AOE 4144: Applied CFD

A series of 12 lectures by Prof. Raj (course co-instructor)

Reflections on the Effectiveness of Applied Computational Aerodynamics for Aircraft Design

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Lecture 12

Topic 6: ACA Effectiveness – Status and Prospects (3 of 3)

Topic 7: Closing Remarks

List of Topics

DNS–*Seemingly The Only Option for Fully Effective ACA*

DNS can produce credible solutions <u>BUT</u> it will require incredible reductions in turnaround time and total cost for DNS to be fully effective in meeting aircraft design needs.

Both "A - Acceptance" and "Q - Quality" factors in $E = Q \times A$ need to be simultaneously maximized for Fully Effective ACA based on DNS

Since DNS is not expected to be feasible—even for a wing—until around 2080, <u>how could we improve ACA effectiveness in the interim</u>?

NASA CFD Vision 2030

Motivation

"…the last decade has seen stagnation in the capabilities used in aerodynamic simulation within the aerospace industry, with RANS methods having become the high fidelity method of choice…"

"…the <u>well-known limitations of RANS methods for separated flows have confined reliable use of CFD to a small region of the flight envelope</u> …"

A Clarion Call to the Community in 2014

NASA/CR–2014-218178

CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences

Jeffrey Slotnick and Abdollah Khodadoust
Boeing Research & Technology, Huntington Beach, California

Juan Alonso
Stanford University, Stanford, California

David Darmofal
Massachusetts Institute of Technology, Cambridge, Massachusetts

William Gropp
National Center for Supercomputing Applications, Urbana, Illinois

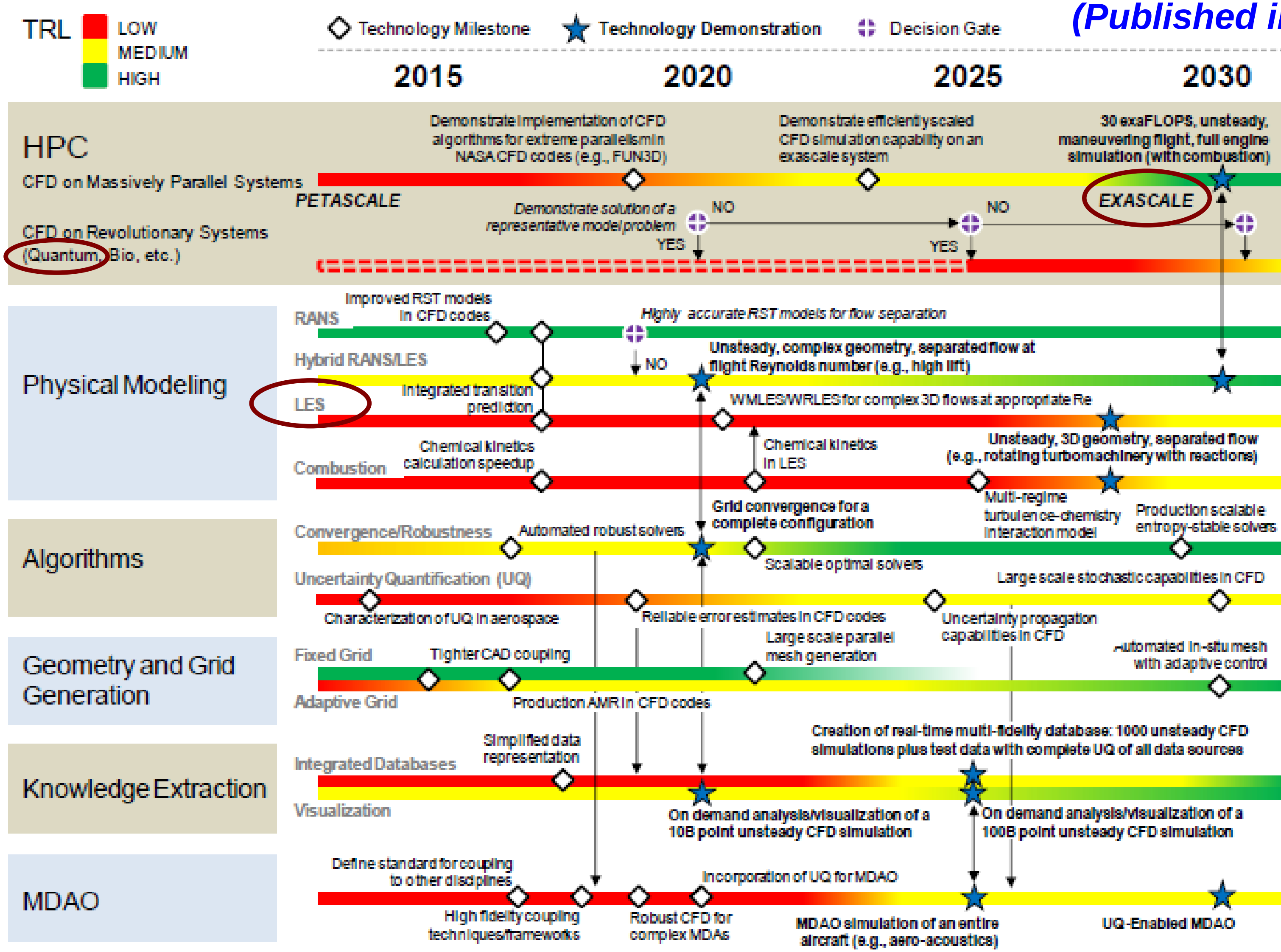
Elizabeth Lurie
Pratt & Whitney, United Technologies Corporation, East Hartford, Connecticut

