

Impact of Vision 2030 on CFD Practices in Propulsion Industry

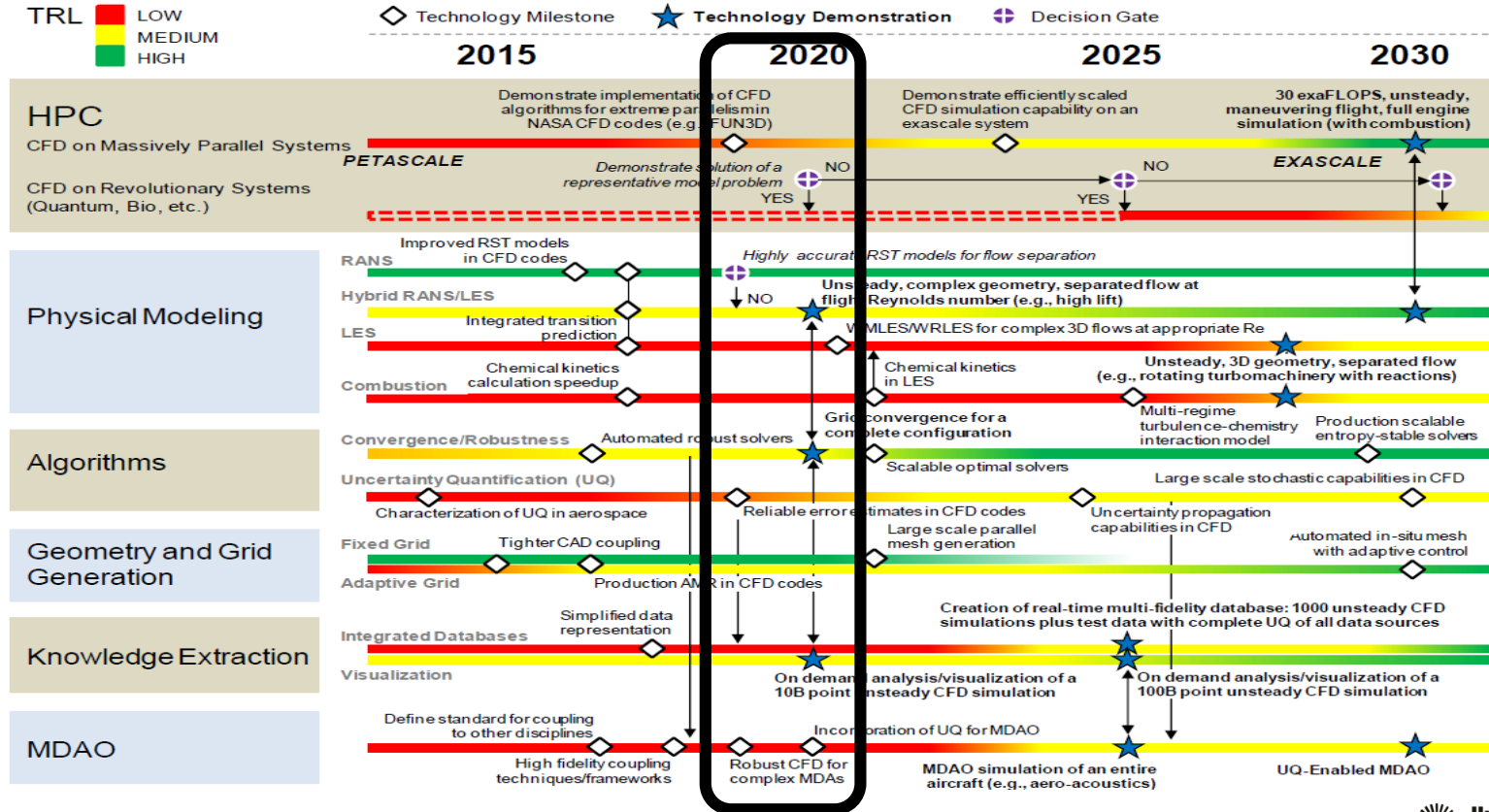
Gorazd Medic
United Technologies Research Center

