Perspectives on RANS Modeling for Separated Flows

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High-Fidelity Industrial LES/DNS Symposium
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Outline

- NASA aeronautics organization and strategy
  - And how turbulence modeling research ties into it
- Problems with Reynolds-averaged Navier-Stokes (RANS) for separated flows
- NASA's 40% Technical Challenge
- RANS approaches
- Results from different RANS models/fixes
  - Linear eddy viscosity model
  - Explicit algebraic stress models (EASM)
  - Reynolds stress model (RSM)
  - K-kL
- Summary

NASA Aeronautics Research Mission Directorate (ARMD) Strategic Implementation Plan and Strategic Thrusts

National Aeronautics and Space Administration

NASA AERONAUTICS

Strategic Implementation Plan

www.nasa.gov

Safe, Efficient Growth in Global Operations

- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Innovation in Commercial Supersonic Aircraft

- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles

- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion

- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance

- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation

- Develop high impact aviation autonomy applications

ARMD Programs and Projects

Seedling Program

Transformative Aeronautics Concepts Program (TACP)

Transformational Tools and Technologies (T^3) Project
Performs deep-discipline research and development of first-of-a-kind capabilities to analyze, understand, predict, and measure performance of aviation systems; research and development of "tall-pole" technologies; all of which enables design of advanced aeronautics systems.

Revolutionary Tools and Methods/ Revolutionary Computational Aerosciences
Development of revolutionary comprehensive physics-based aeronautics analysis and design capability. Philosophically based on Vision 2030 study recommendations

Advanced Air Transport Technology Project
Revolutionary Vertical Lift Technology Project
Commercial Supersonic Technology Project
Hypersonic Technology Project

Advanced Air Vehicles Program (AAVP)

Integrated Aviation Systems Program (IASP)

Airspace Operations and Safety Program (AOSP)

Focused Programs

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National Aeronautics and Space Administration

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Primary area of RCA emphasis

Transition to Low-Carbon Propulsion

- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Primary areas of T^3 project emphasis

Real-Time System-Wide Safety Assurance

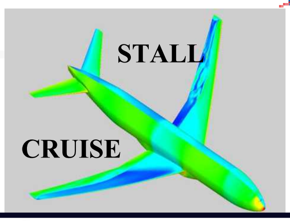
- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation

- Develop high impact aviation autonomy applications

T^3 Project develops cross-cutting tools and technologies

CFD Applications to Ultra-efficient Commercial Vehicles [ARMD Thrust 3]



- **High-fidelity CFD tools enable:**
  - Increasing expansion of CFD prediction at the edges of the flight envelope (e.g., high-lift, stability & control, flutter, etc.) and aeropropulsion performance
    - ➢ Allow efficient design of futuristic concepts
  - Significant reductions in nonrecurring product development costs (e.g., experimental loads and performance testing)
  - Certification by Analysis → savings of up to $300 million in product development

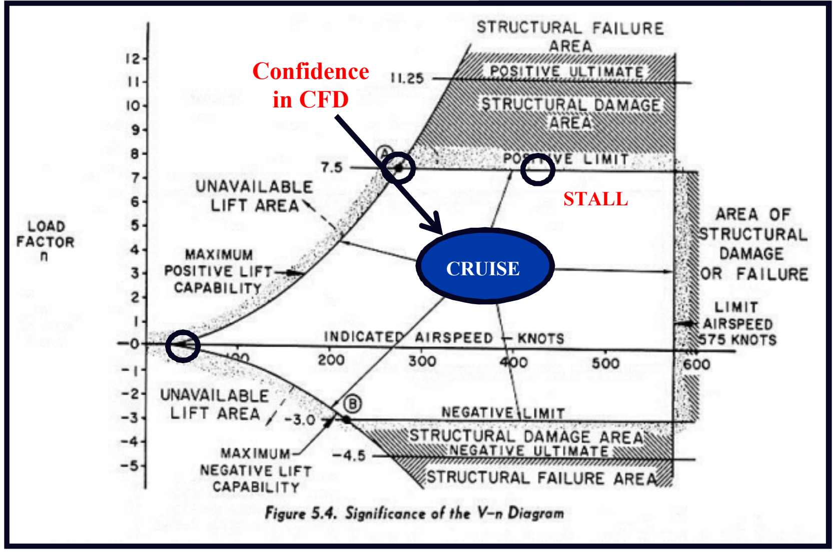


Figure 5.4. Significance of the V–n Diagram

Source: Dole, Charles E., Flight Theory and Aerodynamics, 1981, John Wiley & Sons, Inc, New York, NY, 1981.

