Role and Challenges of CFD in the Design of Gas Turbines

Raul Vazquez\(^{(1)}\) & Paolo Adami\(^{(2)}\)

\(^{(1)}\) Senior Aerothermal Specialist – Fellow  
\(^{(2)}\) Associate Fellow - Turbo Machinery Aerodynamic Methods  

10 April 2019

European Turbomachinery Conference 2019 - ETC13
When computers reached $10^{14}$ flops, simulations would rival wind tunnel tests, with eddy resolving simulations finally being possible.

1979, Dr. Dean R. Chapman
Director of Astronautics at the Ames Research Center
3D NASA 22-INCH Fan Blade iLES Simulation

TIANHE-II, Re = 1.6 M, Nektar++, 8M core hours, 6 convective lengths flow-through time.

By H. Xu, F. Montomoli & S. Sherwin.
Because of the advances in computing technologies, numerical simulations are being used more and more in design and replacing physical testing which are very expensive.

2016, Prof. Parviz Moin
Director of the Centre for Turbulence Research at Stanford and Ames
Agenda

01 Introduction
2 slides

02 Role of CFD in the design of Gas Turbines
6 slides

03 Challenges in the design of Gas Turbines
12 slides

04 A Vision Approach to the future
8 slides
Introduction

2 slides
Computers get faster

‘In Moore’s Law post era, HPC hardware is on the cusp of a paradigm shift that will require significantly new algorithms and software in order to exploit emerging hardware capabilities’

*CFD Vision 2030, NASA*
**Overall Accuracy**

\[ f(\text{AM}, \text{AS}) \]

**Accuracy in the Model**

- **Physics & Maths**
  - Inaccuracies
  - More physical models

**Accuracy in the Settings**

- **Geometry & BC**
  - Inaccuracies
  - More Fidelity

---

**AM**

- Epistemic uncertainties due to assumptions or simplifications of physical models and numerical errors.
- They can be reduced by resolving more scales of the flow - more physical models and by high order methods.

**AS**

- Epistemic uncertainties associated to the specification of the inputs, e.g. geometry, BC, etc. and simplification in the domain.
- Aleatory Uncertainties due to the variability present in the system, e.g. operating conditions, manufacturing tolerance, etc.
02

Role of CFD in the design of Gas Turbines

6 slides
Roles of CFD (i)

No: Number of simulations.

AM: Accuracy in the Physics.

AS: Accuracy in the settings - Fidelity

S: Speed of the simulation (elapsed time)
Roles of CFD (ii)

Use of CFD in Design:
- **1990**: 2d RANS calcs.
- **1995**: 3d single row RANS calcs.
- **2005**: 3D Steady Multistage (RANS) calcs.
- **2015**: 3D Multistage Unsteady (URANS) calcs.

Diagrams and models illustrating the use of CFD in design from 1990 to 2015.
Roles of CFD (ii)

Use of CFD in Design:
- **1990**: 2d RANS calcs.
- **1995**: 3d single row RANS calcs.
- **2005**: 3D Steady Multistage (RANS) calcs.
- **2015**: 3D Multistage Unsteady (URANS) calcs.

**Accuracy in the Physics**

**Fidelity in the Model**
UltraFan®

25% more efficient from 2025

World’s most powerful aerospace gearbox driven by our Advance3 core

Engineered for narrowbody and widebody aircraft

The Ultimate TurboFan
CFD Applications in Gas Turbines

Flow distortion effect on noise source

Fully Featured full annulus 4 stages URANs 2b Grid Nodes in 3840 CPUs

Fan-Intake Interaction at High Angle of Attack by B. Mohankumar & E. Gunn

URANS 3D HPT

Hydra-Precise coupled RANS of HPC Combustor HPT by R. Adousa LU

Wing-engine Interaction

Case 1: Small volume

Snapshot when full span rotating stall is developed

Simulation of surge in Compression by P. Ogier & M. Vendreli, IC

Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics
ETC13, April 8-12, 2018; Lausanne, Switzerland

OPEN ACCESS
Downloaded from www.euroturbo.eu
Benefit of increasing use of CFDs

"Historically the largest reduction in SFC for modern turbofan engines has come from improvements to component efficiencies and not from increased pressure ratios or turbine temperature."