AIAA Aviation Forum – CFD2030 Special Session
June 17, 2019, Dallas, TX, USA

Outline

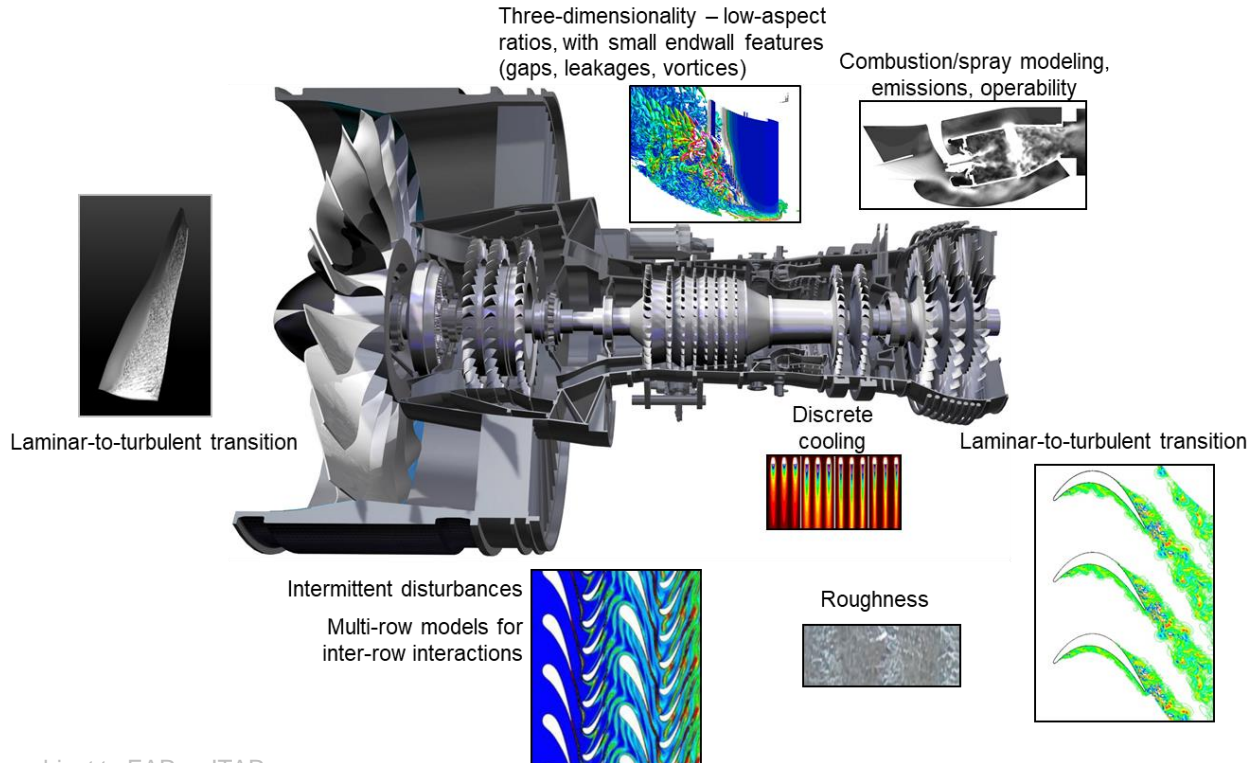
- CFD Vision 2030 Roadmap and Propulsion Industry
- 2019 Survey
- Examples of Recent Progress
 - ✓ Physical Modeling, Algorithms, MDAO, HPC
- Future Directions
 - ✓ Higher Fidelity, Certification by Analysis