- **CFD Challenges:**
  - Boundary layer transition
  - Turbulent flow physics with separation
  - Unsteady flow (toward edges of the operating envelope; propulsion system)
  - Aeroelastics (and other multi-disciplinary interactions)
  - Control surface effects
  - Large database coverage required (with extremely large grid models)
  - Requires computational efficiency, accuracy, robustness

"Three Pillars" of RCA Research

- **Robustness/Reliability**
  - *Ability to generate results with error bounds on every try, by a nonexpert user*
    - Robust solver technology
    - Uncertainty quantification
- **Cost/Efficiency**
  - *Ability to compute faster by orders of magnitude compared to the current practice*
    - Exploit emerging HPC hardware capability
    - Numerical algorithms (e.g., solvers, adaptive grids)
- **Accuracy**
  - *Ability to accurately compute complex turbulent flows (e.g., transition, flow separation, free shear flows, shock/boundary-layer interaction)*
    - Numerical methods (e.g., HOMs), grids, boundary/initial conditions, etc.
    - Improved physical modeling and simulations
      - CFD validation experiments (including physics experiment for model development)

CFD technology with above attributes will enable "Simulation-Based Engineering":

- Application to novel configurations, with confidence, for all NASA missions
  - Aeroplanes (fixed-wing , vertical lift, manned/unmanned)
  - Launch Vehicles, Aerospace Planes
  - Entry, Descent, Landing
- Aircraft certification by analysis

RCA Research Portfolio – 1:Turbulence Modeling and Simulations

OBJECTIVE

Develop new and improved turbulence models and simulation strategies that overcome the existing challenges in prediction of complex turbulent flows and significantly increase the accuracy and range of applicability of the models.

APPROACH

- **RANS Modeling**
  - Higher moment closures
  - Structure-based models
  - Explicit algebraic stress models
  - 2 eq model with improved length scale equation
  - Lag model for non-equilibrium effects
- **Eddy Resolving Methods**
  - Wall-resolved and wall-modelled LES, for high Reynolds number flows
  - Hybrid RANS/LES approaches
  - LES of mixing layers and jet flows
  - DNS of canonical flows to provide data for development/evaluation of turbulence models
- **Experimental Validation**
  - Provide flow physics data for model development/validation
  - Juncture flow experiment
  - Shock/BL interaction
  - Turbulent heat flux

RCA Research Portfolio – 2: Numerical Methods

OBJECTIVE

Develop numerical methods that significantly increase accuracy, efficiency, and robustness of turbulent flow computations for aerodynamic and propulsion applications.

APPROACH

- **Structured and Un-structured Grid Schemes with Low Numerical Dissipation and Dispersion.**
  - Flux reconstruction
  - Discontinuous Galerkin
  - Discontinuous collocation
  - Conservation element/solution element (CE/SE)
  - High-order entropy stable formulations

- **Convergence Acceleration Strategies for Efficient Solution of Navier-Stokes Equations**.
  - Grid adaptation
  - Enhanced linear/nonlinear solvers
  - Temporal integration schemes
  - High Performance Computing

- **Error Estimation and Uncertainty Quantification to Increase Solution Credibility.**

RCA Research Portfolio – 3: Transition Modeling

OBJECTIVE

Develop amplitude-based transition prediction methods for laminar flow wing design and develop reduced order transition prediction models for routine use in CFD codes.

APPROACH

- **Physics-Based Transition Prediction**
  - Receptivity to roughness
  - Linear and nonlinear parabolized stability equations
  - Subsonic/supersonic/hypersonic boundary layers
  - 2D and 3D [TS and crossflow modes]
  - Non-modal growth

- **Direct Numerical Simulation (DNS)**
  - Provide validation for lower fidelity prediction
  - Receptivity and late stage of transition

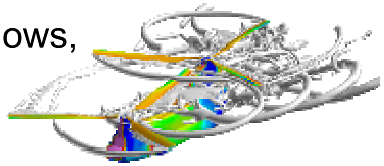
- **Validation Experiments**
  - Supersonic quiet tunnel
  - Roughness effects
  - Surface imperfections/steps
  - Crossflow-induced transition

- **Develop and Implement Reduced-order Transition Models in CFD Codes**

Vision of CFD in 2030

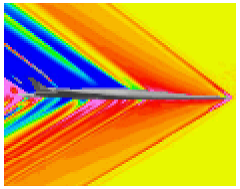
- **Emphasis on physics-based, predictive modeling**

  Transition, turbulence, separation, unsteady/time-accurate, chemically-reacting flows, radiation, heat transfer, acoustics, and constitutive models, among others.