Dimitri Mavriplis
University of Wyoming, Laramie, Wyoming

Source: Refs. 6.2.8

NASA CFD Vision 2030: *Roadmap*

(Published in 2014)



A Comprehensive Plan That Could Significantly Increase ACA Effectiveness by 2050(?)

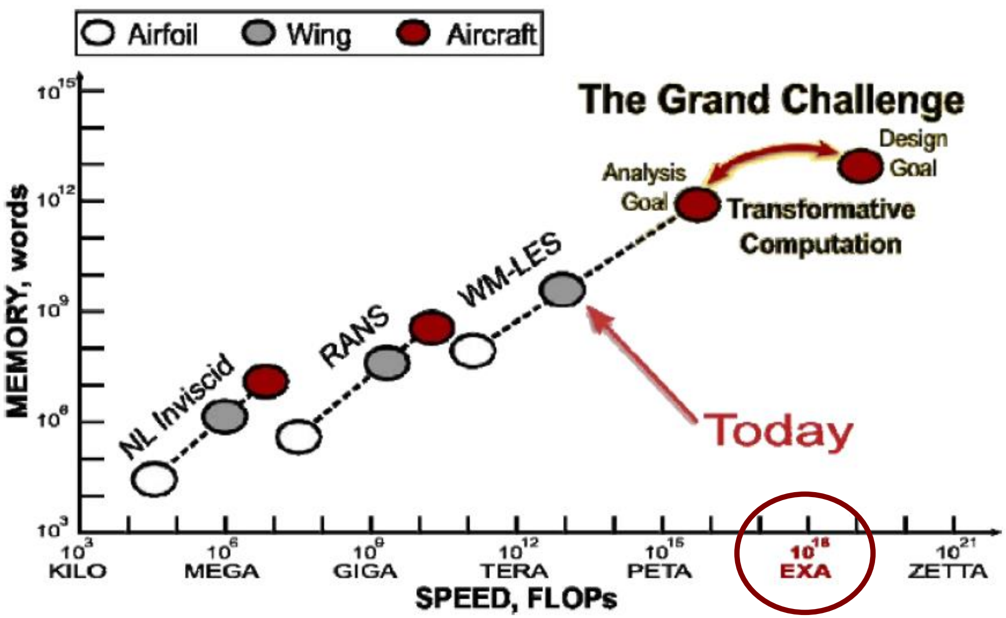
Source: Ref. 6.2.8

LES for Increased ACA Effectiveness

Pace of progress closely tied to advances in many key areas

- **Grids:** Methods for rapidly generating very fine, *truly* boundary-conforming grids
- **Models**: Advanced near-wall sub-grid-scale (SGS) models for WM-LES
- **Algorithms:** Higher-order numerical methods that minimize numerical dissipation
