boldsymbol{d}}_x & \hat{\boldsymbol{d}}_y & \hat{\boldsymbol{d}}_z\end{bmatrix}^{\mathrm{T}}$ represents all nonlinear terms

Matrix A depends on n x n, with n the number of points. Gets very expensive in 3D!!

Other interesting directions - Super-resolution, image recognition?

[3]Cheema, Mathews, Thornber, Vio, AFMC 2016.

Research Problem (2) Numerical Methods

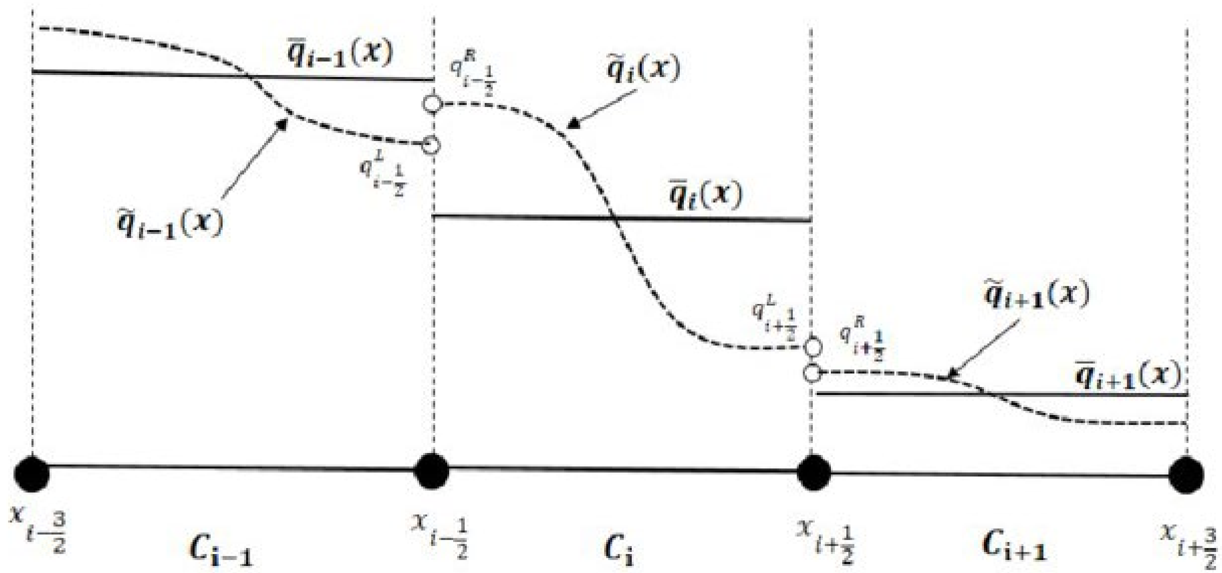
We need to maximise the bandwidth of the numerical scheme (resolution in wavenumber space).

We need to satisfy fundamental conditions in addition to order of accuracy:

- Positivity of scalars (and density!)
- Ability to represent under-resolved features strong shock waves
- Ability to resolve high wavenumber structures accurately without phase error or dissipation
- Mach-uniform dissipation
- Satisfy the 2nd law
- Galilean invariance?

Commercial solvers are largely 2nd order accurate finite volume, and fundamental methods in them have been static for about 2 decades and have numerics from 4 decades ago!