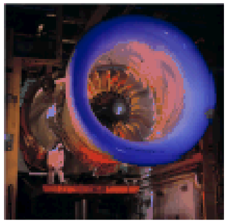
- **Management of errors and uncertainties**

  Quantification of errors and uncertainties arising from physical models (epistemic), mesh and discretization, and natural variability (aleatory) and their effect on important engineering quantities of interest.



- **A much higher degree of automation in all steps of the analysis process**

  Geometry creation, meshing, large databases of simulation results, extraction and understanding of the vast amounts of information generated with minimal user intervention.



- **Ability to effectively utilize massively parallel HPC architectures that will be available in the 2030 time frame**

  Multiple memory hierarchies, latencies, bandwidths, programming paradigms, etc.

- **Flexible use of HPC systems**

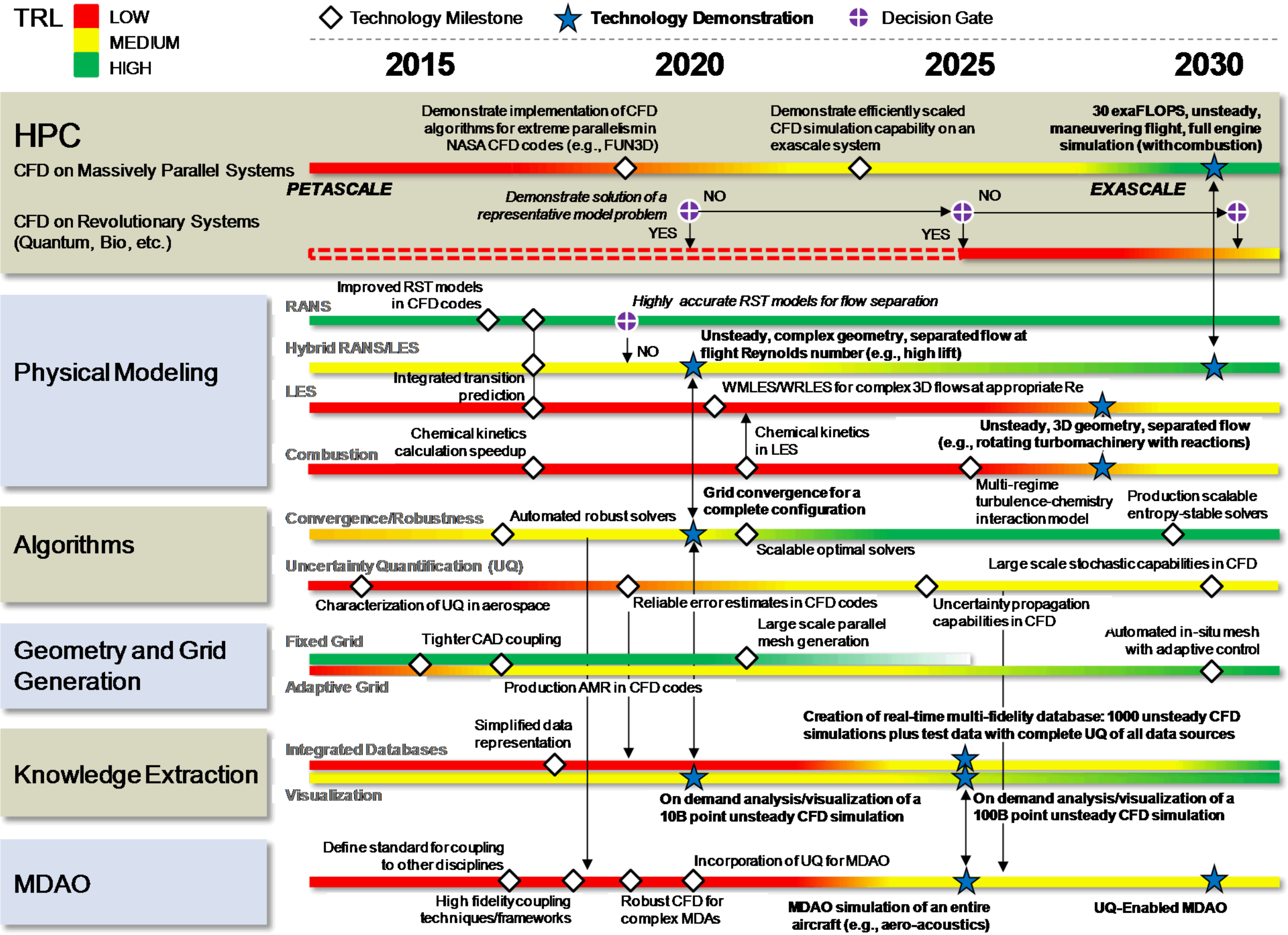
  Capacity- and capability-computing tasks in both industrial and research environments.