CFD Vision 2030 Roadmap



Propulsion Industry – Jet Engines & Rocket Engines

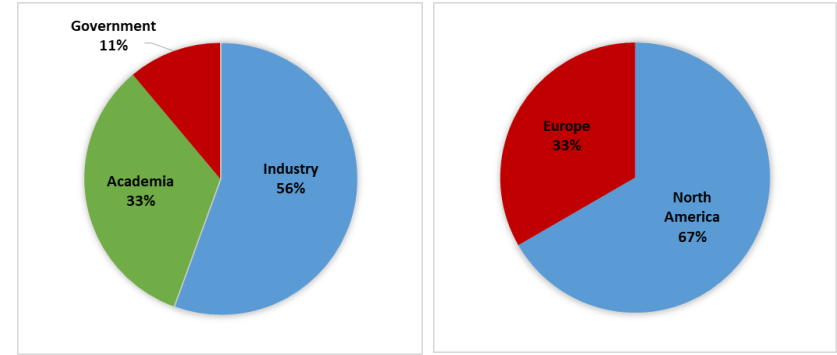
- Some complexities of applying CFD to jet engines ...



2019 Survey

- Informal survey to gauge technical progress since 2014
- Smaller, targeted community of CFD experts working in/with propulsion industry
- Questions:
 - ✓ Remaining technical challenges
 - ✓ Areas of improvement
 - ✓ Areas with no improvement / persistent impediments
 - ✓ Computing capabilities
 - ✓ Multi-physics / multi-disciplinary analyses
 - ✓ Impact of CFD Vision 2030 report

2019 Survey Participation



2019 Survey

(1) What remains the most challenging technical problem that you would like to solve using CFD, if you could devote sufficient resources (time, people, budget) to it and why?

- ✓ Aeromechanics (compression system, turbine, seals)
- ✓ Engine operability
- ✓ Better understanding of flow physics in high OPR/T3 engine cores, including hot section durability
- ✓ Turbine performance with real combustor outlet flows, details of cooling flows & cavities
- ✓ Combustion dynamics in jet engines and thermo/acoustic & flow instabilities in rocket engines
- ✓ Combustor emissions

2019 Survey

(2) What kinds of analyses are available to you today that were not available to you five years ago? What impact has the availability of these analyses had on product development, support, or certification?

(3) Since 2014, what new CFD process and/or tool improvement has been most useful for industrial flow analysis? Why? Please quantify as much as possible?

- ✓ Routine full-annulus URANS and RANS-based MDAO
- ✓ Hybrid RANS/LES and LES, even DNS for 2D profiles
- ✓ Lattice-Boltzmann solvers for complex geometries and acoustics
- ✓ Enabled new applications: propulsion/airframe integration analyses, aeromechanics/aeroacoustics, engine component coupling, ice accretion and performance degradation
- ✓ Some progress with harmonic balance methods for turbomachinery & adjoint solvers for 3D industrial cases, advances in HPC technologies and availability of more massively parallel computing capabilities

2019 Survey

(4) Where has there been little to no improvements? If you could make one CFD impediment go away, what would it be and why?

- ✓ Accuracy is still lacking – transition, laminar/turbulent separation, shock BL interaction, cooling flows, two-phase flows and combustion, complex heat exchangers
- ✓ Computing capacity in the industrial setting continues to be a limiting factor
- ✓ Complexity of multi-stage, multi-passage turbomachinery prohibits routine higher fidelity simulations and optimization

- ✓ Workflows: efficient geometry cleanup and robust high quality meshing (with mesh adaptation), including mesh generation for “as manufactured geometries”
- ✓ Capture realistic geometry features without reducing the accuracy of CFD methods/models near the walls; use of adequate boundary conditions

- ✓ Steep learning curve for new practitioners – need standards that facilitate interoperability

2019 Survey

(5) How much more computing power do you have today than you did in 2014 (stated in terms like “factor of 10”, etc.) and what has that increase in computing power afforded you (like able to run industrial cases 2x faster or able to generate a full database now, etc.)?

- ✓ 5 – 10X more resources
- ✓ Extra capacity split between reducing turnaround and adding fidelity (eddy simulation)
- ✓ New applications, such as mapping compressor stability margin, or analyzing more realistic engine component configurations
- ✓ Generation of databases of simulations for developments of ROMs, AI for model reduction
- ✓ Exploration of larger design spaces in RANS-based optimization

2019 Survey

(6) How much more are you using CFD analyses coupled with other disciplines now compared to 2014, and which multi-physics analyses are most commonly used by your organization?