2016 Emeritus Prof. Nicholas Cumpsty
Imperial College of London
Challenges in the design of Gas Turbines:

- **Accuracy**
- **Speed**

12 slides
Gas Turbines R&D Cycle

Time Constant ~ 15 years

~ O(£10^2 M)

R&T TRL0-6

Design

Validation

~ 10 years

~ 5 years

Open Access
Downloaded from www.euroturbo.eu
Market is demanding faster turnaround

Evolution of fuel burn in turbofans

- Trent 800
- Trent 500
- Trent 900
- Trent 1000
- Trent XWB
- Advance
- UltraFan™

Growing Market

R&D Turnaround

Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics
ETC13, April 8-12, 2018; Lausanne, Switzerland

OPEN ACCESS
Downloaded from www.euroturbo.eu
Sources of inaccuracies in CFDs

Accuracy in the settings (Fidelity)

- Geometry
- Boundary Conditions
- Numerical solution
- Physical Modelling

Accuracy in the Model (Physics & Maths)

Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics
ETC13, April 8-12, 2018; Lausanne, Switzerland

Downloaded from www.euroturbo.eu
Accuracy in the Settings-Fidelity

Geom. Fidelity

Real Geometry

Coupling

Multidisciplinary
UQ: Trusting CFDs

- Quantify & reduce epistemic uncertainties of RANS closures by enveloping models.
- Response surface models for aleatory uncertainties.

Geom. Fidelity

Facilitating fire-extinguishing certification tests by two-phase flow CFD as combination of Lagrangian droplets and Eulerian continuous phase by C. Young Rolls-Royce

Real Geometry

- Impact of manufacturing variability on performance. AIAA 2018 Wen Yao Lee et al.
- Robust Design in the face of Real geometric Variations. J. Kamenik et al. AIAA 2017
Reduce aleatory uncertainties due to BC by coupling

URANS of the LP system of a Modern Turbofan

By Yuri Frei, Rolls-Royce

Mach Number

0.3 0.5 0.75 1 1.2

0.4 0.5 0.6 0.7 0.8
Spectral/hp element method needs reduced number of DOFs for a given accuracy, leading to order of magnitude higher speed up ratios.
‘In 2000, we anticipated that the turbulence would be solved in aeronautics around 2080, but by now we are not confident of this for the 21st century, or even that it will ever happen’

P.R. Spalart 2016

‘The reliable prediction of turbulence can be critical for turbomachinery aerothermal design’

John Denton 2015
Eddy Resolving Simulations in Gas Turbines

- DNS investigation of the effect of non-equilibrium boundary layers on compressor by A. P. S. Wheeler GT2019-64855
- LES investigation of the transition on LP Turbines by A. Cassinelli et al. GT2019-91622
- URANS-SAS of a HPT
- Hybrid LES: DDES Turbulence & acoustic field
- LES of instrumented turbine vane J. Turbomach 141(5), 051013 (Mar 01, 2019) by B. N. Ubald UoC

Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics ETC13, April 8-12, 2018; Lausanne, Switzerland

OPEN ACCESS Downloaded from www.euroturbo.eu
Massive Multidisciplinary Design Space

My Model Has too Many Parameters
A Time Effective ‘Multi-fidelity’ Approach

O(10^2) ‘Low-Cost’ CFD Simulations

Design Variables ~ 10^5

Engine Parameters
The cost of Simplicity

✓ Aero Design \( t = O(10) \) weeks
✓ Low-cost CFD \( t = O(1) \) hour
✓ No of Low-cost CFDs \( n = O(10^4) \)
✓ Hi-Fi CFD \( t = O(1) \) weeks = \( O(10^2) \) h
✓ Aero Design by Hi-Fi CFD \( t = O(10^3) \) weeks

10³ times slower!

What are we doing to speed up the design?