- **Software:** Development and implementation of effective strategies for designing computer software that exploits *emerging computer hardware architectures*
- **V&V and UQ:** Effective approaches for verification and validation of complex software, and for uncertainty quantification
- **Data Management:** Cost-effective approaches for efficiently managing large amounts of data, and for fast processing of extremely large datasets to extract information of value for ACA engineers
- **Etc., etc.**

Computer Requirements



A Midterm Strategy (2050+) At Best

Source: Ref. 6.2.6 & 6.2.7

ExaFLOPS Peak Speed is Within Reach

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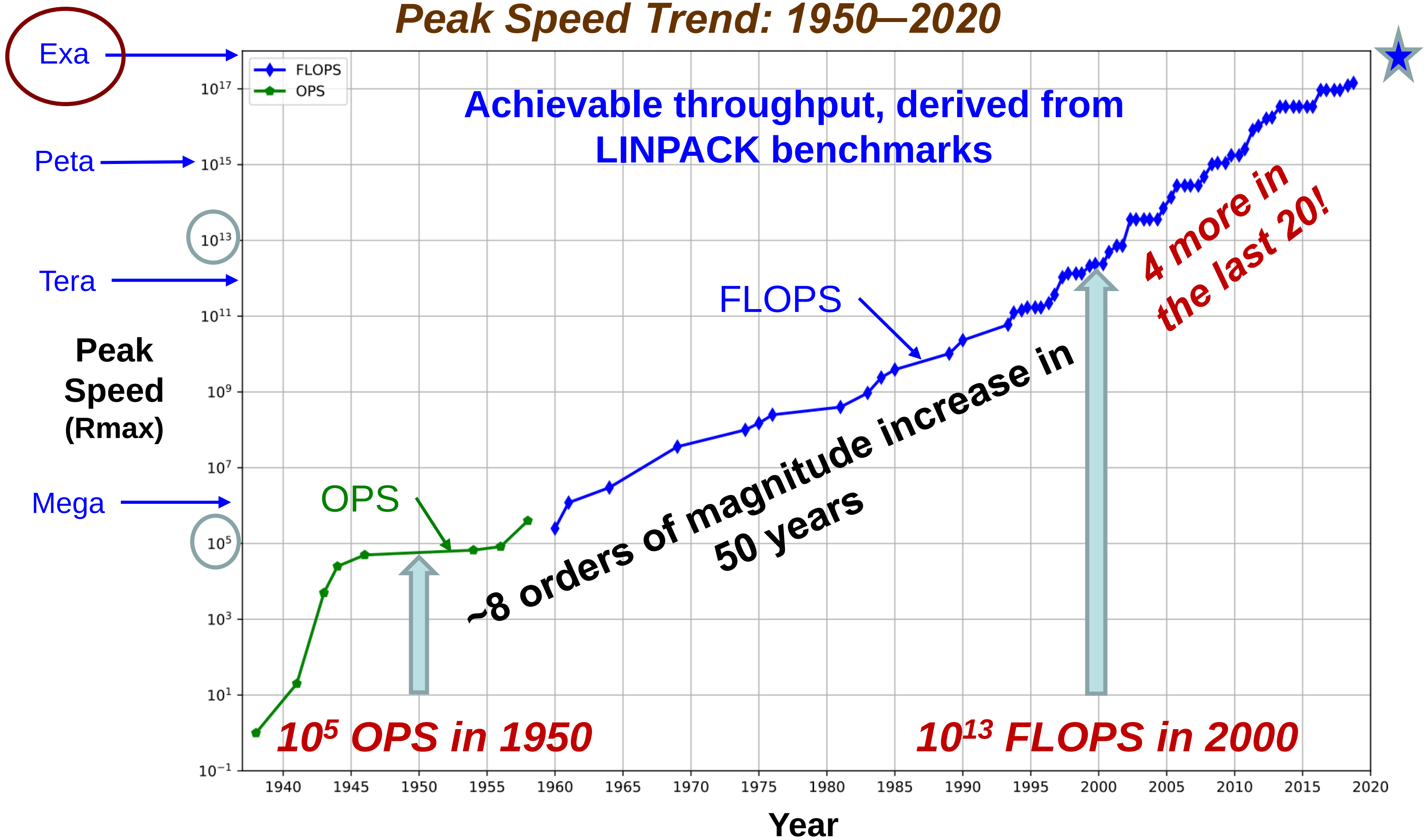
Peak Speed Trend: 1950—2020