Research Problem (2) Numerical Methods



$$q = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \\ \rho Y_k \end{bmatrix} \text{ or } \begin{bmatrix} \rho \\ u \\ v \\ w \\ p \\ Y_k \end{bmatrix}$$

Given: $q_t + Aq_x = 0$, the interface flux may be written as:

$$f_{i+1/2} = \frac{f\left(q^R_{i+1/2}\right) + f(q^L_{i+1/2})}{2} + \frac{1}{2}|A|(q^R_{i+1/2} - q^L_{i-1/2})$$

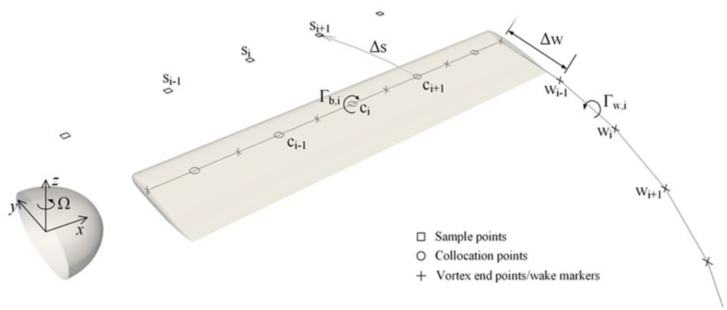
We pioneered methods which introduce flow-adaptation to this process to greatly improve the resolution of shock waves and turbulence[3] and aeroacoustics[4].

Opportunity: ML/AI-based feature identification and reconstruction

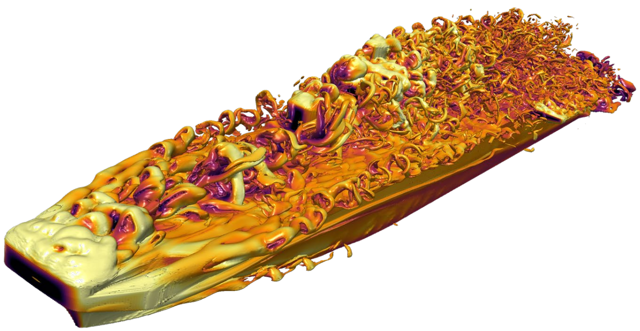
[3]Thornber et al, Journal of Computational Physics 227 (2008) 4873–4894
[4] Yu, Diasinos & Thornber, Computers & Fluids (2021) 214, 104748.