- ✓ Noticeable increase in use of CFD for aeromechanics and aeroacoustics analyses
- ✓ Some increase in aero/thermal analyses (e.g. CHT); however, temperature prediction in hot section still a challenge
- ✓ Two-phase flow modeling becoming more routine

- ✓ Overall, accurate multi-component, multi-physics analyses still rare

2019 Survey

(7) Do you feel like the CFD Vision 2030 report has been effective in advancing technology development? If not, why not?

Positive impact:

- ✓ Focuses CFD community on ‘big objectives’/strategic areas
- ✓ Provides guidance for government funding of CFD development
- ✓ Helps with advocacy

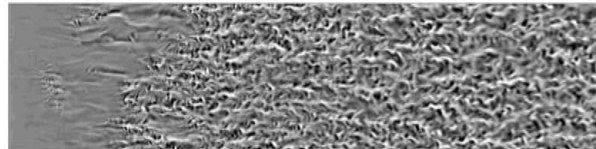
Concerns:

- ✓ What tools/technologies have been developed & transitioned to industry/public domain?
- ✓ Gaps in high quality validation data, in particular in propulsion industry
- ✓ CFD development in industry driven by needs, not vision, focused on short-term time horizons
- ✓ No visible change in terms of increased funding for fundamental research

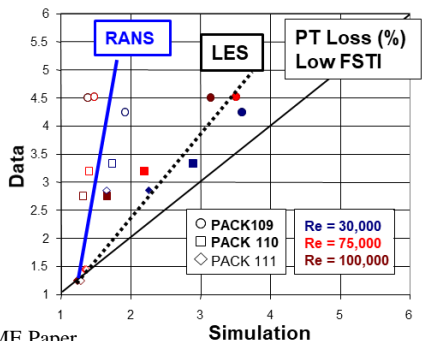
Recent Progress – Physical Modeling

- Eddy simulation – wall-resolved LES for laminar-to-turbulent transition

- ✓ Opportunity – relatively low Reynolds numbers in turbomachinery, apart from fan blades $Re_{\theta}^{TE} < 2,500$
- ✓ Multiple projects since 2010, from 2D profiles (50k core/hours) to 3D blades/vanes (5M core/hours), using in-house solver UTCFD
- ✓ Enables addition of realistic engine effects (e.g. combustor turbulence, wakes, distortion) to simplified configurations, complementing experiments