BUT We Need Sustained Speeds at ExaFLOPS Level for Practical LES Applications

Source: https://en.wikipedia.org/wiki/Supercomputer

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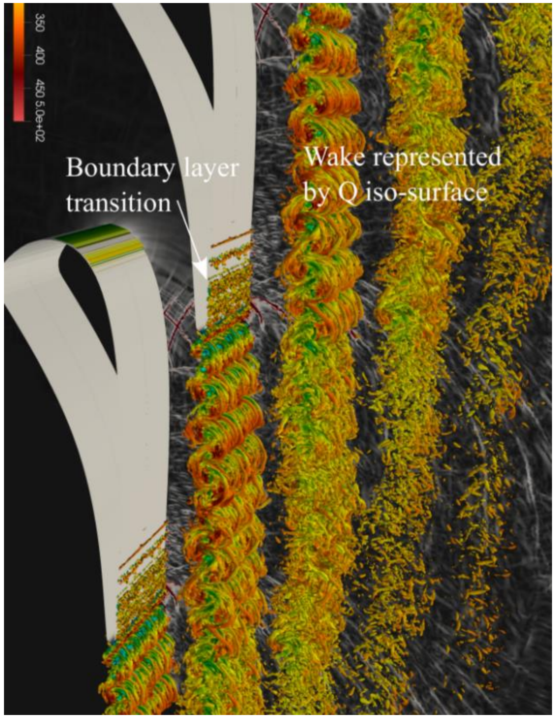
Virginia Tech

State of the Art of LES and DNS

(ca 2023)

Large Eddy Simulation (LES) of Turbomachinery Flow

Y. Fu, W. Shen, J. Cui, Y. Zheng, et al,
Towards Exascale Computation for Turbomachinery Flows,
SC'23, November 12-17, 2023, Denver, CO



Unstructured grid: 1.69 x 10^9 elements

High order solver: up to 8^{th} order

HPC cores: 19.2 million

HPC performance: 115.8 PetaFLOPS (DP)

Gordon Bell Prize nominee

Direct Numerical Simulation (DNS) of Full Aircraft

Unstructured grid: > 10^{20} elements

HPC cores: ???

HPC performance: ???

Evolutionary Path For DNS Faces Many Challenges

How Do We Get There ("Nirvana") From Here?

Quantum Computing (QC)

Offers A Ray of Hope!

- **Ongoing Revolutionary Research**
  - We can perform 2^N computations simultaneously on a quantum computer of N qubits (*qubits are quantum entities manipulated to act like computer bits*)
  - A grid of 2^N elements requires a quantum computer with N qubits

Demo Problem	CFD	Demonstration	HPC cores	QC qubits
Turbomachinery	LES	2023 (now)	19.2 million	30
Full Aircraft	DNS	??? (future)	???	57

- **Quantum-inspired, Hybrid Quantum-Classical, and Quantum Algorithms**
  - An order of magnitude faster and cost-effective simulations using quantum algorithms than classical algorithms on today's HPC have been demonstrated
  - Quantum algorithms running on simulation platform of HPCs and quantum computers could reduce time and cost by nearly three orders of magnitude!