Research Problem (3) Applied Aerodynamics

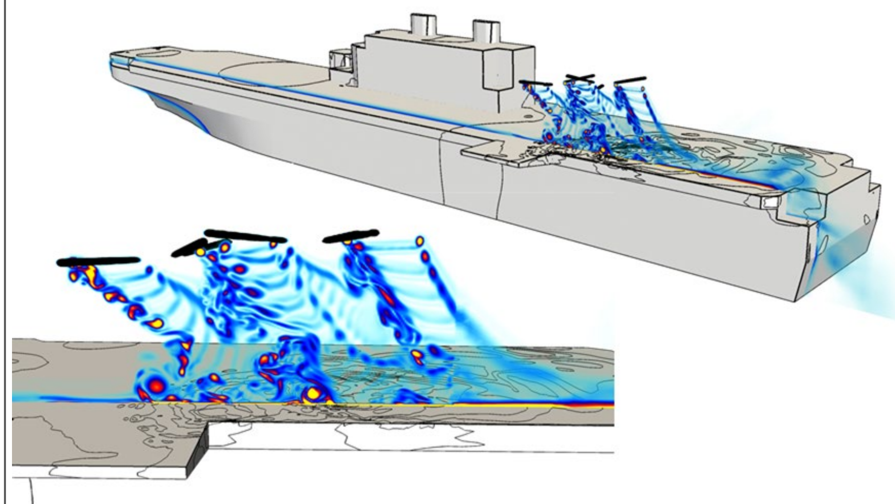
Rotor Model



Ship Airwake CFD



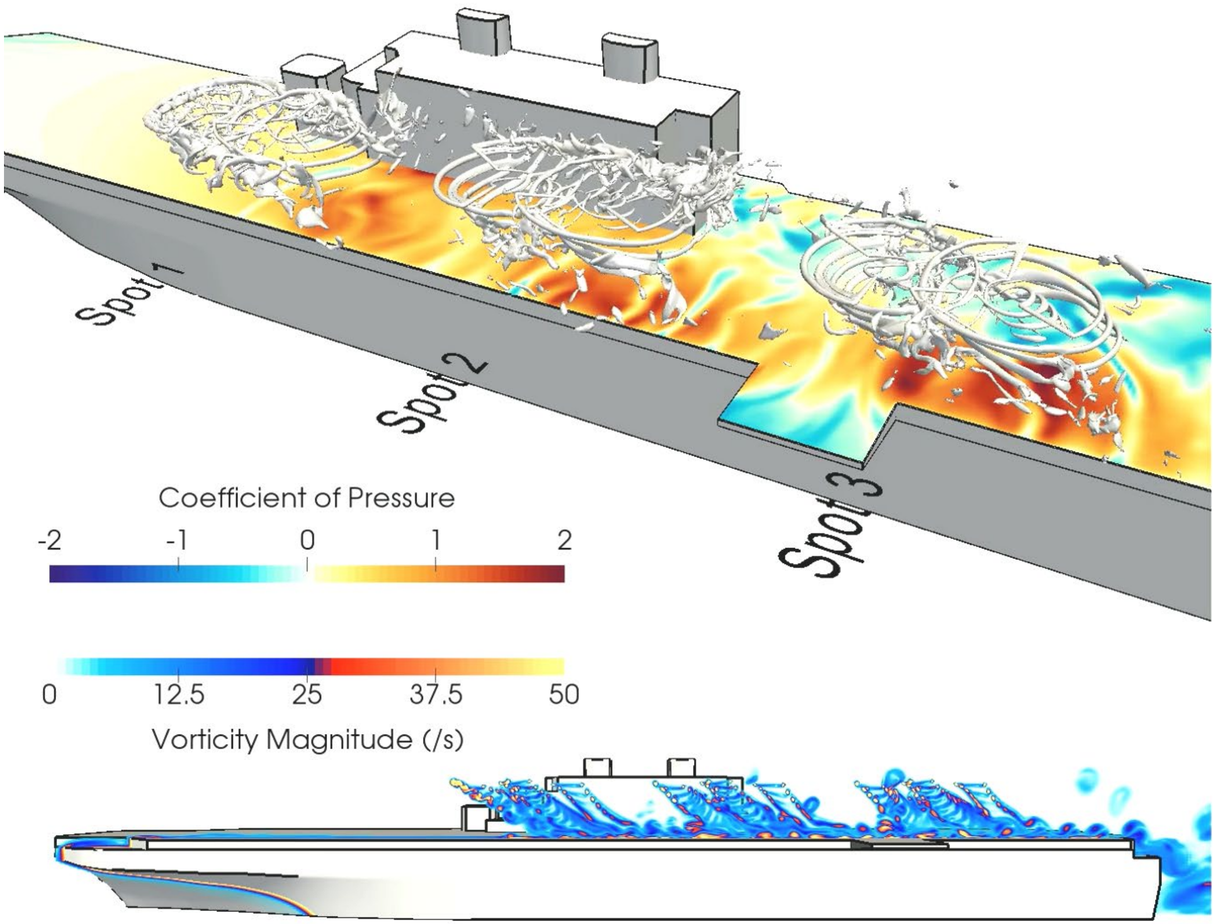
Affordable and accurate dynamic interface simulations (more than 20x faster)