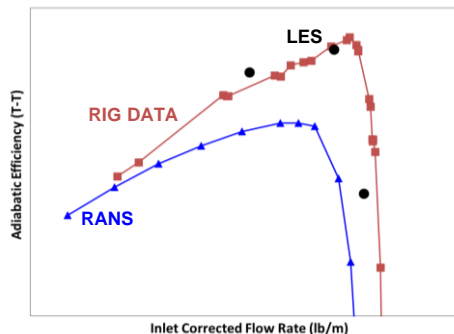


P&W low pressure turbine cascades



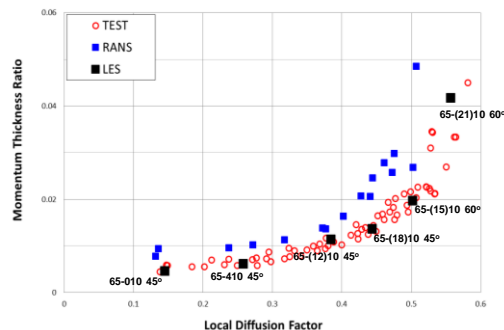
ASME Paper
GT2012-68878

P&W GTF fan blade



ETMM 2014
Marbella, Spain

NACA65 compressor cascades

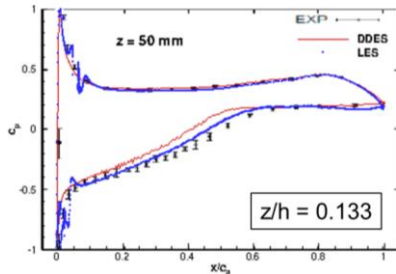
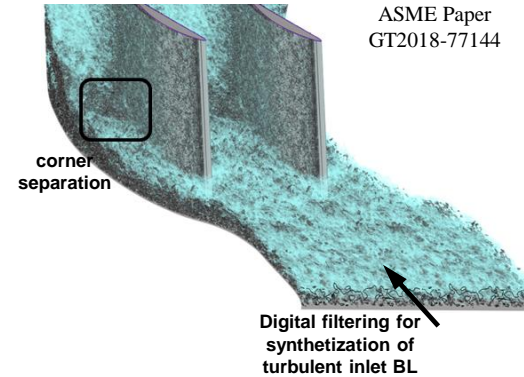


ASME J. Turbomach.
Dec 2016, Vol. 138

Recent Progress – Physical Modeling

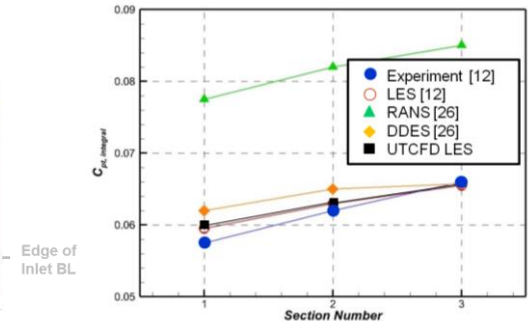
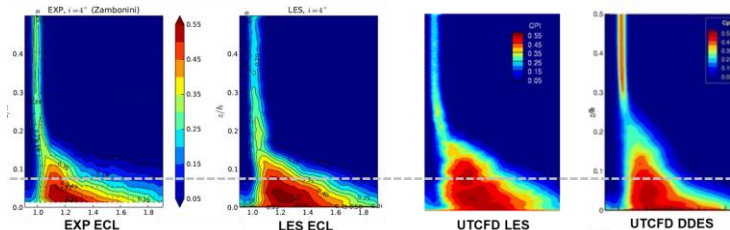
- Eddy simulation – hybrid RANS/LES for turbulent mixing & endwall features

- ✓ An example: corner separation in Ecole Centrale de Lyon compressor cascade
- ✓ Comparison of wall-resolved LES with turbulent turbulent BL vs DDES (100X difference in computational cost)
- ✓ DDES results remarkably good; some discrepancies – wakes too deep (unresolved), separation outside oncoming BL a bit larger, endwall BL thickness downstream of cascade smaller



Edge of the oncoming boundary layer is at $z/h=0.081$ (30 mm off the endwall).

Contours of total pressure loss at axial cross-section
Station 1 at $0.363 c_a$ downstream of trailing edge



Recent Progress – Physical Modeling

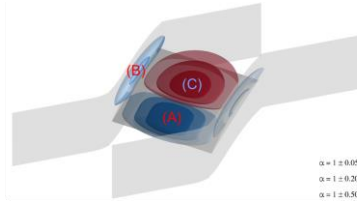
Machine Learning for RANS model enhancements

- ✓ Modify production term in ω equation to reduce the model error to measured C_p
- ✓ Inference – dimensionality reduction by using asymmetric 3D Gaussian kernels
- ✓ Random forest for machine learning

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \rho P - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[\left(\mu + \sigma_k \frac{\rho k}{\omega} \right) \frac{\partial k}{\partial x_j} \right], \quad \text{with } P = \tau_{ij} \frac{\partial u_i}{\partial x_j},$$