Potential for DNS of Full Aircraft Using QC Much Sooner Than The 2080s!

Source: **Personal Communication, Abhishek Chopra, Founder & CEO, BQP (BosonQ Psi) (https://www.bqpsim.com)**

Conundrum for Today's Engineers

RANS is Here to Stay!

"…engineering calculations will have to be done by Reynolds-averaged methods for the foreseeable future…"

"…computer simulations of eddy motion can and will provide the detailed statistics—above all, the pressure fluctuation statistics—that cannot be adequately measured."

"…***we cannot calculate all flows of engineering interest to engineering accuracy. However, the best modern methods allow almost all flows to be calculated to higher accuracy than the best-informed guess***, which means that **the methods are genuinely useful** even if they cannot replace experiments."

Excerpts from TURBULENT SECONDARY FLOWS by Peter Bradshaw
Annual Review of Fluid Mechanics, Vol 19, 1987, pp 53-74

Author's Take: "Glass is half full"

Despite relatively low effectiveness for simulating complex flows, RANS methods can, and do, add value if used wisely

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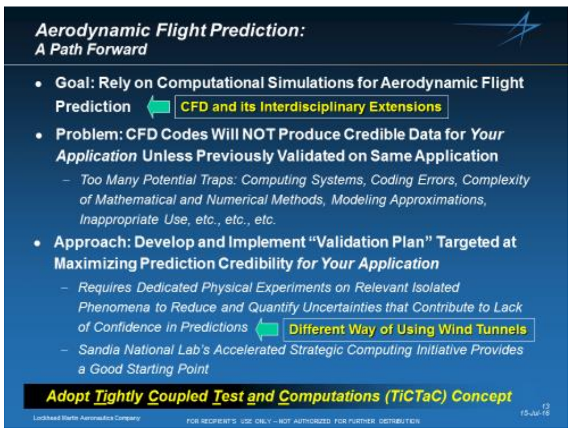
The TiCTaC Paradigm for Improving RANS-based ACA Effectiveness

Tightly Coupled Tests and Computations

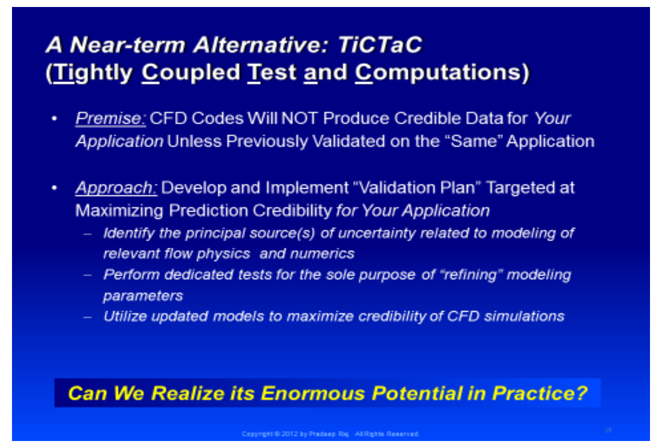
A Near Term "Stopgap" Strategy

Devise the best way of *judiciously* coupling wind tunnel testing (WTT) with RANS CFD to deliver credible aerodynamic solutions—rapidly and affordably

2002: First proposed (Raj)
NASA/DOD Workshop on Aerodynamic Flight Predictions, Williamsburg, VA, USA, Nov 19-21, 2002



2012: Revisited (Raj)
5th Symposium on Integrating CFD and Experiments in Aerodynamics, JAXA, Tokyo, Japan, Oct 3-5, 2012



2014 & 2016: An updated approach (Raj et al) *Applied Aero Conference, Bristol, UK*