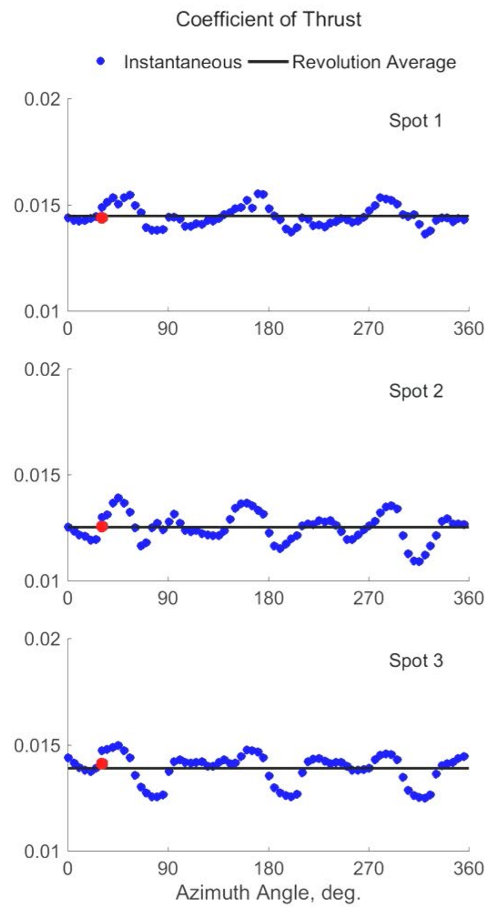


Applications : augmenting and replacing flight tests, analyzing rotorcraft downwash and impacts on surrounding vehicles/personnel etc.

D Linton, B Thornber Ocean Engineering (2021) 229, 108983
D Linton, et al AIAA Journal (2018) 56 (8), 3153-3166 & AIAA J. 2021

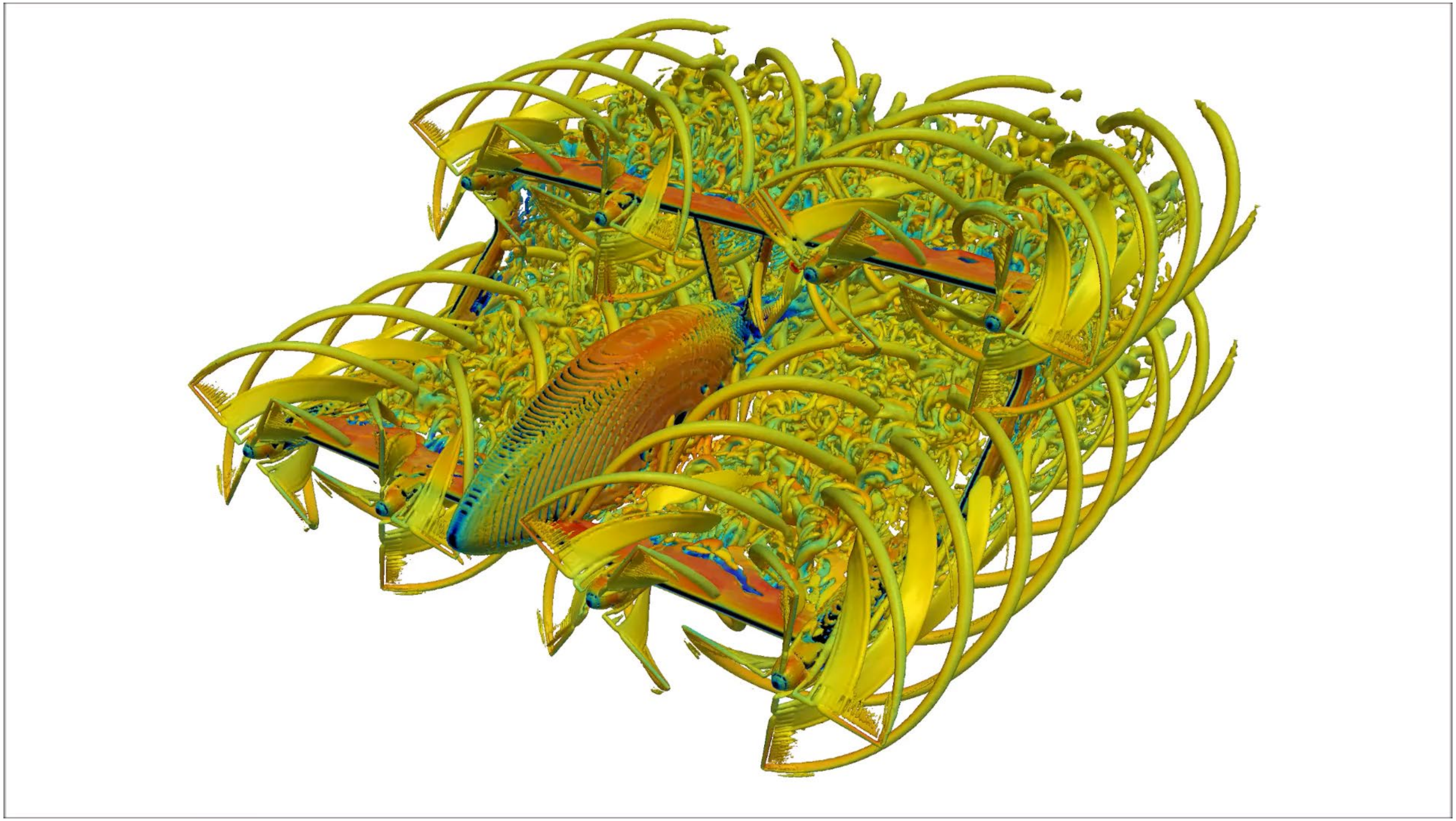
Demonstration: Visualisation of vortices generated by 3 Chinooks hovering over a Navy ship. Computation ran on 64 cores, 2 days





