Verification and Validation of Turbulence Models

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Outline

- Introduction to RANS and V&V
- Overview of some past turbulence-modeling-related workshops
  - ERCOFTAC SIG 15
  - CFD Uncertainty Analysis
  - CFDVAL2004
  - DPW and HiLiftPW
- NASA Turbulence Modeling Resource Website
  - Its purpose and status
- Summary

Reynolds-Averaged Navier-Stokes (RANS)

- RANS is currently the bread-and-butter of the aerospace industry
  - Useful for analysis & design
  - Complex cases can be run in reasonable turn-around times on today's computers
  - Weak link: the RANS turbulence models required to close the equations have some severe limitations
- Scale-resolving methods are typically more accurate than RANS, but are currently too expensive for routine use on complex configurations at high Reynolds numbers
  - Large eddy simulation (LES), Direct numerical simulation (DNS), and hybrid RANS-LES
  - Seen as the future, but when will computers be powerful enough to make these calculations routine?*

*Also, Moore's Law appears to be losing traction! 3

Focus of this talk is on RANS

4

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Verification & Validation (V&V)

- Verification:
  - Software implementation accurately represents developer's description of the model
- Validation:
  - Determination of degree to which model accurately represents the real world (keeping in mind intended use)

Verification & Validation (V&V)

- Verification:
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NO BUGS; coded correctly

- Validation:
  - Determination of degree to which model accurately represents the real world (keeping in mind intended use)

How good is the model?

7

Can RANS results be trusted?

- RANS is considered trustworthy for many attached flow aerodynamic applications
- RANS is not trusted for aerodynamic separated flows
- In an effort to document/improve RANS capabilities, many validation workshops have been held
  - Some to be discussed here
- But without verification, it is often difficult to draw firm conclusions from validation exercises when codes do not agree

8

Example from Drag Prediction Workshop 3 (DPW-3)

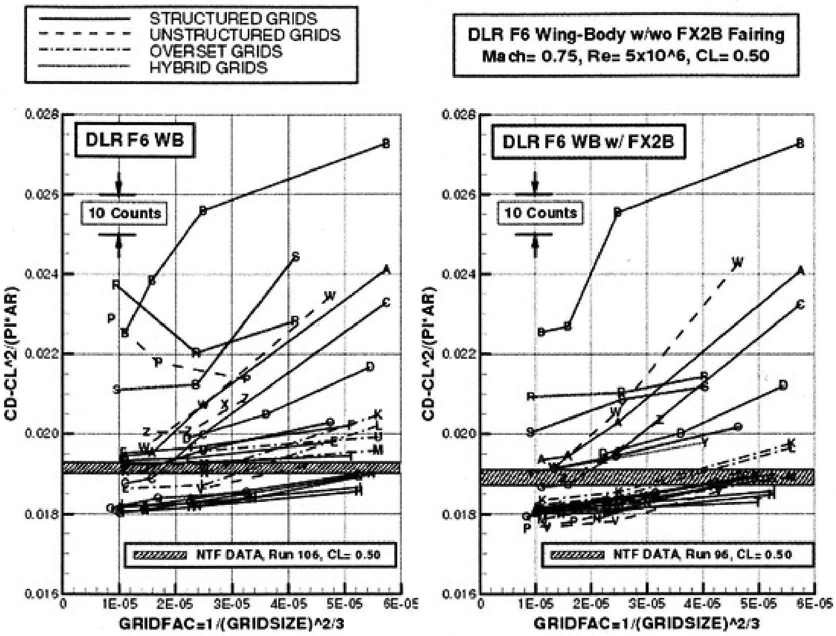

Figure from Vassberg et al., AIAA Paper 2008-6918, August 2008

How easy is it to code a turbulence model as intended?

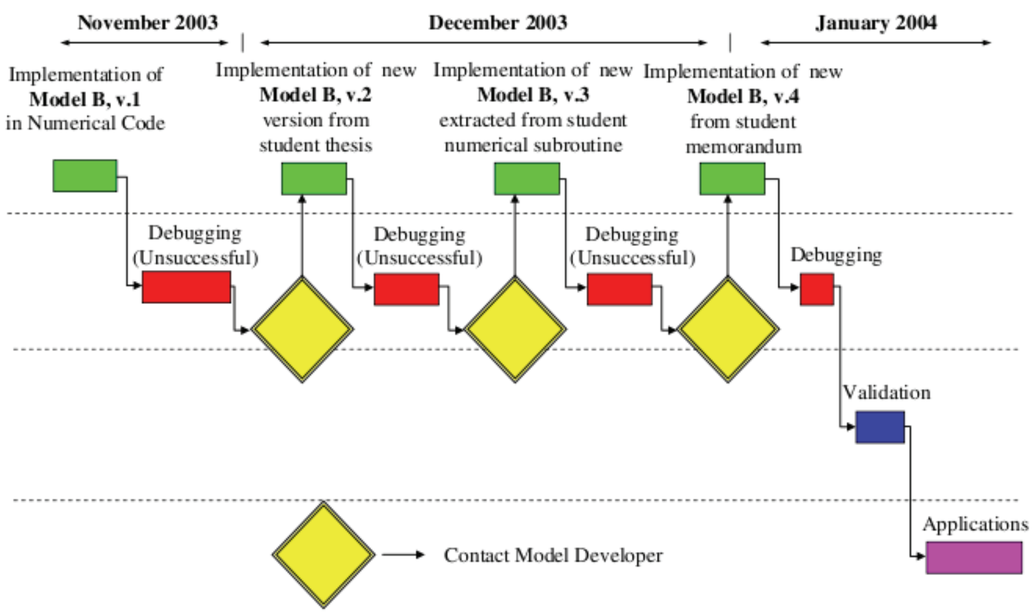

Figure from Computers & Fluids 36 (2007) 1373-1383

What is needed?

- Verification:
  - Method of Manufactured Solutions (MMS), e.g., Roy et al.
  - Compare against known analytic solutions
  - Grid convergence studies and comparison with other verified codes for benchmark problems
- Validation typically involves comparison against experiment, DNS, or LES
  - Care must be taken :
    - To understand the error in the experiment, DNS, or LES
    - To get the BCs and geometry right in the RANS (apples to apples)
    - To reduce discretization error and iterative convergence error in the RANS

11

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rarely done

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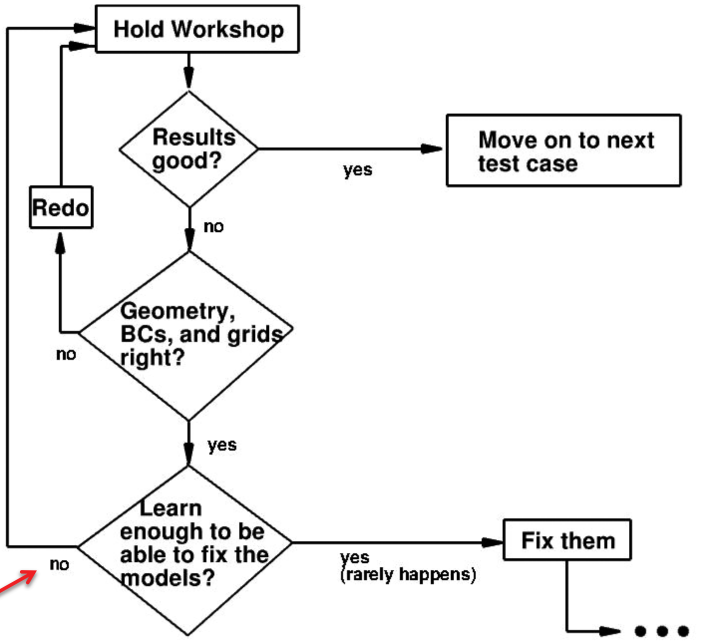
difficult to do right