- **Seamless integration with multi-disciplinary analyses**

  High fidelity CFD tools, interfaces, coupling approaches, etc.

Predictive and automated physics-based tools required for timely analysis/design of novel configurations.

Technology Development Roadmap



TRL 🟥 LOW 🟨 MEDIUM 🟩 HIGH

◇ Technology Milestone ★ **Technology Demonstration** ⊕ Decision Gate

2015 2020 2025 2030

HPC

CFD on Massively Parallel Systems

Demonstrate implementation of CFD algorithms for extreme parallelism in NASA CFD codes (e.g., FUN3D)

Demonstrate efficiently scaled CFD simulation capability on an exascale system

30 exaFLOPS, unsteady, maneuvering flight, full engine simulation (with combustion)

PETASCALE

EXASCALE

CFD on Revolutionary Systems (Quantum, Bio, etc.)

Demonstrate solution of a representative model problem

NO

YES

NO

YES

Physical Modeling

RANS

Improved RST models in CFD codes

Highly accurate RST models for flow separation

NO

Hybrid RANS/LES

Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)

Integrated transition prediction

LES

WMLES/WRLES for complex 3D flows at appropriate Re

Combustion

Chemical kinetics calculation speedup

Chemical kinetics in LES

Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)

Multi-regime turbulence-chemistry interaction model

Algorithms

Convergence/Robustness

Automated robust solvers

Grid convergence for a complete configuration

Scalable optimal solvers

Production scalable entropy-stable solvers

Uncertainty Quantification (UQ)

Characterization of UQ in aerospace

Reliable error estimates in CFD codes

Uncertainty propagation capabilities in CFD

Large scale stochastic capabilities in CFD

Geometry and Grid Generation

Fixed Grid

Tighter CAD coupling

Large scale parallel mesh generation

Adaptive Grid

Production AMR in CFD codes

Automated in-situ mesh with adaptive control

Knowledge Extraction

Integrated Databases

Simplified data representation

Creation of real-time multi-fidelity database: 1000 unsteady CFD simulations plus test data with complete UQ of all data sources

Visualization

On demand analysis/visualization of a 10B point unsteady CFD simulation

On demand analysis/visualization of a 100B point unsteady CFD simulation

MDAO

Define standard for coupling to other disciplines

High fidelity coupling techniques/frameworks

Robust CFD for complex MDAs

Incorporation of UQ for MDAO

MDAO simulation of an entire aircraft (e.g., aero-acoustics)

UQ-Enabled MDAO

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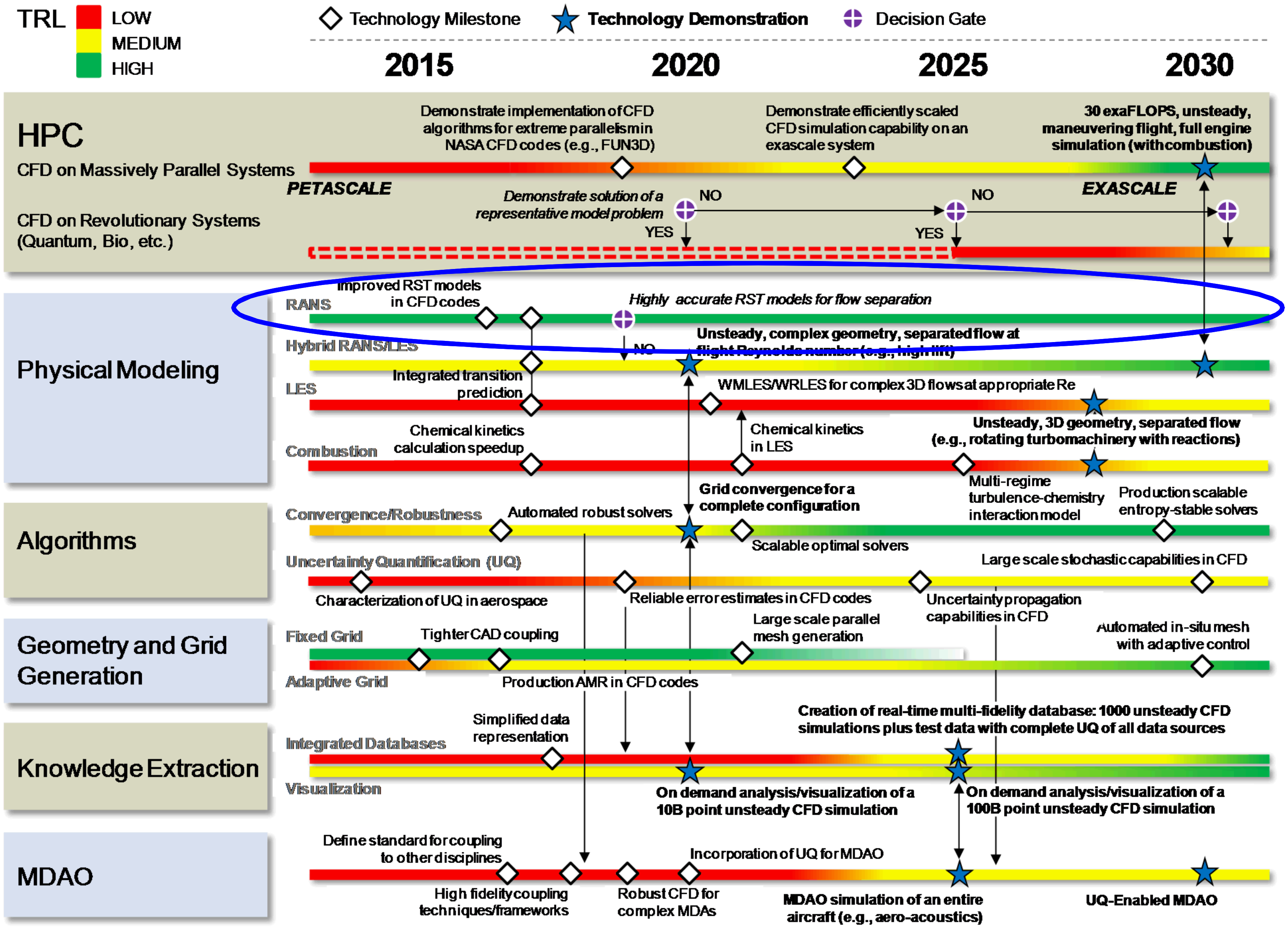

