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

Pradeep Raj, Ph.D.
Collegiate Professor Emeritus
Kevin T. Crofton Department of Aerospace and Ocean Engineering
Virginia Tech, Blacksburg, Virginia, USA
http://www.aoe.vt.edu/people/emeritus/raj.html

Program Management Director, Lockheed Martin (Retired)
Deputy Director, Technology Development & Integration
The Skunk Works®, Palmdale, California, USA

Advanced Development Programs

LOCKHEED MARTIN

Lecture 11

Topic 6: ACA Effectiveness – Status and Prospects (2 of 3)

List of Topics

No Shortage of Turbulence Models for RANS Equations!

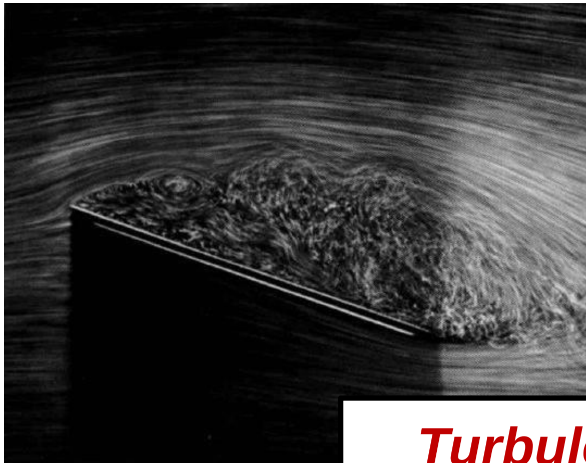
- **Zero-equation models**
  - Cebeci-Smith (1967) and Baldwin-Lomax (1978): *two layer, algebraic*
- **Half-equation models**
  - Johnson-King (1985): *ODE to specify shear stress level*
- **One-equation models**
  - Baldwin-Barth (1990) and Spalart-Allmaras (1992): *turbulent kinetic energy*
- **Two-equation models**
  - Jones-Launder (1972): k-ε (*turbulent kinetic energy and turbulent dissipation)*
  - Wilcox (1988): k-ω; Smith (1990): k-$k\ell$; Menter (1993): SST* k-ω
- **Explicit Algebraic Reynolds Stress Models (EARSM or ASM)**
  - Gatzki-Speziale (1993); Girimaji (1996)
- **Reynolds Stress Transport Models (RSTM or RSM)**
  - Speziale-Sarkar-Gatski (1991)

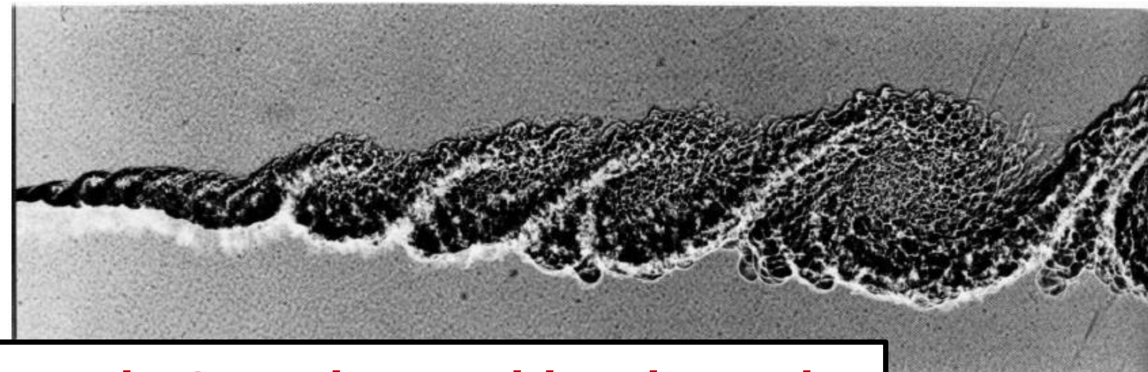
> ***"…no model is universal, giving good results for all flows of interest."***
>
> ***Peter Bradshaw, FRS, Imperial College & Stanford, 1999***