12

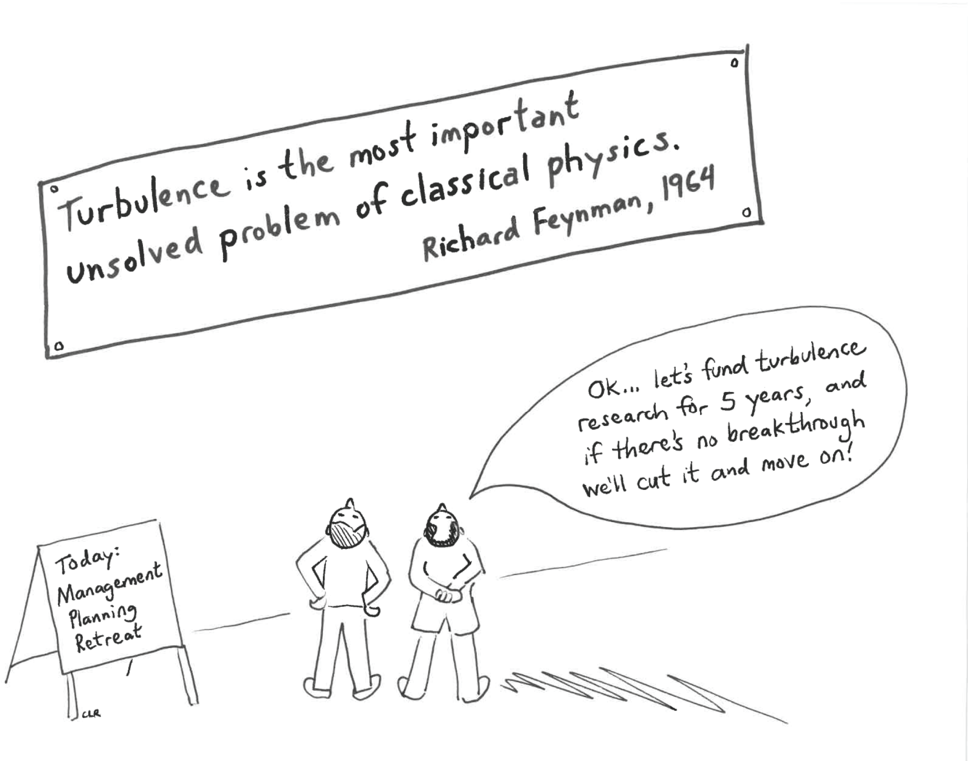
Turbulence Modeling Workshops



...because model results are all over the map!

13

Where does this leave us?



14

Summary of some past workshops (related to turbulence modeling)

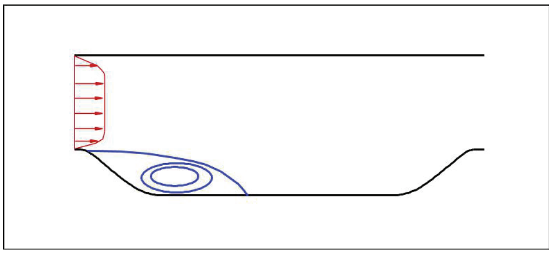
ERCOFTAC SIG 15

- Special interest group on “refined turbulence modeling”
- 14 workshops since early 1990s
- Recently have started to include eddy-resolving methods (e.g., LES, hybrid RANS-LES)
- Some major conclusions:
  - RANS predicts 2-D separated hill flows poorly

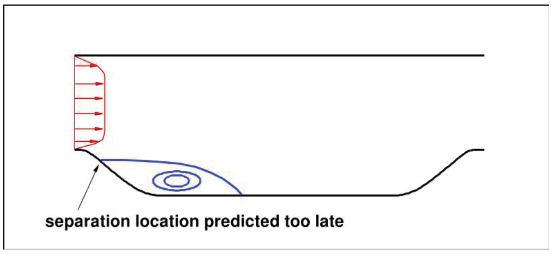
ERCOFTAC = European Research Community on Flow, Turbulence, and Combustion

Hill-type separated flows

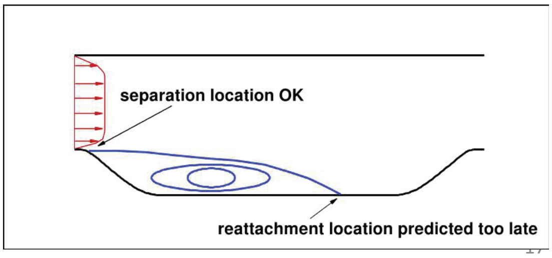
Correct result



Incorrect result typical with k-epsilon



Incorrect result typical with SA, SST, k-omega



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18

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  – Complex cases (e.g., flow inside curved duct, jet impinging on rotating disk, 3-D separated diffuser) tend to be predicted by EASMs and RSMs better than linear models

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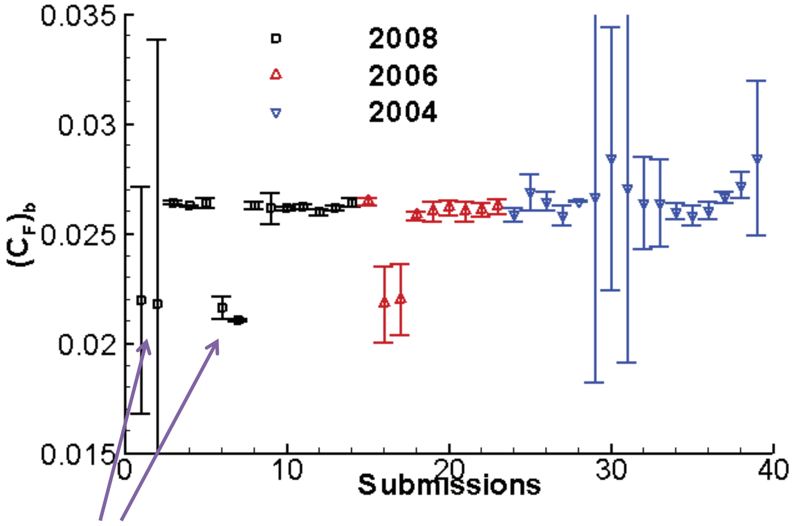
  – Complex cases (e.g., flow inside curved duct, jet impinging on rotating disk, 3-D separated diffuser) tend to be predicted by EASMs and RSMs better than linear models
  – Different codes with same turbulence models often obtain very different results – REASONS UNKNOWN

CFD Uncertainty Analysis

- Series of 3 workshops held in Lisbon during 2000s
- Focus on uncertainty estimators, such as Roache's Grid Convergence Index (GCI)
- 2-D hill and 2-D backward facing step
- Progressive improvement seen:
  - 1st workshop: possibility of undetected coding errors
  - 2nd workshop: prescribed use of MMS
  - 3rd workshop: included MMS, grid convergence, and uncertainty estimates for both CFD and experiment