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UQ-Enabled MDAO

Problems with RANS

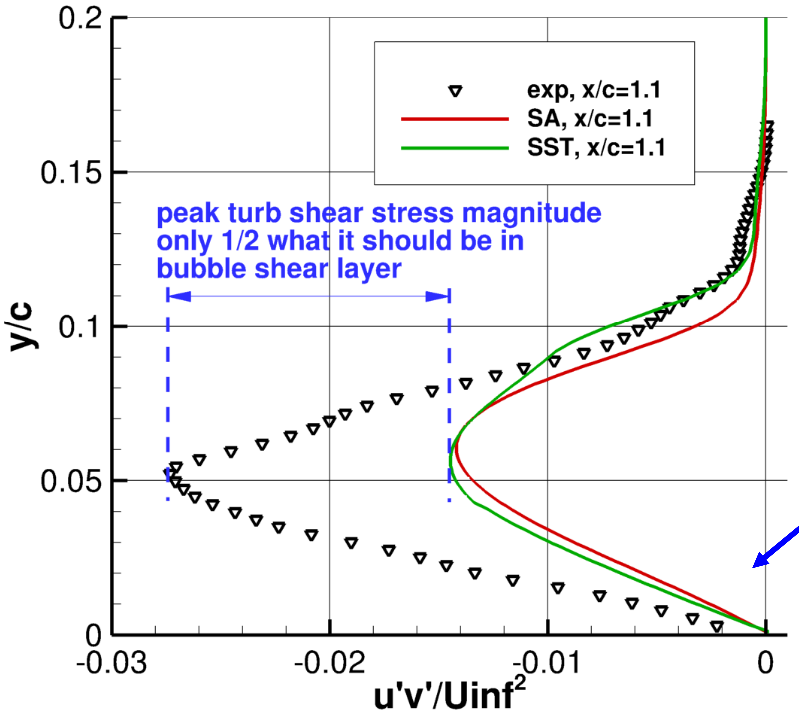
- CFD's lack of reliability for predicting separated flows is well known
  - In some cases it has been difficult to separate the effects of turbulence model from other problems (insufficient grid, unknown BCs, geometric inconsistency, etc.)
  - But after many careful studies with unit problems, it has become clear that (most? all?) RANS turbulence models are generally deficient for smooth-body separated flows

Problems with RANS (cont'd)

- Turbulent flows are inherently unsteady, with a statistical average "steady state"
  - RANS uses a model to predict this mean flow
  - URANS is simply RANS run time-accurately; it can therefore capture some large-scale time-dependent mean-flow variation (but URANS is not resolving turbulent eddies like LES or hybrid RANS/LES))
- Widely-used RANS models typically predict attached mean flows well
- But there is more going on in separated flows
  - Turbulent shear layers: may be flapping, breathing
  - Separation and reattachment locations are moving