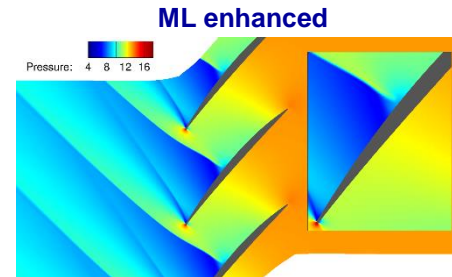
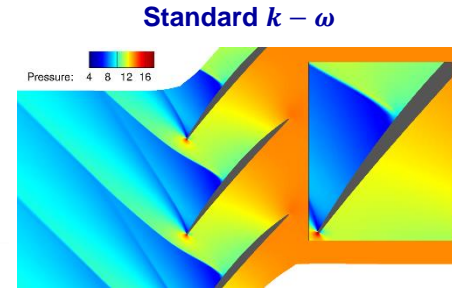
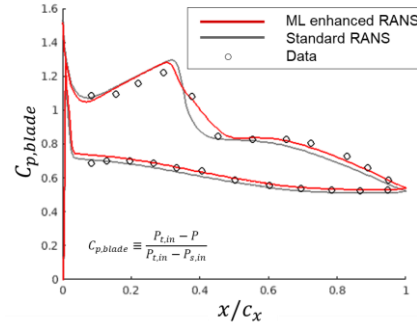
$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \alpha \frac{\gamma \omega}{k} P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[\left(\mu + \sigma_\omega \frac{\rho k}{\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + \frac{\rho \sigma_d}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}.$$

$$\tilde{\alpha} = f(\overline{\Omega^2}, \overline{\nabla \cdot u}, \overline{\frac{\partial \omega}{\partial x}}, \overline{\frac{\partial \omega}{\partial y}}, \overline{\frac{\partial \omega}{\partial z}}, \overline{\frac{\partial(p/\rho)}{\partial x}})$$



Areas for correction:

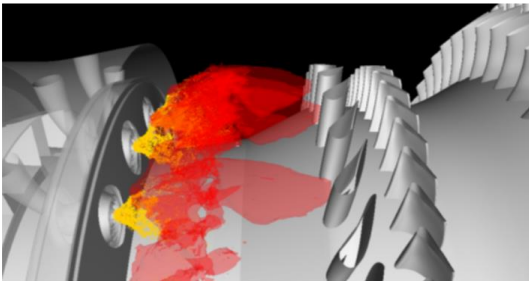
- Baseline over predicts turbulence
 - Laminar-to-turbulent transition (A)
- Endwall / corner flow (B)
- Baseline under predicts turbulence
 - Separated flow after the shock (C)



Recent Progress – Physical Modeling

Hot Section Durability – Combustor/Turbine Wall Heat Transfer Workshop

- ✓ Benchmarked the state-of-the-art in modeling, methods, and validation datasets
- ✓ Four technical areas identified: (1) near-wall modeling, (2) conjugate heat transfer, (3) environmental effects, (4) radiation and soot
- ✓ Follow-up session at IGTI meeting in Phoenix, AZ



80 Participants from 18 Organizations...



Stanford

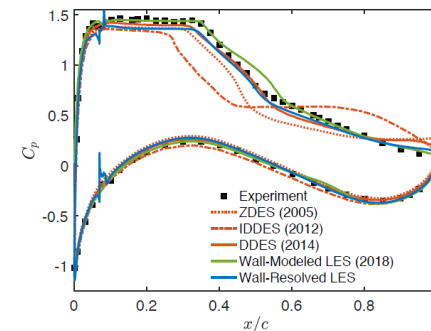
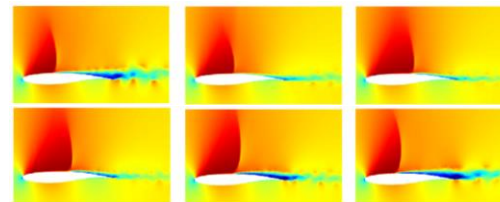


Recent Progress – Algorithms

■ High-order discontinuous Galerkin methods for wall-resolved LES

- ✓ Hybrid discontinuous Galerkin methods with BDF/DIRK temporal discretization
- ✓ Newton solver with pseudo-time, preconditioned restarted GMRES solver
- ✓ Programming language: C++ language with MPI parallelization and CUDA backend for GPUs; with external libraries: BLAS, LAPACK, CUBLAS
- ✓ Wall-resolved ILES, 4.5 million grid points, 100 chord time units with 1 million time steps using 32 NVIDIA V100 GPUs, for 720 hours