21

MMS: led to more consistency for backward facing step



Two outliers in 2008: one used much coarser grid than everyone else, the other did not perform code verification (MMS) exercise

Figure from AIAA 2009-3647

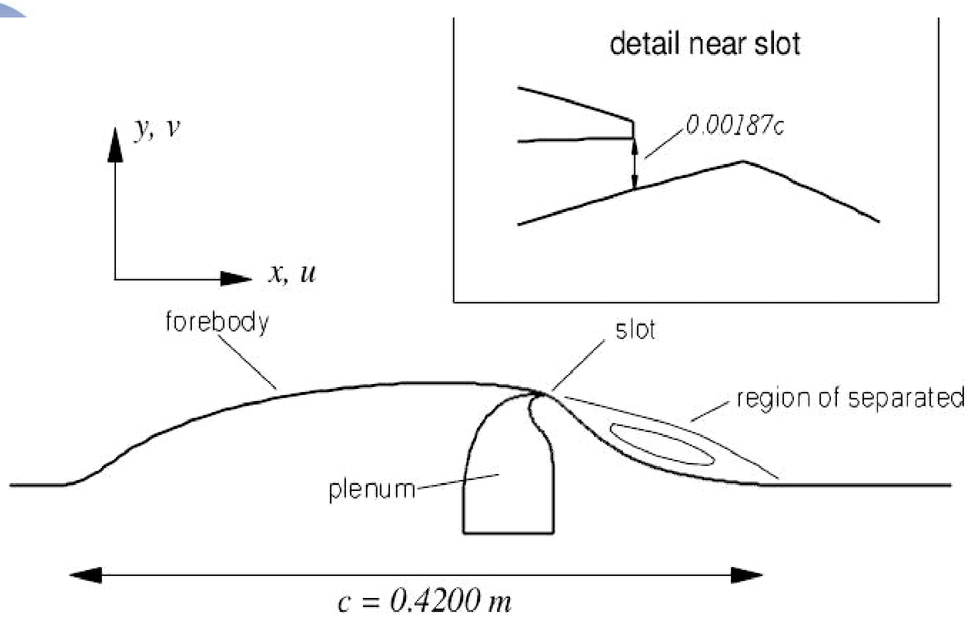
22

CFDVAL2004

- Workshop focused on synthetic jets and turbulent separation control
- Three cases:
  - Case 1: 2-D synthetic jet into quiescent air
  - Case 2: circular synthetic jet in crossflow
  - Case 3: 2-D flow over wall mounted hump (no flow control, steady suction, and synthetic jet)
- Major conclusions:
  - Difficulty measuring time-dependent BCs in experiment
  - Inconsistent application of BCs in CFD
  - Case 3 provided clear evidence of RANS deficiencies
  - Use of website to post data, grids, etc. promoted wide use (over 40 subsequent papers on Case 3 alone)

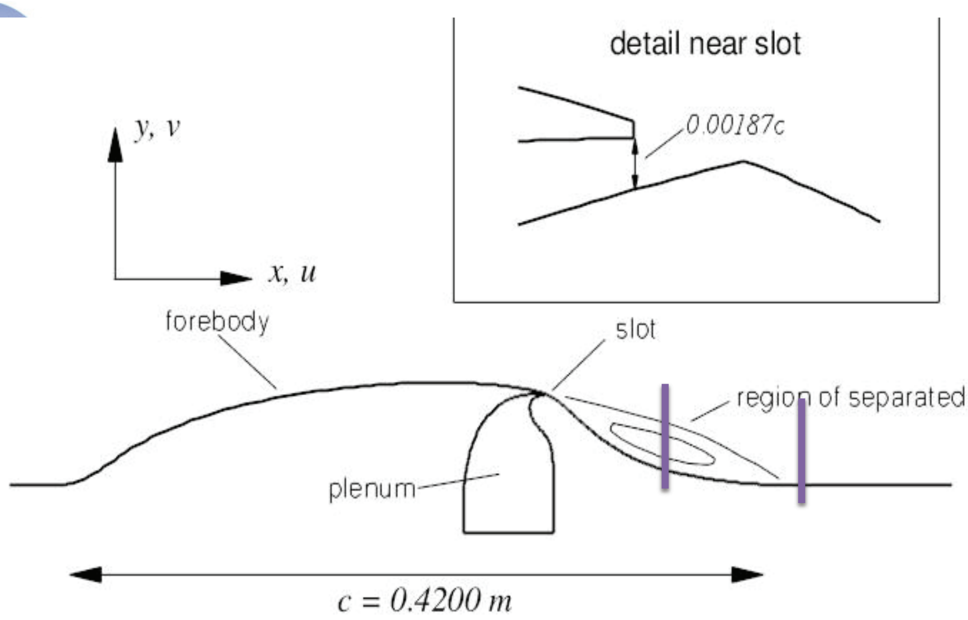
23

Wall-mounted 2-D hump



24

Wall-mounted 2-D hump

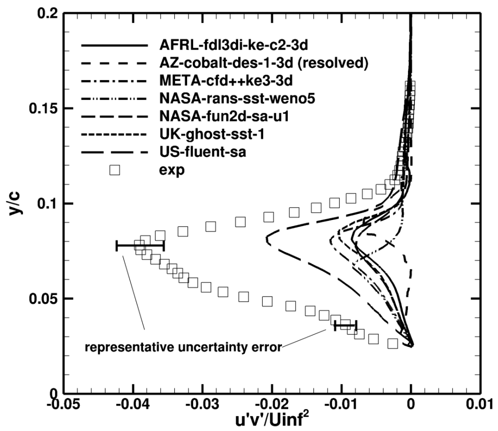


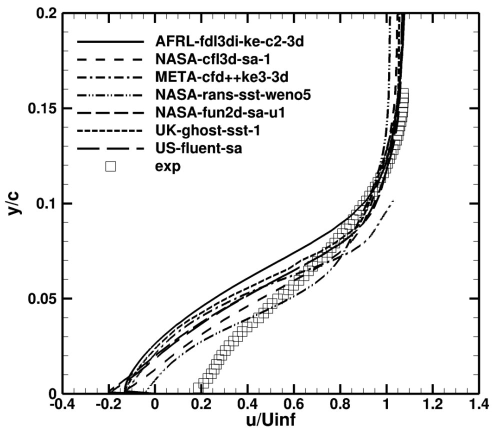
25

Hump flow predictions by RANS

Inside bubble

Downstream of exp reattachment



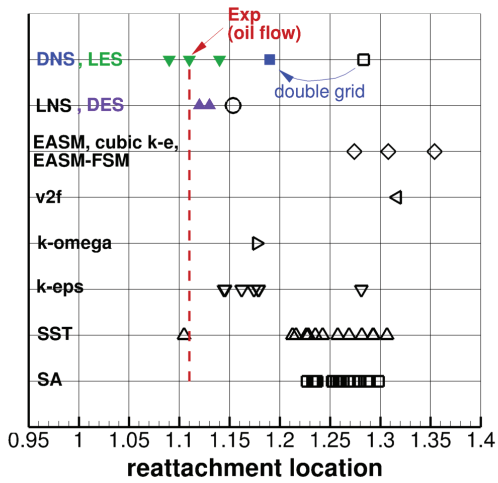


Turbulent shear stress magnitude in separated shear layer severely under-predicted by RANS. Consequently too little turbulent mixing; reattachment & recovery comes too late.