*Shear Stress Transport

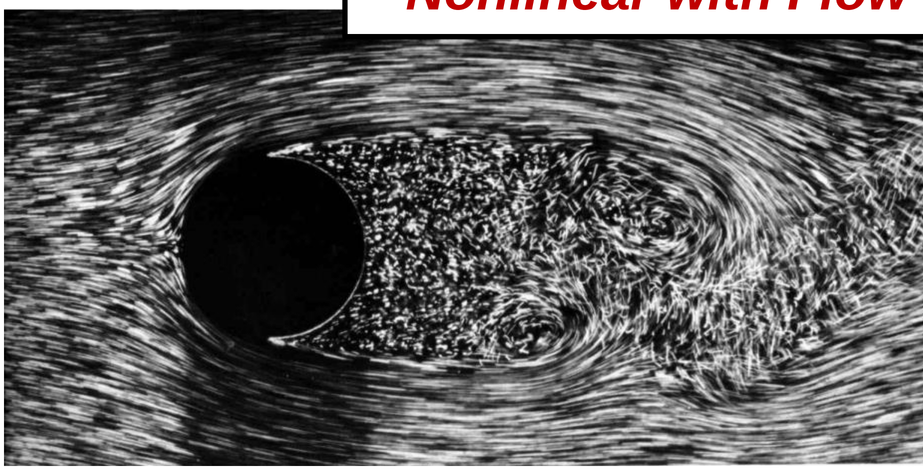
Source: Ref. 6.1.12

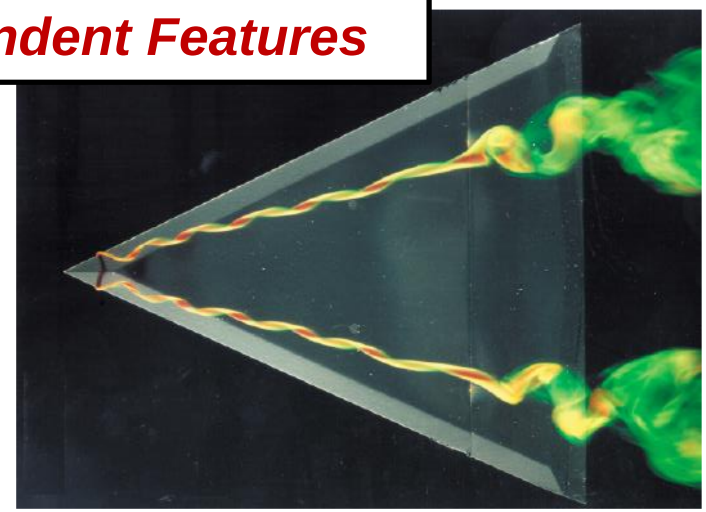
Why Don't We Have a Universal Turbulence Model?





Turbulence is Complex, Multiscale, and Nonlinear with Flow-dependent Features



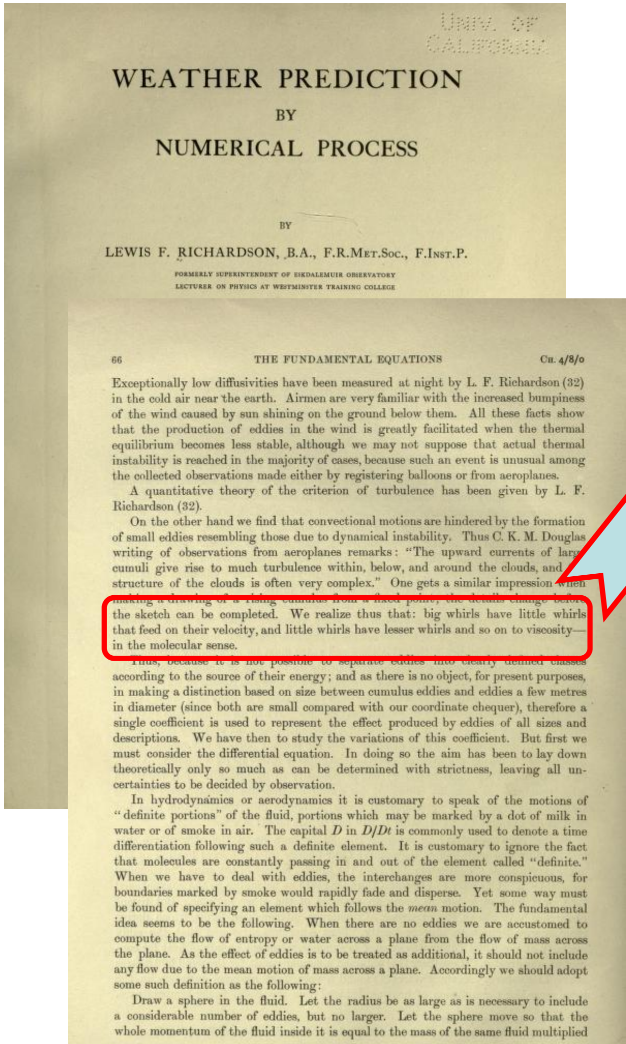


Accurate Modeling of <u>Complex, Multiscale, Nonlinear</u> Phenomena with a Few Free Parameters is an <u>Extremely Long Shot Indeed</u>

Source: Ref 6.1.14

COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

Fundamental Nature of Turbulence



UNIV. OF CALIFORNIA

WEATHER PREDICTION BY NUMERICAL PROCESS

BY

LEWIS F. RICHARDSON, B.A., F.R.MET.SOC., F.INST.P.

FORMERLY SUPERINTENDENT OF ESKDALEMUIR OBSERVATORY
LECTURER ON PHYSICS AT WESTMINSTER TRAINING COLLEGE

66 THE FUNDAMENTAL EQUATIONS CH. 4/8/0

Exceptionally low diffusivities have been measured at night by L. F. Richardson (32) in the cold air near the earth. Airmen are very familiar with the increased bumpiness of the wind caused by sun shining on the ground below them. All these facts show that the production of eddies in the wind is greatly facilitated when the thermal equilibrium becomes less stable, although we may not suppose that actual thermal instability is reached in the majority of cases, because such an event is unusual among the collected observations made either by registering balloons or from aeroplanes.

A quantitative theory of the criterion of turbulence has been given by L. F. Richardson (32).

On the other hand we find that convectional motions are hindered by the formation of small eddies resembling those due to dynamical instability. Thus C. K. M. Douglas writing of observations from aeroplanes remarks: "The upward currents of large cumuli give rise to much turbulence within, below, and around the clouds, and the structure of the clouds is often very complex." One gets a similar impression when making a drawing of a rising cumulus from a fixed point; the details change before the sketch can be completed. We realize thus that: big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity—in the molecular sense.