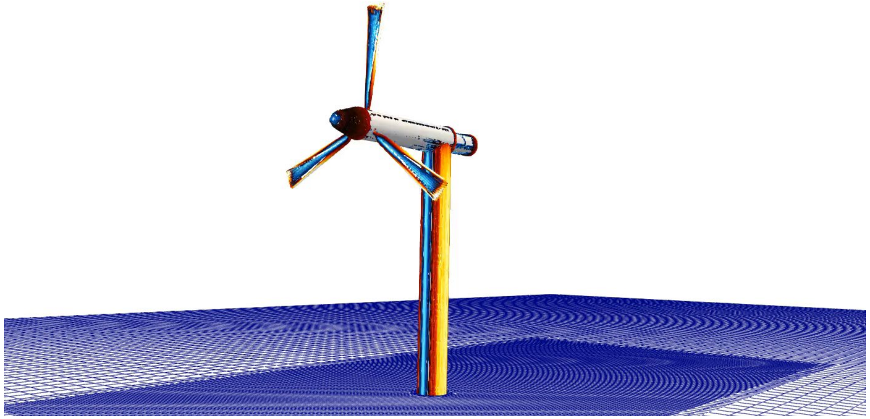
Key message: The <u>fastest method in the world</u> for computing interactions between multiple flight vehicles including unsteady rotor or propeller effects and delivering unsteady thrust information

Demonstration: Proposed medical evacuation vehicle, under development by AMSL Aero
Computation ran on 16 cores in 10 hours



Key message: It is 40x faster than the nearest equivalent computations. We gain full system performance predictions

Recent highlights (1/9)
UAS, Urban Mobility and Wind Turbines



Our vision:

"Develop computational methods able to assess and optimise operations of complex groups of rotorcraft, UAS or wind turbines"

Pathway:

- Adopt advanced computational frameworks developed in the US: They are 'Exascale ready' being designed for the world's fastest computers
- Development and integration of a flight controller and dynamics model for both helicopters, UAVs and wind turbines
- Integration of additional physics representing specific operations.

Optimisation – e.g. wind farms, UAS and rotorcraft recovery.

<u>Opportunity 1:</u> a grouping of 3 turbines studies have ~50k measure configurations when binned in 4° sectors for a single wind direction. How can we manage this?

<u>Opportunity 2:</u> Connect to live systems and optimize the model and system on the fly

Conclusions and Acknowledgements

Gave a quick introduction to our research thrusts in governing equation development, modelling, numerical methods and fluid physics.

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