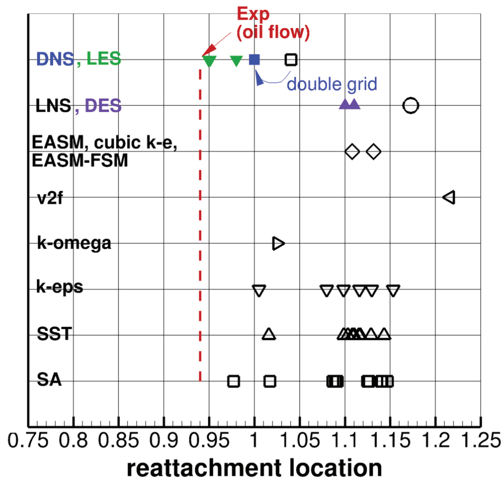
26

Scale-resolving methods can do better (but not always*)

No flow control



Steady suction flow control

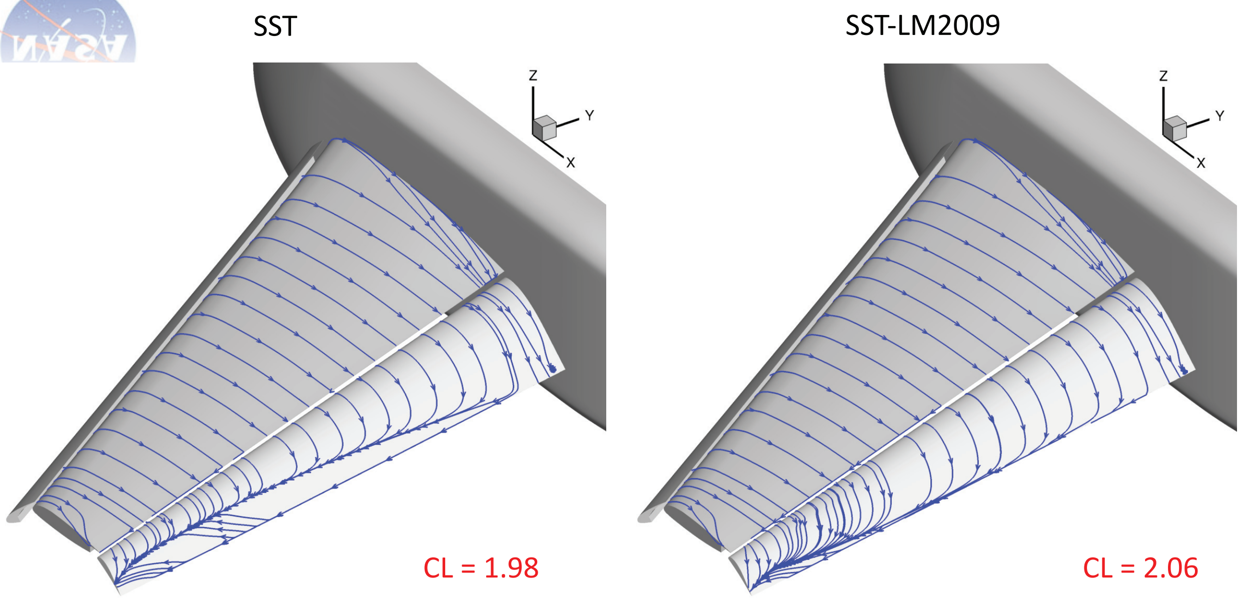


* Considerable expertise seems to be required to perform scale-resolving simulations correctly!

DPW and HiLiftPW

- Focus on drag prediction and high lift prediction for aircraft configurations
- Most participants have used SA or SST turbulence models
- Lack of consistency between codes using the same model
- DPW:
  - A big issue has been wing-root separation bubble
  - Strongly a function of grid size, grid topology, numerical method, and turbulence model
- HiLiftPW:
  - SA-based models generally agree better with experiment
  - But transition is typically not accounted for

Example effect of transition on HiLiftPW flowfield



When you account for transition, SST results improve dramatically

Experimental C_L = 2.05 @ alpha=13 deg.

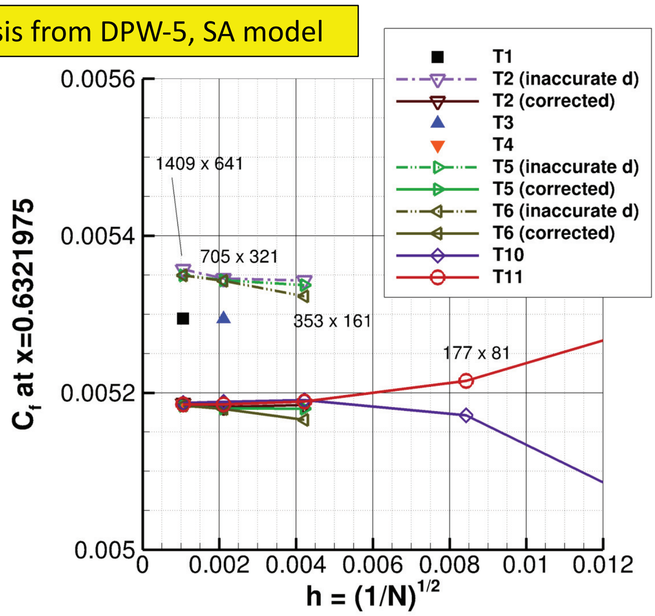
But this does not explain why “fully turbulent” SA model also yields good C_L results

Turbulence Modeling Resource (TMR) Website

- Established in late 2000s by NASA in collaboration with AIAA Turbulence Model Benchmarking Working Group (TMBWG)
- Goals:
  - Provide accurate and up-to-date information on widely-used RANS turbulence models, including model naming conventions
  - Help verify that turbulence models are implemented correctly (*as intended*)
  - Compare model predictions for fundamental flow problems
  - Serve as forum for helping to disseminate new models
  - Provide some additional resources:
    - Experimental, DNS, and LES databases (incl data from “Stanford Olympics”, Bradshaw et al.)
    - MMS resources and information
    - Convergence properties, numerics, etc.

How has the NASA TMR website been useful?

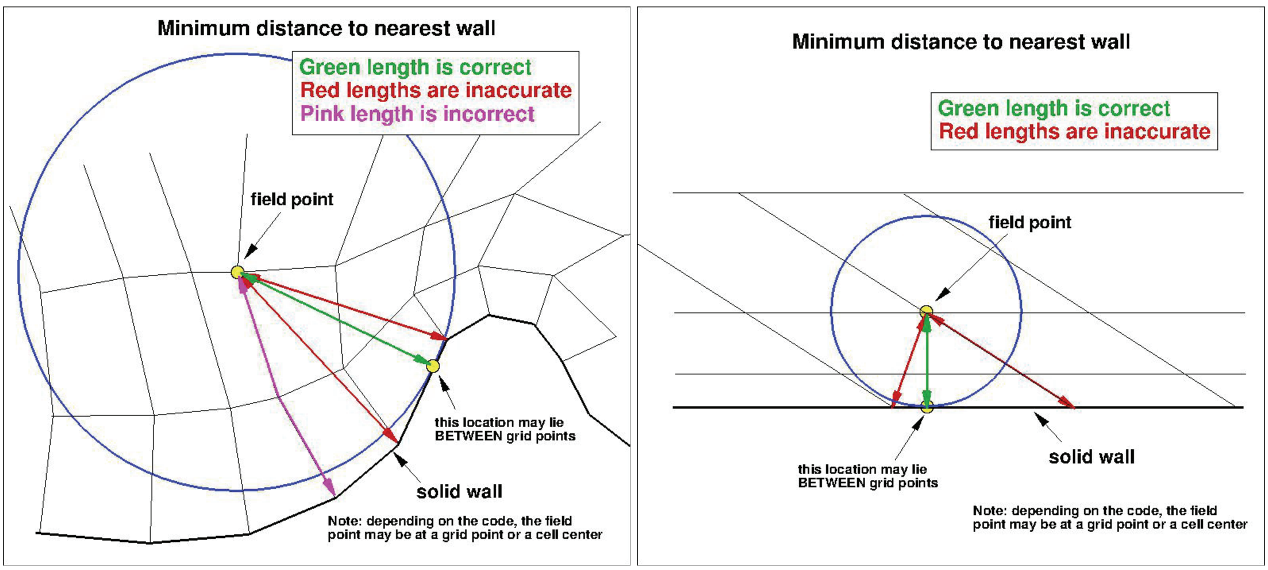
Verification analysis from DPW-5, SA model