Thus, because it is not possible to separate eddies into clearly defined classes according to the source of their energy; and as there is no object, for present purposes, in making a distinction based on size between cumulus eddies and eddies a few metres in diameter (since both are small compared with our coordinate chequer), therefore a single coefficient is used to represent the effect produced by eddies of all sizes and descriptions. We have then to study the variations of this coefficient. But first we must consider the differential equation. In doing so the aim has been to lay down theoretically only so much as can be determined with strictness, leaving all uncertainties to be decided by observation.

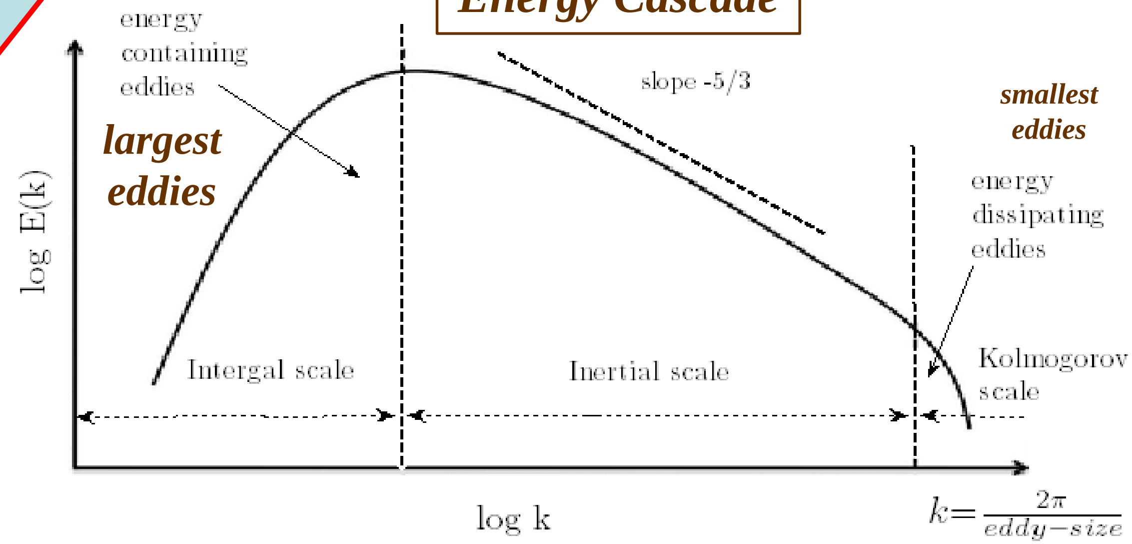
In hydrodynamics or aerodynamics it is customary to speak of the motions of "definite portions" of the fluid, portions which may be marked by a dot of milk in water or of smoke in air. The capital D in D/Dt is commonly used to denote a time differentiation following such a definite element. It is customary to ignore the fact that molecules are constantly passing in and out of the element called "definite." When we have to deal with eddies, the interchanges are more conspicuous, for boundaries marked by smoke would rapidly fade and disperse. Yet some way must be found of specifying an element which follows the *mean* motion. The fundamental idea seems to be the following. When there are no eddies we are accustomed to compute the flow of entropy or water across a plane from the flow of mass across the plane. As the effect of eddies is to be treated as additional, it should not include any flow due to the mean motion of mass across a plane. Accordingly we should adopt some such definition as the following:

Draw a sphere in the fluid. Let the radius be as large as is necessary to include a considerable number of eddies, but no larger. Let the sphere move so that the whole momentum of the fluid inside it is equal to the mass of the same fluid multiplied

"big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity"

Lewis F. Richardson, 1922

Energy Cascade



Multiscale in Space and Time!

Ratio of the Largest to Smallest Length Scale in Turbulent Flows is ~ $Re^{3/4}$ (Re based on the largest eddy)

Source: Ref. 6.1.15 and 6.1.16

How Complex is Turbulence?

"I am an old man now, and when I die and go to Heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am really rather optimistic."

Sir Horace Lamb
Address to British Association for the Advancement of Science
London, U.K., 1932

27 Nov 1849 – 4 Dec 1934

Turbulence Has Been the Bane of Fluid Dynamicist's Existence—Seemingly Forever!

Leonardo da Vinci, Flow behind obstacle, **ca. 1510 – 1513**, (from Royal Collection Trust, London, UK)

Source: Ref. 4.6

COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF
AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

What's the Dominant Contributor to Error in RANS Solutions?

Is it the Mesh, the Solver, or the Turbulence Model?

Ollivier-Gooch, *AIAA 2019-1334*

Interesting Findings from ["Crude"] Statistical Analysis

- ***Approach:*** 39 datasets from Third High-Lift Prediction Workshop (2017) and 31 datasets from Fifth Drag Prediction Workshop (2016) matched into groups based on three primary variables: mesh, flow solver, and turbulence model.
- ***"Crude" statistical analysis*** due to sparse amount of data in each group.
- ***Qualitative Conclusions***
  - **Mesh and turbulence model appear to have about equally large impacts on outputs**.
    - ✓ Results of different mesh sets with the same flow solver and turbulence model differed about as much as the average results for the three groups varied from each other!
  - Even with relatively fine meshes used, there are still **flow features resolved by some meshes and not others.**
  - **Flow solver is at least as big a difference as other factors.**
    - ✓ Community needs to do a better job of *verification* of numerical model and turbulence model implementations.
  - **User selected input parameters can cause significant variation in output values**.
    - ✓ Improved user training can help.