- Develop and implement *TiCTaC*: leverage complementary strengths of CFD and EFD by exploiting ongoing technological advances in both WTT and CFD
  - ✓ WTT (*Additive Manufacturing, Rapid Prototype Testing, Measurement Techniques*)
  - ✓ CFD (*Grid Adaption, High Performance Computing, Uncertainty Quantification*)

Source: Refs. 6.2.9 thru 6.2.12

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Topic 6

6 ACA Effectiveness: Status and Prospects *(2000-20xx)*

6.2 Prospects for Fully Effective ACA (Beyond 2025)

6.2.1 Spalart, P., Reflections on RANS Modeling, June-August 2012. https://www.cespr.fsu.edu/people/myh/CFD-Conference/Session-4/Philippe-Spalart-Presentation.pdf

6.2.4 Carton de Wiart, C., and Hillewaert, K., "DNS and ILES of transitional flows around a SD7003 using a high order Discontinuous Galerkin Method," ICCFD7-2012-3604, Seventh International Conference on Computational Fluid Dynamics, Big Island, Hawaii, 9-13 July 2012. https://www.iccfd.org/iccfd7/assets/pdf/papers/ICCFD7-3604_paper.pdf

6.2.5 Uranga, A., Persson, P-O, Drela, M., and Peraire, J., "Implicit Large Eddy Simulation of Transitional Flows Over Airfoils and Wings," AIAA 2009-4131, 19th AIAA Computational Fluid Dynamics Conference, San Antonio, TX, 22-25 June 2009. https://doi.org/10.2514/6.2009-4131

6.2.6 Piomelli, U., "Large eddy simulation in 2030 and beyond," Philosophical Transactions of the Royal Society A, Volume 372, Issue 2022, 13 August 2014. https://doi.org/10.1098/rsta.2013.0320

6.2.7 Witherden, F.D., and Jameson, A., "Future Directions of Computational Fluid Dynamics," AIAA 2017-3791, 23rd Computational Fluid Dynamics Conference, AIAA AVIATION Forum, Denver, Colorado, 5-9 June 2017. https://arc.aiaa.org/doi/10.2514/6.2017-3791

6.2.8 Slotnick, J., Khodadoust, A., Alonso, J., Darmofal, D., Gropp, W., Lurie, E., and Mavriplis, D., "CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences," NASA/CR-2014-218178, March 2014. https://permanent.access.gpo.gov/gpo53497/20140003093.pdf

6.2.9 Raj, P., "Aerodynamic Flight Prediction: A Perspective," NASA/DoD Workshop on Aerodynamic Flight Prediction, Williamsburg, VA, 19-21 November 2002.

6.2.10 Raj, P., "CFD for Aerodynamic Flight Performance Prediction: From Irrational Exuberance to Sobering Reality (Invited)," 5th Symposium on Integrating CFD and Experiments in Aerodynamics, Tokyo, Japan, October 3-5, 2012.

6.2.11 Raj, P. and Friedman, A., "On timely and cost-effective prediction of aerodynamic data to meet aircraft design needs," Paper H.1, RAeS Applied Aerodynamics Conference, Bristol, UK, July 22-24, 2014.

6.2.12 Raj, P. and Choi, S., "TiCTaC: An Innovative Paradigm for Aerodynamic Data Generation to Meet Aircraft Conceptual Design Needs," Paper C.2, RAeS Applied Aerodynamics Conference, Bristol, UK, July 19-21, 2016.

List of Topics

Pursuit of Fully Effective Applied Computational Aerodynamics (ACA) Started Long Ago…

"Both for engineering and for many of the less exact sciences, such as biology, there is a demand for ***rapid methods, easy to be understood*** *and* ***applicable to unusual equations and irregular bodies****. If they can be* ***accurate****, so much the better; but* ***1 per cent, would suffice*** *for many purposes."* ***– Richardson, 1910***

"Prospective users…rarely interested in whether or not an accurate solution of an idealized problem can be obtained, but are concerned with ***how well the calculated flow agrees with the real flow****."* ***– Hess and Smith, 1967***

"The ***effectiveness*** *of computational aerodynamics* ***depends not only on the accuracy*** *of the codes* ***but*** *to a very large degree—perhaps more than is generally appreciated—****on their robustness, ease and economy of use****."* ***– Miranda, 1982***

…and Continues Today!