T2, T5, and T6 found to be inaccurate due to use of approximate minimum distance function

Distance function

- Used by SA, SST, other models
- If not done accurately, results can be inconsistent (grid-dependent)



Description of Turbulence Models

Turbulence Models

- One-Equation Models:
  - Spalart-Allmaras
  - Nut-92
  - Wray-Agarwal
- Two-Equation Models:
  - Menter k-omega SST
  - Menter k-omega BSL
  - Wilcox k-omega
  - Chien k-epsilon
  - K-kL
  - Explicit Algebraic Stress k-omega
- Three-Equation Models:
  - K-e-Rt
- Three-Equation Models plus Elliptic Relaxation:
  - K-e-zeta-f
- Seven-Equation Omega-Based Full Reynolds Stress Models:
  - Wilcox Stress-omega
  - SSG/LRR
- Seven-Equation Epsilon-Based Full Reynolds Stress Models:
  - GLVY Stress-epsilon

Turbulence+Transition Models

- One-Equation Models:
  - SA-BC
- Two-Equation Models:
  - ...
- Four-Equation Models:
  - SST-2003-LM2009

(Guidelines for submitting a new turbulence model description: Guideline-turbmodeldescription.pdf)

Implementing Turbulence Models into the Compressible RANS Equations

Notes on running the cases with CFD

Currently 16 different models described, plus variants;
defines NAMING CONVENTIONS

New models can be added, with input from model developer(s)

V&V currently not done for all models, due to limited resources

33

Verification Cases

Implementing Turbulence Models into the Compressible RANS Equations

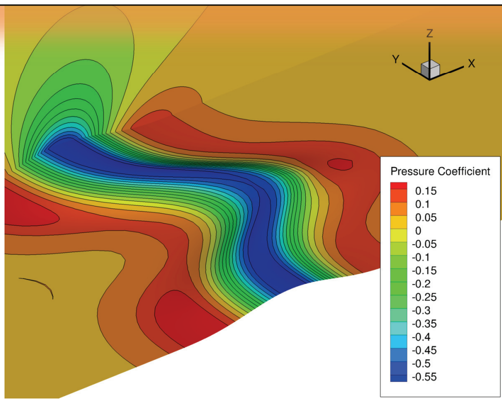
Notes on running the cases with CFD

Turbulence Model Verification Cases and Grids

- **VERIF/2DZP:** 2D Zero pressure gradient flat plate
- **VERIF/2DCJ:** 2D Coflowing jet
- **VERIF/2DB:** 2D Bump-in-channel
- **VERIF/2DANW:** 2D Airfoil Near-Wake
- **VERIF/3DB:** 3D Bump-in-channel

Website began with 4 cases; the VERIF/2DANW case has been recently added

All grids are provided



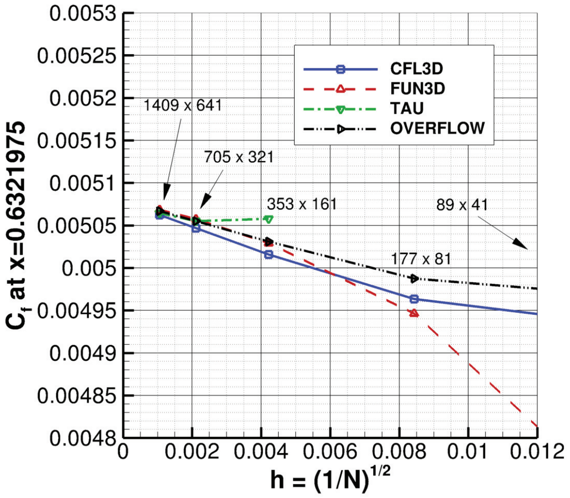
3-D Bump-in-channel verification example, using Wilcox2006 model

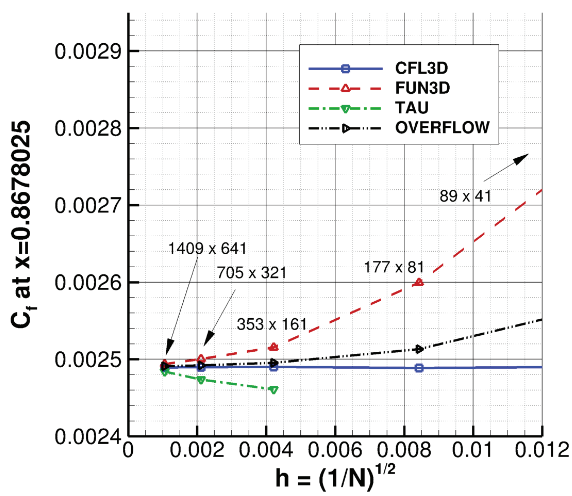
34

"Verification via Comparison"

- Use grid-convergence studies and comparison with other verified codes for benchmark problems