Source: Ref. 6.1.17

RANS-Based ACA Effectiveness: *Author's Summary Assessment*

With Advances in High Performance Computing (HPC) and Numerical Modeling, Effectiveness of RANS-based ACA Will Steadily Increase, But RANS Will Not Produce Credible Data Due to Turbulence [and Transition] Modeling Inadequacies.

RANS-based ACA is Unlikely to be Fully Effective for All Types of Flows Anytime Soon, If Ever!

"It is the mark of an educated man to look for precision in each class of things just so far as the nature of the subject admits." – Aristotle

Source: Internet for image and quote

RANS-Based ACA Effectiveness: *An Expert's Assessment*

"…the state of aeronautical CFD makes difficult to evade the conclusion that a decisive improvement in turbulence accuracy must be achieved before CFD becomes general."

"…the author [Spalart] deems it unlikely that a RANS model, even complex and costly [RSTM], will provide the accuracy needed in the variety of separated and vortical flows we need to predict."

Philippe R. Spalart

Senior Technical Fellow
Boeing Commercial Airplanes

"…it is more than plausible that Reynolds averaging suppresses too much information, and that the only recourse is to renounce it to some extent, which means calculating at least the largest eddies simply for their nonlinear interaction with the mean flow."

Source: Ref. 6.1.18

So What Are the Prospects for Fully Effective ACA?

COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

Topics

Future Prospects of Fully Effective ACA

If RANS cannot provide credible solutions, what are the other options that could possibly be used to computationally simulate turbulent flows?

Typical Commercial Transport Aircraft Wing

AR = 12, Re_x = 50 million

	RANS (Reynolds-Averaged Navier-Stokes)	DES (Detached Eddy Simulation)	LES (Large Eddy Simulation)	DNS (Direct Numerical Simulation)
Level of Empiricism	**High**	**Medium**	**Low**	**None**
Unsteady Flows	**No**	**Yes**	**Yes**	**Yes**
# of Grid Points	**10^7**	**10^7 to 10^8**	**10^{11}**	**10^{20}**
Feasibility Demonstration	**1995**	**2010**	**2045***	**2080***

*Estimated feasibility demonstration time frame assuming Moore's Law will still hold!

Note: Dense grids also need extra time steps—hence *much more computational time*!

DNS, With No Empiricism, Is the Only Option for Fully Effective ACA

DNS and LES Grid Requirements

- **DNS**: Grids must be fine enough to accurately resolve small-scale eddies

  DNS computational domain for flat plate turbulent boundary layer $L_x \times \delta \times L_z$

  # of grid points: $N_{DNS} = 0.000153 \frac{L_z}{L_x} Re_{L_x}^{37/14} \left[1 - \left(\frac{Re_{x_0}}{Re_{L_x}} \right)^{23/14} \right]$

  x_0 is streamwise location beyond which flow is turbulent

- **WR-LES** (Wall Resolved LES): small-scale eddies near the wall accounted for by inherent numerical dissipation [aka implicit LES or ILES]
- **WM-LES** (Wall Modeled LES): small scale eddies near the wall modeled using sub-grid-scale (SGS) models

Airfoil: *LES computational domain for turbulent boundary layer, no separation*

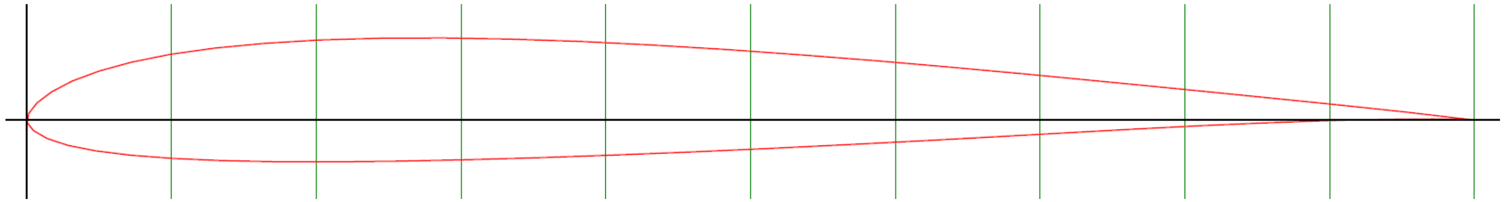
Aspect Ratio 4, $Re_{x0} = 5 \times 10^5$

Re_c	N_{wm}	N_{wr}
10^6	3.63×10^7	5.23×10^7
10^7	8.20×10^8	7.76×10^9
10^8	9.09×10^9	5.98×10^{11}
10^9	9.26×10^{10}	4.34×10^{13}

Haecheon Choi and Parviz Moin, *"Grid-point requirements for large eddy simulation: Chapman's estimates revisited" Physics of Fluid*, 24, Jan 2012