Source: Refs. 5.1.9, 5.2.1

ACA Effectiveness

Present Status (~2025)

RANS-based ACA is Unlikely to be Fully Effective Anytime Soon, If Ever!

Future Prospects (beyond 2025)

Long-term: DNS-based ACA May Lead to Fully Effective Capability in the 2080 Time Frame
Many Decades Hence—A Bridge Too Far?

Mid-term: LES-based ACA Offers a Promising Alternative in the 2050 Tiem Frame

Near-term: TiCTaC (Judicious Coupling of Wind Tunnel Testing and RANS CFD) Offers a "Stopgap" Option

Author's Advice for ACA Engineers

Use Effectiveness as a Guide to Wisely Choose CFD Codes for ACA Studies to Support Aircraft Design

1. Understand the Problem

- Develop a *comprehensive* understanding of the scope of customer needs (potential impact of solution, desired level of accuracy, type and amount of data, etc.) and constraints (cost and schedule)

2. Devise an Approach to Solving the Problem

- Examine all four levels of available CFD codes for solving the problem with effectiveness as the key measure of merit; "Know the Flow"
- Choose a code that can best meet customer's needs and constraints [consider the type, amount, and quality of the required aerodynamic data along with the specified constraints in choosing the code]

3. Execute to Generate and Deliver a *Best Solution* that Adds Value

- Provide a solution that *best* meets customer needs while satisfying all constraints

Don't Use a Hammer When You Need a Screwdriver!

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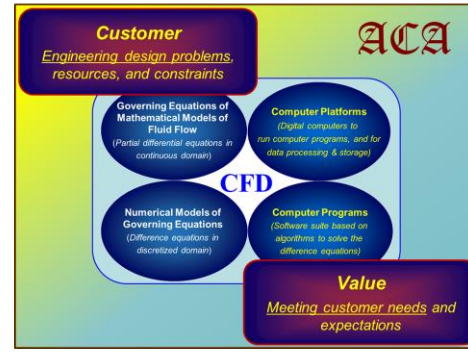
My Top 10 Takeaways

From my journey on a long and winding road

1. **ACA is an engineering discipline enabled by CFD**
   - *CFD is to ACA as airplane is to air transportation.*
   - *CFD produces data, à la EFD. ACA produces solutions*.

     Don't confuse data with solution!
   - ACA uses CFD to create **<u>value</u>** by delivering *credible solutions*, on time & on budget, to meet customer's pressing needs.

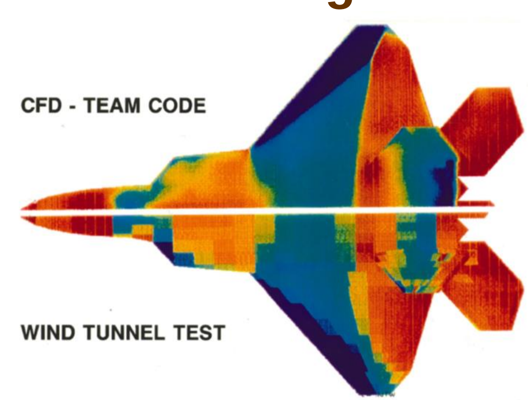


2. **EFD remains the best source of data for assessing CFD 'goodness'**
   - If CFD and EFD data don't match, ask why? If they do, *most definitely ask why*?