Example from TMR website, SST model



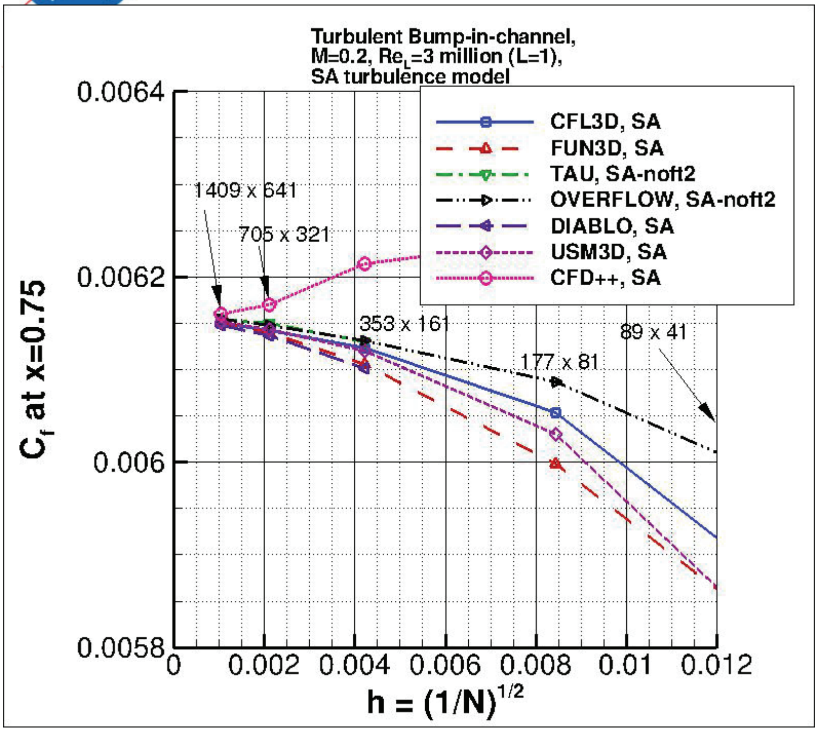


Many more details available on website

Verification Cases

- "Verification by comparison" is not fool-proof
  - Sufficient iterative convergence is very important!
  - 2 (or more) codes may have similar errors, or particular errors may not show up for the cases considered
  - But the more codes that agree, and the more cases we do, the more confidence we have
  - Transparency and openness of TMR allows the whole world to check its accuracy (and tell us if a problem or inconsistency is found)
- Model Readiness Rating (MRR) system
  - 0=no results yet; model description only
  - 1=model only in one code on TMR
  - 2=two or more codes agree on at least two cases on TMR
  - 3=two or more codes from different organizations agree on TMR (independently obtained)
  - 4=turbulence model underwent Method of Manufactured Solutions in at least 1 code

Verification Cases



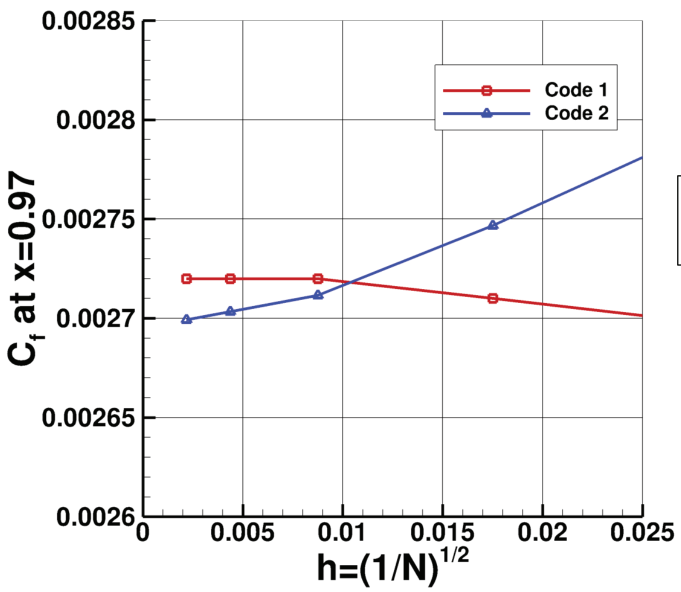
Example of a turbulence model (SA) with MRR Level=4

We have very high confidence in the SA results on the TMR – users can trust these results

Other models with MRR Level=3 or 4 currently:
- -SA
- -SA-RC
- -SST
- -SST-V
- -SSG/LRR-RSM-w2012
- -K-kL-MEAH2015

Verification Cases

Example of a turbulence model NOT posted, because “verification by comparison” has not yet been successfully achieved



“Visual extrapolation” to h=0

Validation Cases

Turbulence Model Validation Cases and Grids

- **Basic Cases:**
  - **2DZP:** 2D Zero pressure gradient flat plate
  - **2DML:** 2D Mixing Layer
  - **2DANW:** 2D Airfoil near-wake
  - **2DN00:** 2D NACA 0012 airfoil
  - **ASJ:** Axisymmetric Subsonic jet
  - **AHSJ:** Axisymmetric Hot subsonic jet
  - **ANSJ:** Axisymmetric Near-sonic jet
  - **ASBL:** Axisymmetric Separated boundary layer
  - **ATB:** Axisymmetric Transonic Bump
- **Extended Cases:**
  - **2DZPH:** 2D Zero pressure gradient high Mach number flat plate
  - **2DBFS:** 2D Backward facing step
  - **2DN44:** 2D NACA 4412 airfoil trailing edge separation
  - **2DCC:** 2D Convex curvature boundary layer
  - **2DWMH:** 2D NASA wall-mounted hump separated flow
  - **ASWBLI:** Axisymmetric Shock Wave Boundary Layer Interaction near M=7
  - **ACSSJ:** Axisymmetric Cold Supersonic Jet
  - **AHSSJ:** Axisymmetric Hot Supersonic Jet
  - **3DSSD:** 3D Supersonic square duct

9 "basic" cases and 9 "extended" cases, as determined by the TMBWG committee

Validation Cases

		Free shear flows			Wall flows		P-grad-ients	Curv-ature	Compressibility			Secon-dary flows	Turb Heat Flux	Higher Mach	Vortex flows	Shock	Separ-ation
		Jet Anom-aly	Mixing layer	Wakes	Law of wall	Law of wake			Mixing	Van Driest I	Van Driest II						
Boundary layers	2DZP*				Y	Y											
	2DZPH									Y	Y		Y	Y			
	ASBL*				Y		weak										weak
Mixing layer/ wakes	2DML*		Y														
	2DANW*			Y													
Jets	ASJ*	Y															
	ANSJ*	Y							Y					Y			
	AHSJ*	Y											Y				
	ACSSJ*	Y							Y					Y			
	AHSSJ*	Y							Y				Y	Y			
Airfoils	2DN00*						Y										weak
	2DN44						Y										Y
Bump flows	ATB*						Y							Y		Y	Y
	2DWMH						Y										Y
Shock/boundary layer interaction flows	ASWBLI						Y						Y	Y		Y	Y
Internal flows	2DCC						Y	Y									
	2DBFS						strong										Y
	3DSSD						Y					Y	Y	Y			

(* indicates "Basic Case")

Other Aspects of TMR

- Databases
- Manufactured Solutions
- Numerical Analysis

Turbulent Flow Validation Databases

The data in the following links are publicly available and are provided here as a convenience. They are provided as-is and accuracy is not guaranteed; questions should be directed to the sources of the data provided.

- Data from "Collaborative Testing of Turbulence Models"
- Data from Other Experiments
- Data from Other Direct Numerical Simulations (DNS)
- Data from Other Large Eddy Simulations (LES)

Turbulent Manufactured Solutions

- Information from Lisbon "Workshop on CFD Uncertainty Analysis" series

Cases and Grids for Turbulence Model Numerical Analysis

- 2D Finite Flat Plate
- 2D NACA 0012 Airfoil
- 2D Hemisphere Cylinder
- 3D Modified Bump
- 3D Modified Supersonic Square Duct
- 3D Hemisphere Cylinder (old)
- 3D Hemisphere Cylinder (new)
- 3D ONERA M6 Wing

Data from "Collaborative Testing"

- From Bradshaw et al. (used with permission)
- Includes data from "Stanford Olympics"

Incompressible Flow Cases from 1980-81 Data Library

This grouping contains the incompressible-flow cases from the 1980-81 Data Library. The data in the original files are in normalized format, as explained on p. 60 of the 1980-81 Proceedings ("The 1980-81 AFOSR-HTTM Stanford Conference on Complex Turbulent Flows: A Comparison of Computation and Experiment," Volumes I, II, and III, edited by S. J. Kline, B. J. Cantwell, and G. M. Lilley, Stanford University, 1981). The 1980-81 Conference Proceedings also give a full description of the cases. (These cases comprise the contents of the original disk "d1", with the exception of 0411 (Cantwell cylinder), 0441 (Wadcock airfoil), 0511 (Shabaka wing-body junction), 0512 (Humphrey bend), which were too large to fit on the original disk.)