DNS and LES of Flow Past an Airfoil: *An Example*

Selig/Donovan SD7003 Low Reynolds Number Airfoil



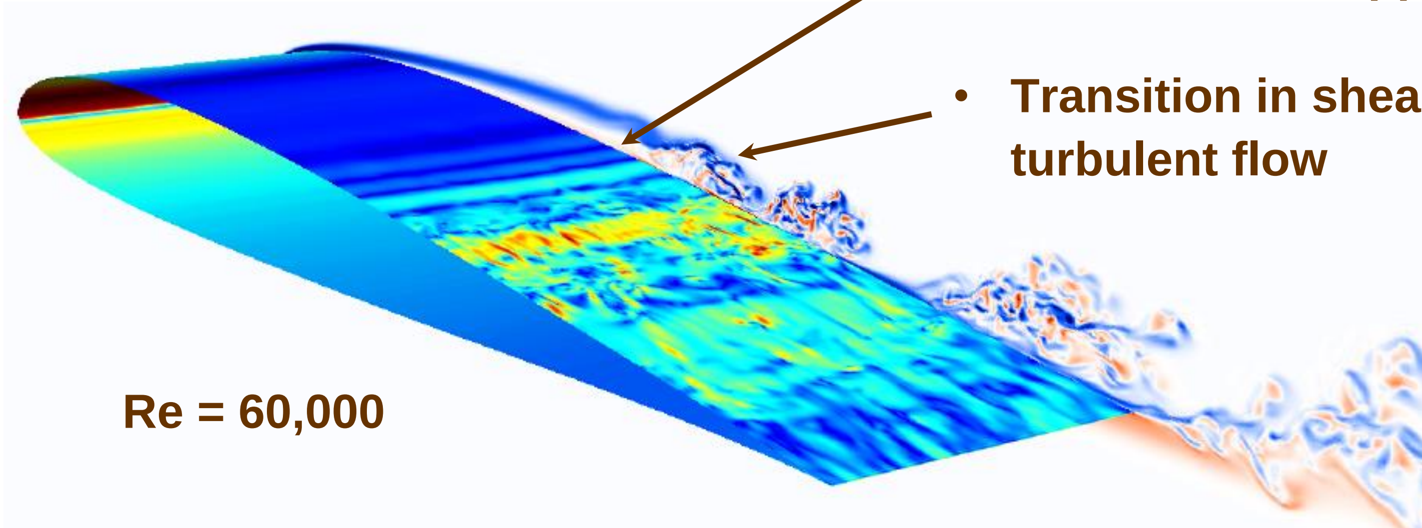
Max thickness 8.5% at 24.4% chord   Max camber 1.2% at 38.3% chord

Source: UIUC Airfoil Coordinates Database

Typical Flow Features Exhibited in Experiments and Computations

M = 0.1 α = 4°

- **Fairly stable laminar separation bubble on the upper surface**
- **Transition in shear layer leads to turbulent flow**