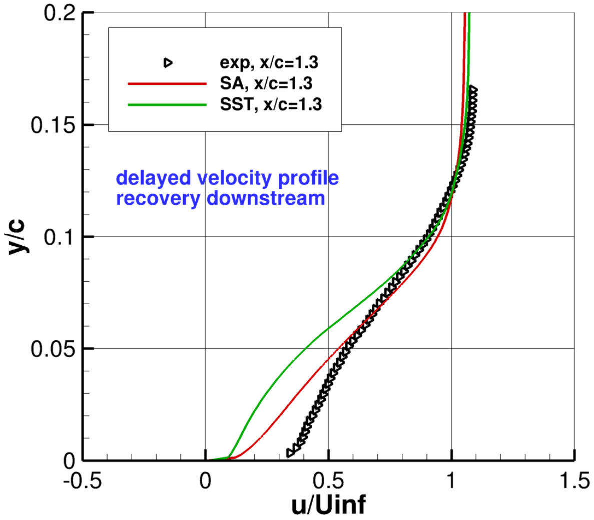
Problems with RANS (cont'd)

- The RANS philosophy itself may be inappropriate for capturing the mean effects of the inherent unsteadiness of certain types of separated flows
- One specific issue has been identified: RANS tends to underpredict the magnitude of turbulence levels in the separated region
  - Not enough turbulent mixing
  - Delayed reattachment



peak turb shear stress magnitude only 1/2 what it should be in bubble shear layer

wrong slope



delayed velocity profile recovery downstream

Problems with RANS (cont'd)

- We now ask ourselves:
  - Where do we stand?
  - Is there hope for improving RANS?
  - Where should we put our future turbulence modeling research efforts?

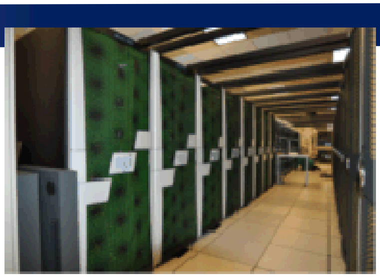
RCA Technical Challenge (TC)

RCA Research is Foundational

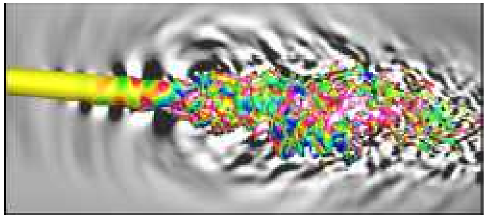
However, programmatically, it must work toward a defined technical challenge with measurable metrics

- **A first challenge was defined in FY 2013**
- **Standard Test Cases were defined in FY 2014**
  - Presented at AIAA SciTech 2015, January 2015.
    - Rumsey, C., Debonis, J. and Malik, M., “Test Cases for NASA’s Revolutionary Computational Aerosciences Technical Challenge”
    - Available at TMR website: https://turbmodels.larc.nasa.gov/StandardTestCasesFinal6.pdf
- **Challenge was concluded in mid 2018**

RCA Technical Challenge

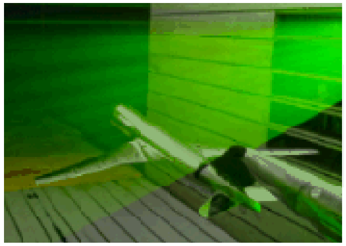


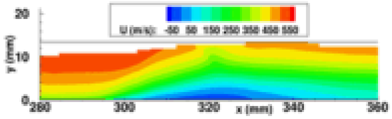
Identify and downselect critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware.



Technical Areas and Approaches

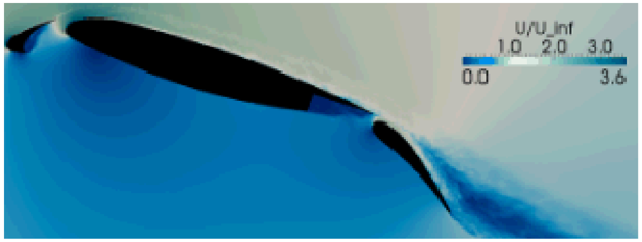
- Development of more accurate physics-based methods (e.g., higher moment closure, large eddy simulation (LES))
- Advanced numerical methods
- Transition prediction and modeling
- Validation experiments
- Multidisciplinary analysis and design (high fidelity)





Benefit/Pay-off

- Capability will be used by the aeronautics community to improve designs and reduce design cycle times.
- Facilitates accelerated introduction of advanced air vehicles and propulsion systems into the airspace system.
- Supports ARMD Strategic Thrusts # 3 (primary), 2 and 4.
- Enables aircraft certification by analysis.