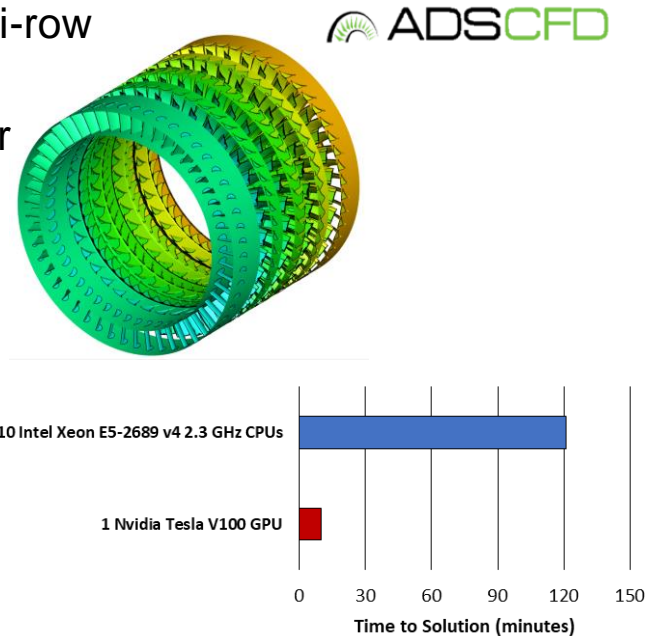
Supercritical wing OAT15A
 $Re = 3M$, $Ma = 0.73$, $AoA = 3.5^\circ$



N. C. Nguyen, S. Terrana, and J. Peraire, “Massively parallel discontinuous Galerkin methods for wall-resolved large eddy simulation of transonic aeroelasticity”, Aerospace Computational Design Laboratory, Department of Aeronautics and Astronautics, MIT, presented at P&W/UTRC, April, 2019.

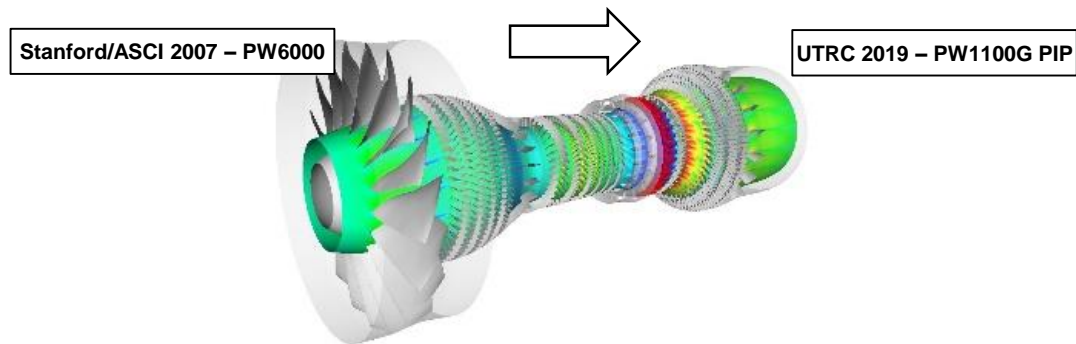
Recent Progress – HPC

- Application of GPUs for RANS in turbomachinery
 - ✓ Benchmarking LEO (from ADS) for a realistic multi-row P&W compressor configuration
 - ✓ Comparison of multi-block structured RANS solver on CPUs and GPUs
 - ✓ 15X reduction in turnaround time
 - ✓ Feasibility of computing 8-10 point speedline in one hour on a single GPU-enabled node
→ towards commodity CFD, digital thread



Recent Progress – MDAO

- Multi-physics component coupling – full engine simulations



- Need for higher fidelity remains:
 - ✓ Flow physics → LES everywhere?
 - ✓ Environmental effects
 - ✓ Multi-scale modeling (geometry, timescales)
 - ✓ Integration/coupling (aero/thermal, aero/structural)
 - ✓ Computational speed → HW accelerators (GPUs)?