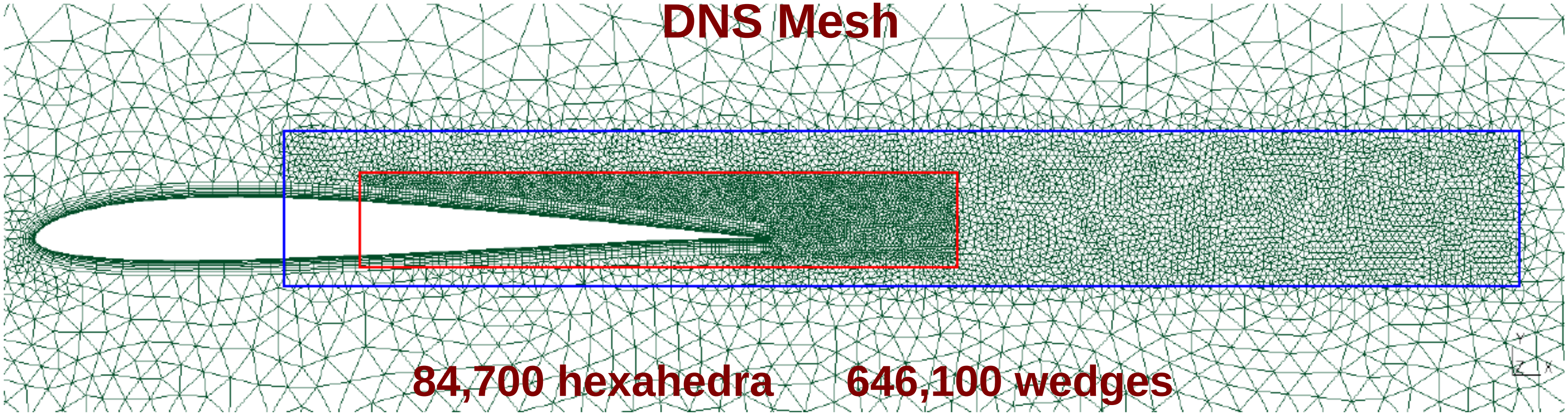


Source: Ref. 6.2.4

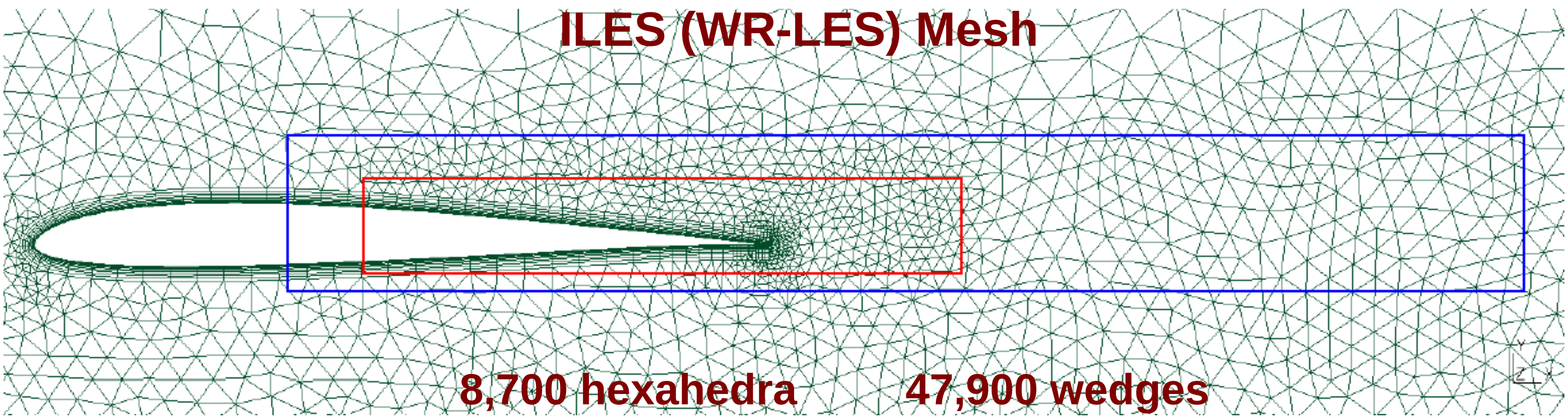
DNS and LES of Flow Past an Airfoil

SD7003 Low Reynolds Number Airfoil **M = 0.1, α = 4°, Re = 60,000**

AR = 0.2 **Far-field boundary at 100 chords**



DNS requires much finer grids than LES!