RCA Standard Test Cases

- **Selected after discussions within NASA and with AIAA Turbulence Modeling Benchmark Working Group**
  - Test cases possess the relevant flow physics
  - Simple enough to be useful (avoid complex geometries/additional uncertainties)
  - RANS typically fails to provide accurate solution

- **“Best” available test cases (but in no way “ideal”)**
  - Case 1: 2D NASA hump
  - Case 2: Axisymmetric transonic bump
  - Case 3: Compressible mixing layer
  - Case 4: Round jets (cold and hot)
  - Case 5: Axisymmetric compression corner

- **Issues**
  - Not necessarily free of WT/facility effects
  - Scale-resolving simulations require more detailed boundary info than RANS
  - Some cases too old → Exercise caution on level of trust put in the results
  - What quantitative metrics for progress assessment?
    - Define some relevant metrics, but allow some leeway and use judgement
  - Note: No test case for BL transition specified

- **Case for new standard/benchmark experiments**
  - Leverage advances in measurement techniques

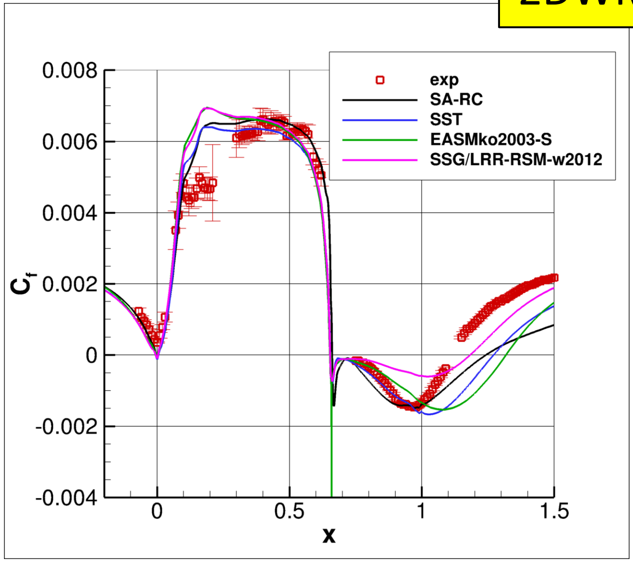
RANS approaches

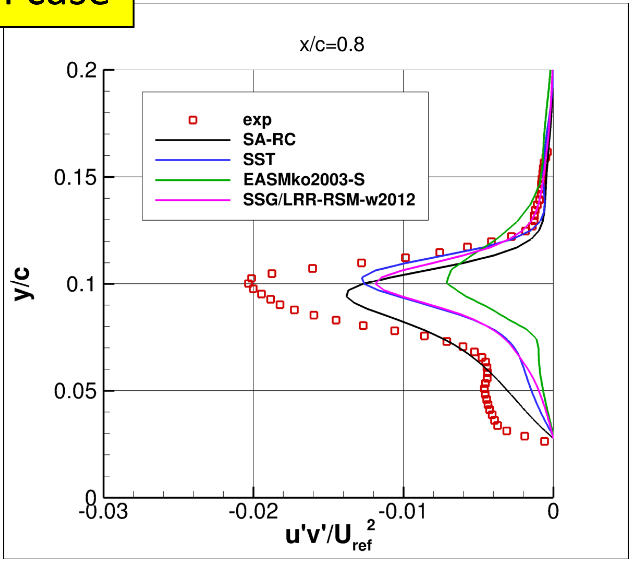
- Reynolds Stress Models (RSM)
  - 7 turbulence transport equations: one for each Reynolds stress and one for scale-determining variable (epsilon, omega, etc.)
- Nonlinear eddy-viscosity models
  - Can be built on few-equation (1,2,3) framework
  - High-order (quadratic, cubic) constitutive models
  - Algebraic models
    - EASM: Explicit Algebraic Stress Models
    - ASBM: Algebraic Structure-Based Models
- Linear eddy-viscosity models (Boussinesq)
  - These are most commonly used (e.g., SA, SST, k-omega)

RANS approaches

- Existing models from all categories are deficient
- Examples:

2DWMH case





	Separation error	Reattachment error	Bubble length error	Peak u'v' error at x=0.8
SA-RC	-0.6%	12.9%	33.6%	-31.5%
SST	-1.7%	15.6%	41.9%	-36.2%
EASMko2003-S	-1.9%	19.8%	52.9%	-64.5%
SSG/LRR-RSM-w2012	-1.7%	7.5%	21.6%	-40.5%