- Case F-0111: Developing Flow in a Square Duct (Po et al)
- Case F-0112: Secondary Currents in the Turbulent Flow Through a Straight Conduit (Hinze)
- Case F-0141: Increasingly Adverse Pressure Gradient Flow (Samuel and Joubert)
- Case F-0142: Six-Degree Conical Diffuser Flow, Low and High Core Turbulence (Pozzorini)
- Case F-0211: Effect of Free Stream Turbulence (Bradshaw and Hancock)
- Case F-0231: Turbulent Boundary Layers on Surfaces of Mild Longitudinal Curvature (Hoffmann and Bradshaw)
- Case F-0233: Turbulent Boundary Layer on a Convex, Curved Surface (Gillis and Johnston)
- Case F-0234: Effects of Small Streamline Curvature on Turbulent Duct Flow (Hunt and Joubert)
- Case F-0235: The Effects of Short Regions of High Surface Curvature on Turbulent Boundary Layers (Convex 30 degrees) (Smits et al)
    - Corrected data for Case F-0235
- Case F-0241: Zero Pressure Gradient Constant Injection (Andersen et al)
- Case F-0242: Adverse Pressure Gradient with Constant Suction (Andersen et al)
- Case F-0244: Zero Pressure Gradient with Constant Suction (Favre et al)
- Case F-0251: NLR Infinite Swept Wing Experiment
- Case F-0252: Part-Rotating Cylinder Experiment (Bissonnette et al)
- Case F-0253: Cylinder on a Flat Test Plate (Dechow and Felsch)
- Case F-0254: Part-Rotating Cylinder (Lohmann)
- Case F-0261: Turbulent Wall Jet Data Collected from Various Sources
- Case F-0311: Planar Mixing Layer Developing from Turbulent Wall Boundary Layers
- Case F-0331: The Turbulence Structure of a Highly Curved Mixing Layer (Castro)

etc…

Data from Other Experiments

- Experimental data posted (or linked) here
  - For data that may be useful for RANS development or validation

Experimental Data

- Common Research Model (NASA) (independent website, will open new window)
- Shock Wave / Turbulent Boundary Layer Flows at High Mach Numbers (CUBRC) (independent website, will open new window)

- 2-D Coanda Airfoil with Tangential Wall Jet (under construction)
- Round Synthetic Jets for Separation Control on 2-D Ramp
- FAITH Hill 3-D Separated Flow
- Flow Behind a NACA 0012 Wingtip
- Shock Boundary Layer Interaction at M=2.05
- Various Hypersonic Shock Boundary Layer Interactions (NASA/TM-2013-216604)
- Planar Turbulent Wake in Various Pressure Gradients

43

Data from Other DNS

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Incompressible Flow Cases

- Channel Flow of Jimenez et al (independent website, will open new window)
- Boundary Layer Flow of Jimenez et al (independent website, will open new window)
- 3-D "Cherry" Diffuser (independent website, will open new window)

- Converging-Diverging Channel, Re=12600
- High-Order Moments in Unstrained and Strained Channel Flow

Compressible Flow Cases

- Compressible Supersonic Isothermal-Wall Channel Flow
- Compressible Periodic Hill <- new!

44

Data from Other LES

- LES data posted (or linked) here
  - For data that may be useful for RANS development or validation

Incompressible Flow Cases

- Coanda Airfoil with Tangential Wall Jet
- Periodic Hill
- Curved Backward-Facing Step
- NASA Wall-Mounted Hump
- Converging-Diverging Channel, Re=20580

Compressible Flow Cases

- NASA Wall-Mounted Hump <- new!

45

Turbulent Manufactured Solutions

- From Eca (used with permission)
- Used for series of V&V workshops at IST (Lisbon)

Information from Lisbon "Workshop on CFD Uncertainty Analysis" series

This web page provides some information from a series of turbulence-related Validation and Verification workshops held in Lisbon, Portugal, at the Instituto Superior Tecnico (IST). It includes manufactured solutions for wall-bounded incompressible turbulent flow. Everything on this page was provided courtesy of the workshop organizer Luis Eca, of IST. NASA assumes no responsibility for the accuracy of this information; questions should be directed to the originator. Additional details about the three workshops can be found in the American Institute of Aeronautics and Astronautics papers AIAA-2005-4728 (Toronto, June 2005), AIAA-2007-4089 (Miami, June 2007), and AIAA-2009-3647 (San Antonio, June 2009). See also Int. J. Numer. Meth. Fluids 54:119-154, 2007 and Int. J. Computational Fluid Dynamics 21(3-4):175-188, 2007 for details on the construction of manufactured solutions for one- and two-equation eddy-viscosity turbulence models.

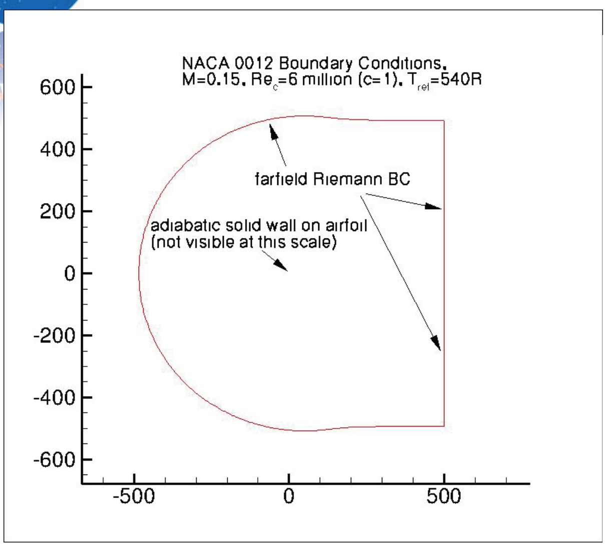
- Note describing test cases for the third workshop (pdf file)
- Note describing validation procedure for the third workshop (pdf file)
- Report IST D72-34 (2005), describing turbulent manufactured solutions for the workshop (pdf file)
- Report IST D72-36 (2006), describing turbulent manufactured solutions for the workshop (pdf file)
- Note describing manufactured functions available (pdf file)
- Fortran files associated with the workshop (tarred and gzipped directory)

46

Turbulence Model Numerical Analysis

- Purpose: more in-depth analysis of particular cases
- Different / finer grids than those on validation pages
- 8 cases have been built up to date
  - Coordinated with FDTC Solver Technology for Turbulent Flows DG
  - Currently focused on SA model only
  - Attempts to establish “reference solutions”
    - Handy for evaluating high-order schemes, novel numerical schemes, grid adaption, etc.
- See, e.g., Diskin et al.:
  - AIAA Journal, Vol. 54, No. 9, 2016, pp. 2563-2588
  - AIAA-2015-1746
  - AIAA-2018-1102