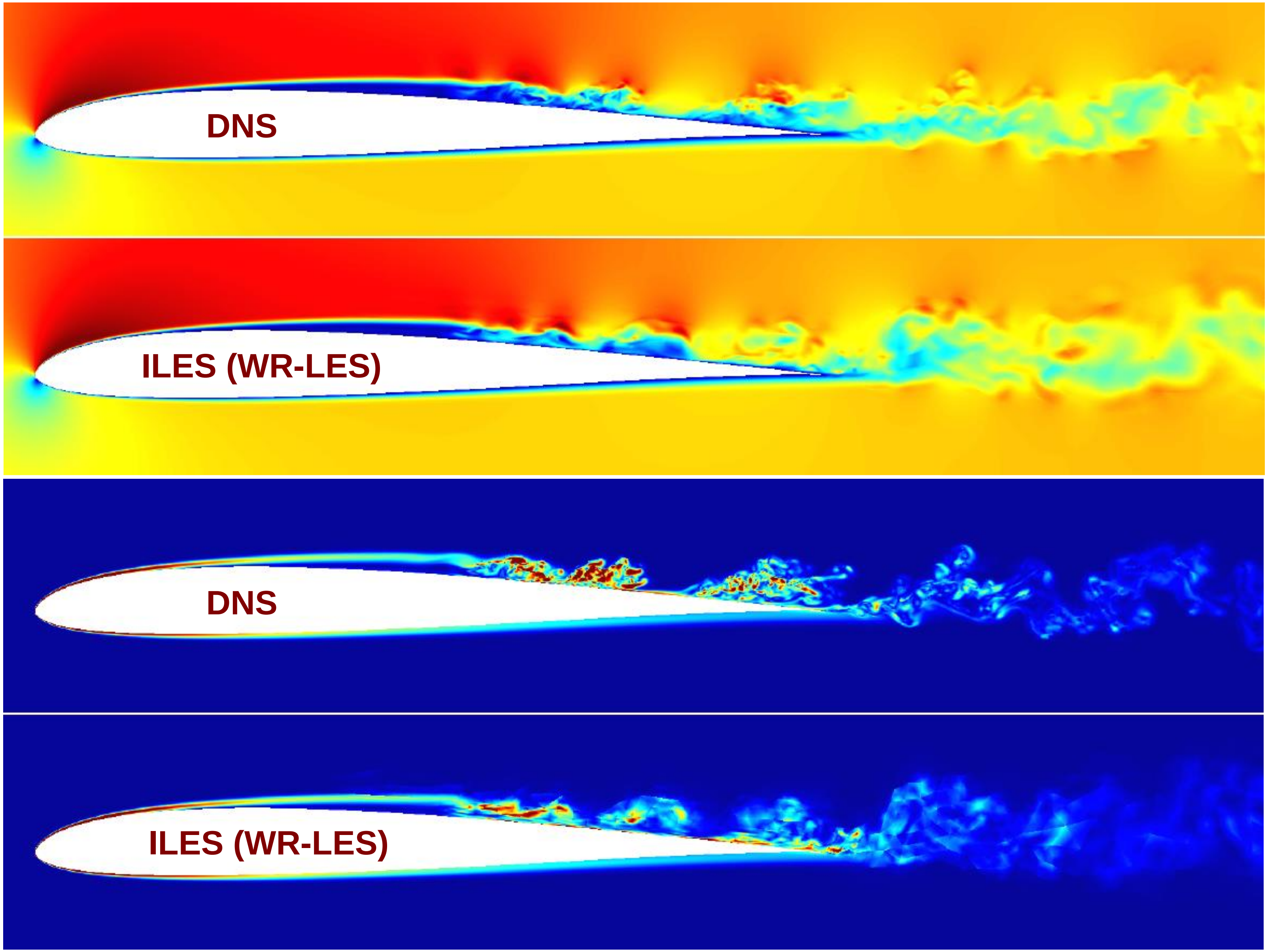
Source: Ref. 6.2.4

DNS and LES of Flow Past an Airfoil

SD7003 Low Reynolds Number Airfoil M = 0.1, α = 4°, Re = 60,000

Snapshot of **Velocity** norm

Snapshot of **Vorticity** norm

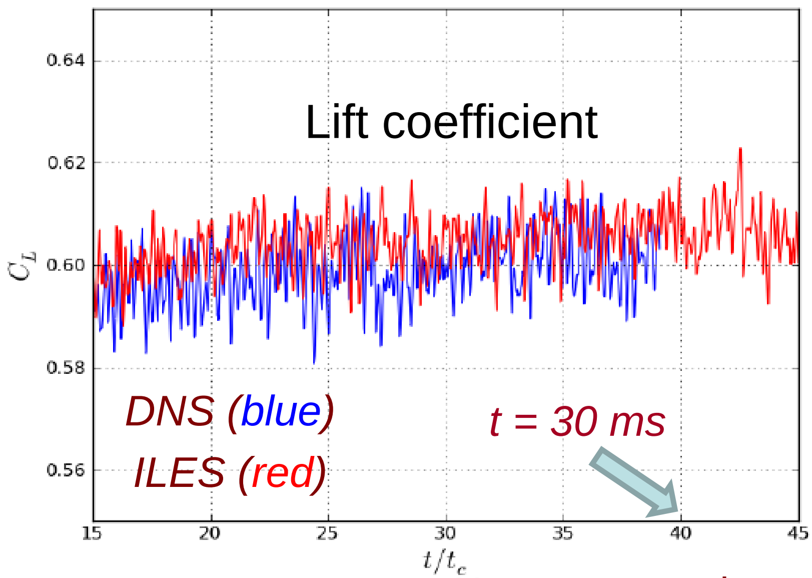


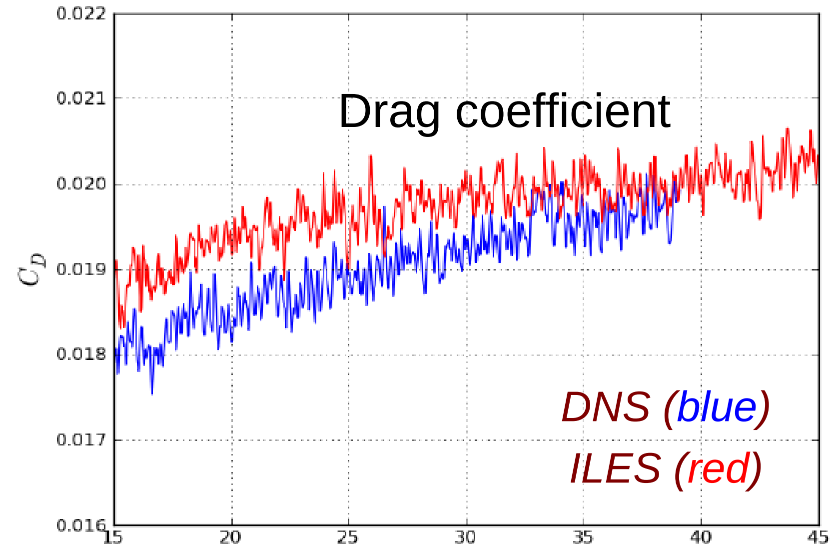
Source: Ref. 6.2.4

DNS and LES of Flow Past an Airfoil

SD7003 Low Reynolds Number Airfoil   M = 0.1, α = 4º, Re = 60,000

Temporal evolution of lift and drag coefficients





Note: $t_c = c/U_\infty$ is convective time = 7.6x10^{-4} sec (est.)

	DNS	ILES	XFoil	Expt. (TU-BS)	Expt. (AFRL)
C_L *(mean)*	0.602	0.607	0.583	-	
C_D *(mean)*	0.0196	0.020	0.0181	-	
Separation (x_{sep}/c)	0.209	0.207	0.26	0.30	0.18
Reattachment (x_r/c)	0.654	0.647	0.57	0.62	0.58
CPU-Hrs* for one t_c	**11,001**	**415**	-	-	

DNS took 25X more CPU time than ILES

*16,000 CPUs on "Jugene" (https://en.wikipedia.org/wiki/JUGENE)

Source: Ref. 6.2.4 & 6.2.5

Lecture 11: Key Takeaways

- **Turbulence Modeling**
  - No shortage of turbulence models ranging from simple algebraic to complicated Reynolds stress transport (RSTM)
- **RANS-based ACA is Unlikely to be Fully Effective Anytime Soon, If Ever!**
  - Accurate modeling of Complex, Multiscale, Nonlinear phenomena that characterize turbulence using just a few free parameters is an Extremely Long Shot Indeed
- ***DNS is Seemingly the Only Path to Fully Effective ACA—but…***
  - DNS is not expected to be feasible—*even for a wing*—until around 2080, LES is probably a more promising option to explore to improve ACA effectiveness
  - Incredible reductions in turnaround times and total cost are required to produce ***credible*** solutions using DNS for airplane configurations
  - DNS effectiveness low in spite of its extremely high 'Quality' factor because of very low 'Acceptance' factor

BIBLIOGRAPHY

SECTION 6

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

6.1 Assessment of Effectiveness (2000–2020)

6.1.1 Cunningham, A.M., Jr., Anderson, W.D., Patel, S.R., and Black, C.L., "Lockheed Martin Aeronautics Perspective on Aircraft Buffet Prediction and Analysis," Symposium on Flow-Induced Unsteady Loads and Impact on Military Applications, Applied Vehicle Technology Panel (AVT), NATO, Budapest, Hungary, 25-28 April 2005.