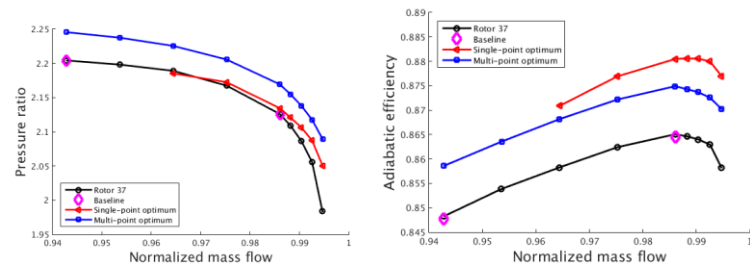
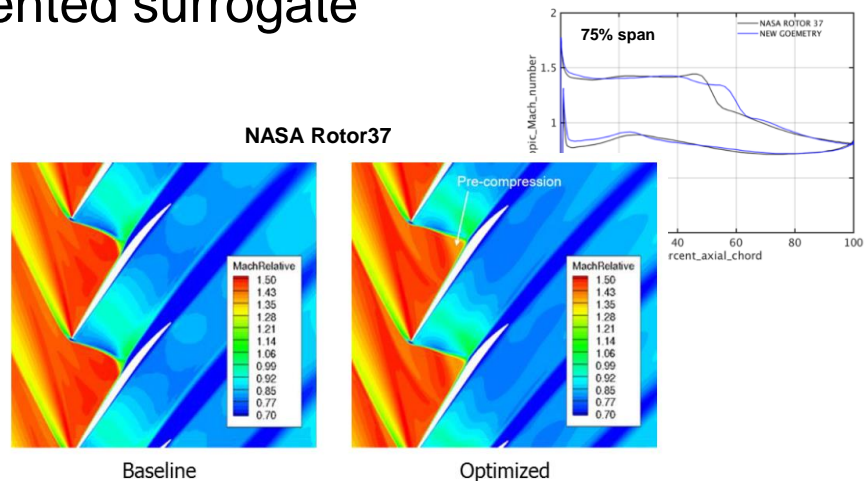
Recent Progress – MDAO

- Multi-fidelity Machine Learning augmented surrogate assisted optimization

- ✓ Scalable and structure-free surrogate model with dynamic training and tuning
- ✓ Adaptive evolution control for diversity, reduced design space sparsity and mitigated model uncertainty
- ✓ Multi-point, multi-disciplinary optimization
- ✓ Multi-fidelity –CFD of varying fidelity, meanline & streamline ROMs

Michael Joly, Soumalya Sarkar, and Dhagash Mehta, “Machine learning enabled adaptive optimization of transonic compressor rotor with precompression”, ASME Paper GT2018-77098.

Sudepta Mondal, Michael Joly, and Soumalya Sarkar, “Multi-fidelity global-local optimization of a transonic compressor rotor”, ASME Paper GT2019-91778.



Future Directions – Higher Fidelity

- Advancing engine technology increasingly difficult
 - ✓ New insights about the physics
 - ✓ More accurate predictions, faster, sooner in the design cycle
 - ✓ Aero/structural, aero/thermal trades

- Apply hybrid RANS/LES or WMLES at engine scale
 - ✓ Laminar-to-turbulent transition needs to be handled right
 - ✓ Computational cost? GPUization?

Future Directions – Certification by Analysis

- 2019 NASA NRA “Requirements for Certification by Analysis”



- Deliverables:

- ✓ Detailed requirements for certification using predictive computational methods
- ✓ Comprehensive research roadmap to develop computational technologies for fulfilling the requirements – to complement NASA Vision 2030

- Part 33 – Airworthiness Standards: Aircraft Engines

- ✓ Specific engine tests required by regulation:
fan blade containment, rotor stress, induction icing, sea level & altitude operability, water and hail storm ingestion, bird ingestion, initial maintenance inspection, endurance, engine overtemperature, smoke and emissions
- ✓ Computational/modeling challenges:
full engine simulations, aero/structural/thermal analyses, compressor & combustor operability, combustor emissions