Numerical Analysis – NACA 0012 with SA model



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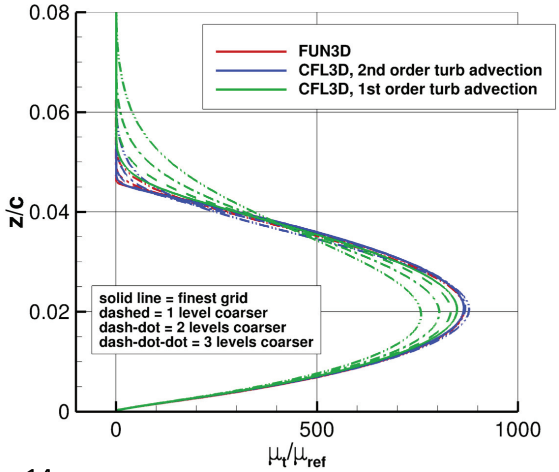
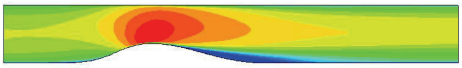


- Based on grid convergence study results (using over 14 million grid points) and 3 codes (plus others in AIAA special session SciTech 2015), we have a good sense of the “reference solution”, even without clear asymptotic rates of convergence
  - E.g., CL to within 0.0002, or 0.02%
  - E.g., CD to within 0.00001, or 1/10th drag count

Includes additional analysis of streamwise grid resolution influence near T.E.

http://turbmodels.larc.nasa.gov



- TMR seeks to bring consistency to the testing, verification, and validation of RANS turbulence models for the CFD community
- One of biggest reason for its success may be its “openness”
  - By including all details (equations, grids, BCs, existing CFD results), it encourages quick comparisons and makes inter-organizational collaborations easier
  - Mistakes on the website are occasionally found by the community; its openness makes the process of finding and fixing them more efficient
  - TMBWG is an open working group; anyone can join

TMR Open Questions

- How to find the time to verify/validate additional models for posting to TMR?
  - It is tedious, unglamorous work
  - Currently requires author’s collaboration (NASA site is not a wiki)
- How to create stronger connection between the TMR and researchers with new RANS ideas?
  - Original hope for site: to facilitate the dissemination of new turbulence models to the community
  - To date, very few modelers have done this
- How to handle the fact that codes (and their results) might change over time?
- What about hybrid RANS-LES and LES models?
  - They can be described, but how to verify them?
  - New site (http://wmles.umd.edu/) is beginning to attempt this for wall-modeled LES (WMLES)

Summary

- Most workshops focusing on turbulence models have suffered from "same model… different code… different results" syndrome
  - Different model versions used, errors introduced, or undocumented features added
  - Muddies the workshop conclusions
- To make workshops more useful, codes should be <u>verified</u>
  - Via MMS, or…
  - NASA TMR website makes crude verification very easy for many modern RANS models SA, SA-RC, SST, SST-V, SST-2003, Wilcox2006, k-kL-MEAH2015, SSG/LRR-RSM-w2012 (other models will eventually be added)
  - No additional coding needed; just run simple cases on sequence of grids provided, and compare against posted results
  - AIAA's DPW and HiLiftPW series have started to promote this way of thinking
- With verification done, we could focus on more important issues

51

Important issues…

- Improved geometric fidelity
- Use of appropriate boundary conditions
- Better grids
  - Finer resolution
  - Improved quality
  - Automatic grid adaption
- Better numerics
  - Higher order accuracy
  - Better iterative convergence
- Improved physics
  - Transition
  - More widely applicable turbulence models (e.g., for separated flow)

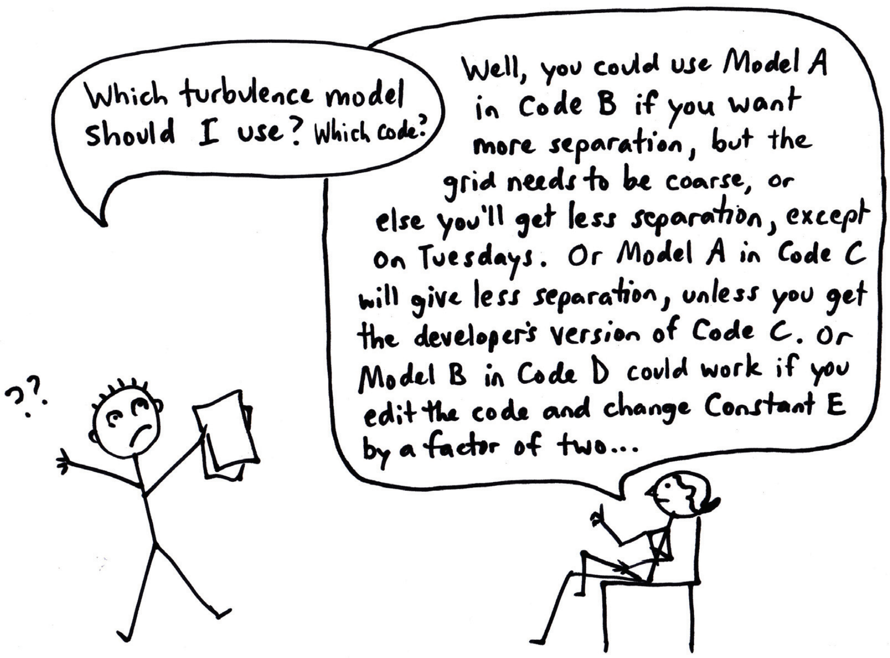
52

Executive summary

- Use websites to encourage crowd-sourcing of ideas
  - Post data, grids, everything… make it easy for people to use your results and learn from them
- Continue to invest in RANS research
  - Collective improvement through workshops, including both verification and validation
  - Verification prior to validation!

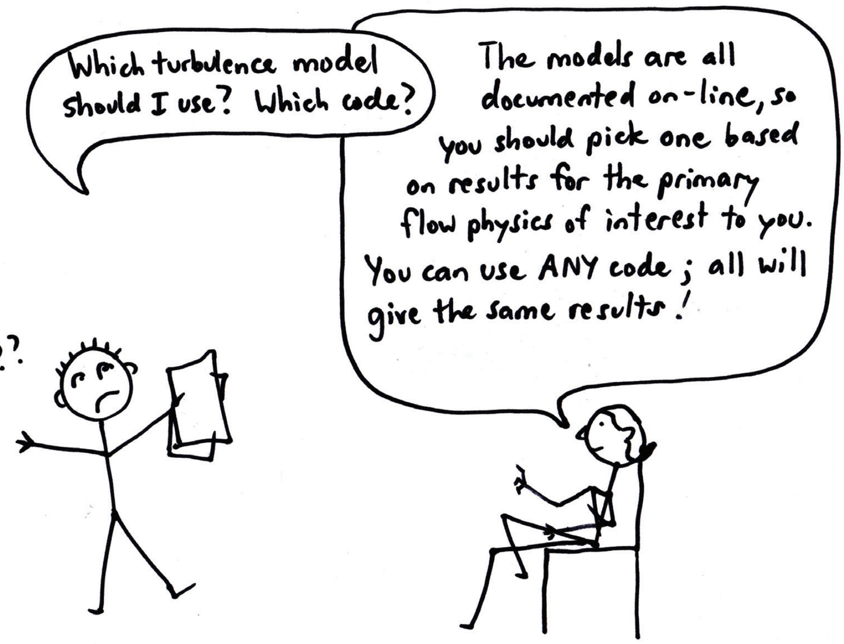
53

Move from this…



54

… toward this



55