6.1.2 Hooker, J.R., Hoyle, D.L., and Be6.1s, D.N., "The Application of CFD for the Aerodynamic Development of the C-5M Galaxy," AIAA 2006-0856, 44th Aerospace Sciences Meeting, Reno, Nevada, 9-12 January 2006.

6.1.3 Wooden, P.A., Smith, B.R. and Azevedo, J.J., "CFD Predictions of Wing Pressure Distributions on the F-35 at Angles-of-Attack for Transonic Maneuvers," AIAA-2007-4433, 25th Applied Aerodynamics Conference, Miami, Florida, 25-28 June 2007.

6.1.4 Morgenstern, J., Buonanno, M., and Norstrud, N., "N+2 Low Boom Wind Tunnel Model Design and Validation," AIAA 2012-3217, 30th Applied Aerodynamics Conference, New Orleans, LA, 27 June 2012.

6.1.5 Tinoco, E., Bogue, D., Kao, T., Yu, N., Li, P., and Ball, D., "Progress toward CFD for full flight envelope," The Aeronautical Journal, Vol. 109, Issue 1100, pp 451-460. https://doi.org/10.1017/S0001924000000865

6.1.6 Tinoco, E.N., Brodersen, O.P., Keye, S., Laflin, K.R., Feltrop, E., Vassberg, J.C., Mani, M., Rider, B., Wahls, R.A., Morrison, J.H., Hue, D., Roy, C.J., Mavriplis, D.J., and Murayama, M., "Summary Data from the Sixth AIAA CFD Drag Prediction Workshop: CRM Cases," Journal of Aircraft, Vol. 55, No. 4, July-August 2018, pp 1352-1379.

6.1.7 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.

6.1.8 Wilson, C.M., "F-22 Aerodynamics: Prediction vs. Flight," NASA/DoD Workshop on Aerodynamic Flight Prediction, Williamsburg, VA, 19-21 November 2002.

6.1.9 Giunta, A.A., Golividov, O., Knill, D.L., Grossman, B., Haftka, R.T., Mason, W.H., and Watson, L.T., "Multidisciplinary Design Optimization of Advanced Aircraft Configurations," MAD Center Report 96-06-01, Virginia Tech, Blacksburg, VA.

6.1.10 Frink, N., Tormalm, M., and Schmidt, S., "Three Unstructured Computational Fluid Dynamics Studies on Generic Uninhabited Combat Air Vehicle," AIAA Journal of Aircraft, Vol. 49, No. 6, Nov-Dec 2012, pp 1619-1637.

6.1.11 Rumsey, C.L., Slotnick, J.P., and Sclafani, A.J., "Overview and Summary of the Third AIAA High Lift Prediction Workshop," AIAA 2018-1258, AIAA SciTech Forum, Kissimmee, Florida, 8-12 January 2018.

6.1.12 Karman, S.L., Wyman, N., and Steinbrenner, J.P., "Mesh Generation Challenges: A Commercial Software Perspective," AIAA-2017-3790, 23rd AIAA Computational Fluid Dynamics Conference, A6.1ATION Forum, Denver, Colorado, 5-9 June 2017.

BIBLIOGRAPHY
SECTION 6 (contd.)

6.1.13 Jameson, A., "Computational Fluid Dynamics and Airplane Design: Its Current and Future Impact," Lecture Slides, University of Cincinnati, February 28, 2008.

6.1.14 Bradshaw, P., "The Best Turbulence Models for Engineers," M.D. Salas et al. (eds.), Modeling Complex Turbulent Flows, Kluwer Academic Publishers, 1999, pp 9-28.

6.1.15 Van Dyke, M., "An Album of Fluid Motion," The Parabolic Press, Stanford, California, 1982.

6.1.16 Ollivier-Gooch, C., "Is the Problem with the Mesh, the Turbulence Model, or the Solver," AIAA 2019-1334, AIAA SciTech Forum, San Diego, California, 7-11 January 2019. https://doi.org/10.2514/6.2019-1334

6.1.17 Spalart, P.R., "Strategies for turbulence modelling and simulations," International Journal of Heat and Fluid Flow, 21, 2000, pp 252-263 DOI: 10.1016/S0142-727X(00)00007-2

BIBLIOGRAPHY

SECTION 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

6.2.2 Richardson, L.F., "Weather Prediction by Numerical Process," The University Press, Cambridge, UK, 1922, p. 66.

6.2.3 Sinha, N., "Towards RANS Parameterization of Vertical Mixing by Langmuir Turbulence in Shallow Coastal Shelves," Ph.D. Dissertation, Nov. 2013. DOI: 10.13140/RG.2.2.26443.90404

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.