- Fully Integrated and automatic design systems (Davinci).
- Most effective and accurate Low & Medium Fidelity Models.
- Exploiting emerging hardware capabilities, e.g. GPUs
- Nonlinear harmonic method (Ning and He, 1998)
- Space-time gradient method (Yi and He, 2015)
A Vision Approach to the future
8 slides
Projection of Computing Power by end of the next decade

2008 45 nm
2010 32 nm
2012 22 nm
2014 14 nm
2018 10 nm
...
5 nm
...
END

Quantum Computers – A game changer?

2D Viscous

3D Viscous

Single Row

3D Multistage

URANS

x10^5

3D Multistage

RANS

x10^5

HPC in Industry

Top1

year

Exaflop/s

Petaflop/s

Teraflop/s

1990 2000 2010 2020 2030 2040

Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics
ETC13, April 8-12, 2018; Lausanne, Switzerland

OPEN ACCESS
Downloaded from www.euroturbo.eu
Increase of computer power requested for reduction of CFD uncertainties.

$\times 10^7 - 10^8$

$\times 10^3 - 10^4$

TODAY

Virtual Testing

Geom. & BC

Num. & Turbulence
Improving Accuracy:

- Improving accuracy by very high fidelity, multidisciplinary simulations (RANS & URANS).
- Improving turbulence modelling by Eddy resolving simulations + machine learning.

Expanding Design Space:

- Dimension reduction strategies for innovation.
- Optimisation by many low-cost simulations (>10⁶)
- Data driven response surface metamodels based on Eddy resolving simulations.
1  Dimension Reduction
Designing with dimension reduction by active subspaces performance maps for visualization and optimisation of the design space of blades. P. Seshadri et al. GT2017-64528

2  Intelligent Design
Of turbomachinery by a Radial Basis Function (RBF) neural network trained a priori on a data base of designs. C.J. Clark GT2019-96637

3  Tackling Uncertainty
A regularized multivariate regression framework for spatial averaging uncertainty reduction. Engine patterns are identified by Machine learning. P. Seshadri 2019
Paradigm shift – Modelling vs. Speed

- Speed
  - Spalart-Allmaras: 1992
  - HPC in Industry
  - Turbulence Modelling
  - SST k-omega: 1994

Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics
ETC13, April 8-12, 2018; Lausanne, Switzerland

Downloaded from www.euroturbo.eu
Turbulence Modelling

Improving Model Uncertainties by fast Eddy resolving tools and algorithms that process a large amount of data to extract patterns for turbomachinery applications—Machine Learning.

Prof. Alexander M. Polyakov
Princeton University
Understanding the underline physics of Tb’s of data

Effect of gapping on compressor performance
by P. Przytarski & A. Wheeler 2019

Agile Eddy Resolving Simulations

<table>
<thead>
<tr>
<th>Case</th>
<th>DOF</th>
<th>Comp. time *</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>60M</td>
<td>2h</td>
</tr>
<tr>
<td>5</td>
<td>120M</td>
<td>5.5h</td>
</tr>
<tr>
<td>7</td>
<td>240M</td>
<td>21h</td>
</tr>
<tr>
<td>9</td>
<td>360M</td>
<td>60h</td>
</tr>
</tbody>
</table>

(*): Computing time for one chord-base flow-through time on 100 cores, based only on average timesteping

Proceedings of 13th European Conference on Turbomachinery Fluid dynamics & Thermodynamics
ETC13, April 8-12, 2018, Lausanne, Switzerland

Downloaded from www.euroturbo.eu
Role and Challenges of CFD

By Raul Vazquez
“With the advent and growing availability of large scale computing power and facilities and the maturation of cutting edge high order numerical methods, a new era of turbulence research is opening with the ability to resolve the necessary turbulent scales in-house for industrial relevant flow configurations. The use of eddy resolving simulations and machine learning in the industry, is opening exciting new avenues towards understanding and modelling turbulence and transition. It will change the Turbomachinery Research in the near future (vision 5) and it will leverage industrial virtual testing in mid and long term. These new capabilities will improve the prediction of the aerodynamic flow in gas turbines, reducing the amount of testing required to validate designs, thus saving money and improving efficiency”

Raul Vazquez 2019