3. **Effectiveness is the best Measure of Merit for Assessing ACA**
   - Effectiveness = quality x acceptance***:*** $\boldsymbol{E = Q \times A}$
   - *ACA Effectiveness is ultimately assessed by design teams (who initiate the "Value Chain") in collaboration with ACA engineers—not by CFD code developers.*

4. **Predicting aerodynamic characteristics isn't that hard…making <u>credible</u> predictions is. *And it's <u>REALLY HARD</u>!***

5. **Converting basic research concept into an *effective* capability is a long and arduous process marked by *invention, initiative, and innovation…and lots of patience!****



*see a backup slide

My Top 10 Takeaways (contd.)

From my journey on a long and winding road

6. **Communication, Coordination & Collaboration across *all* stakeholders is essential to succeed in any endeavor.**

7. **Talent trumps tools, any day of the week!**
   - *It's the airplane, not the tools, stupid!*
   - *A talented engineer can do wonders even with poor tools. With proper tools, a talented engineer makes impossible possible!*
   - *What matters most to the customers is results, not tools.*
   - ***Use Your Talents!***

8. **Nothing—*absolutely nothing*—is worth compromising your integrity.**

9. **Your ability to learn, not just what you know, is a key differentiator.**

10. **Life is akin to an unsteady system with unsteady boundary conditions, *don't expect a steady solution.***
    - ***Don't underestimate the role of luck!***

Lewis, Michael, "Don't Eat Fortune's Cookie," Princeton University's 2012 Baccalaureate Remarks
https://www.princeton.edu/news/2012/06/03/princeton-universitys-2012-baccalaureate-remarks

Be Mindful of Four "Immutable" Laws and Principles!

Murphy's Law

"If anything can go wrong, it will."

Parkinson's Law

"Work expands so as to fill the time available for its completion."

The Peter Principle

"In a hierarchy, every employee tends to rise to his level of incompetence."

The Dilbert Principle

"Companies tend to systematically promote their least-competent employees to management (generally middle management) in order to limit the amount of damage they are capable of doing."

You will never be disappointed in your professional life!

"Look ahead where the horizons are absolutely unlimited"

Robert E. Gross

Entrepreneur, Industrialist

Founder, Lockheed Aircraft Corporation (now Lockheed Martin)

Enshrinee, The National Aviation Hall of Fame

11 May 1897 – 3 Sep 1961

VITA

Pradeep Raj is currently a collegiate professor emeritus in the Kevin T. Crofton Department of Aerospace and Ocean Engineering at Virginia Tech in Blacksburg, Virginia, USA. Since 2012 through 2024, his primary responsibilities at VT included (a) teaching the AOE undergraduate Capstone Aircraft Design courses, and (b) pursuing collaborative research in multidisciplinary analysis, design, and optimization (MADO) tools and processes, with emphasis on applied aerodynamics, to enable simulation based design of affordable flight vehicles.

Raj joined VT in 2012 after a 32-year career with Lockheed Martin. Starting out in 1979 as a Senior Aerodynamics Engineer at the Lockheed-California Company in Burbank, he assumed positions of increasing responsibility before retiring in 2011 as a Director from Advanced Development Programs, Palmdale, California, commonly known as the Skunk Works® and widely recognized for creating breakthrough technologies and landmark aircraft. For the first 20 years, including 8 as Technical Fellow (1991-1999), Pradeep was instrumental in enhancing the effectiveness of applied computational aerodynamics for aircraft design through several research, development, and application campaigns.

Prior to joining LM, Raj spent one year (1978-79) as an assistant professor at the University of Missouri-Rolla (now Missouri Science & Technology University), and two years (1976-78) as a research assistant professor at the Iowa State University, Ames, Iowa. Pradeep earned his Ph.D. in Aerospace Engineering from Georgia Tech in 1976. Before going to GT, he earned a Master of Engineering (with Distinction) in Aeronautical Engineering in 1972, and a Bachelor of Engineering (with Distinction) in Electrical Technology in 1970, both from the Indian Institute of Science, Bangalore, India. He received a Bachelor of Science (with Honors) from Meerut University in 1967.

Pradeep Raj is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA), of the Royal Aeronautical Society (RAeS), and of the Institute for the Advancement of Engineering (IAE).

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