Attempted progress…

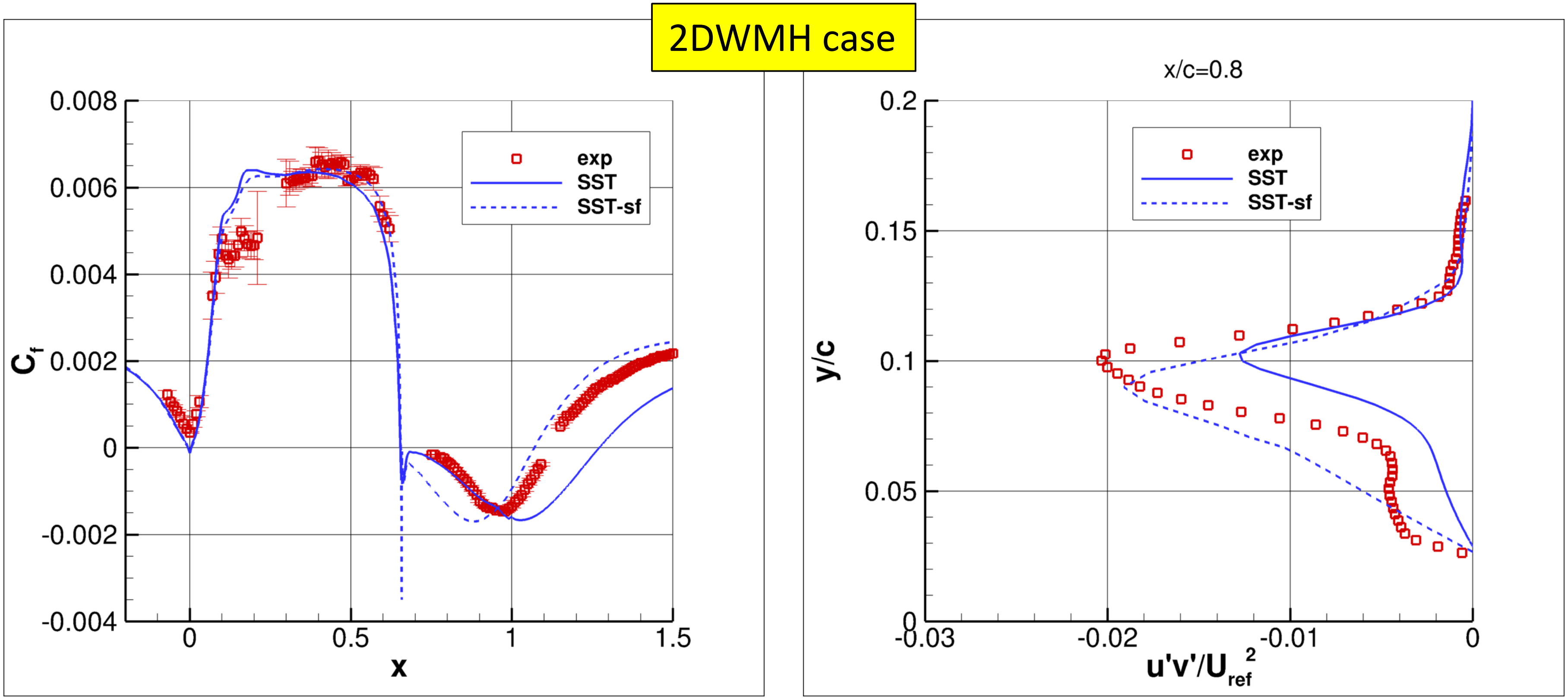
- Several recent efforts have been geared toward “fixing” existing RANS models for separated flows
- New k-kL model variants have also been developed and tested

SST separation fix

- Described in NASA/TM-2009-215952
- Briefly:
  - It has been noted that P/e tends to be high (e.g., 3-8) in separated shear layers immediately downstream of separation
  - Destruction term in omega eqn is multiplied by F_{sf}
  - F_{sf} is a function of local P/e, turned off inside boundary layers using f_d function from DDES
  - Idea behind the fix: when P/e exceeds 1.5 in separated shear layers, omega destruction increases, which decreases omega and increases eddy viscosity

SST separation fix

2DWMH case



	Separation error	Reattachment error	Bubble length error	Peak u'v' error at x=0.8
SST	-1.7%	15.6%	41.9%	-36.2%
SST-sf	-1.5%	-2.8%	-4.7%	-4.3%

SST separation fix

- SST fix improves results for NASA hump (2DWMH)
- Other results (see NASA/TM-2009-215952):
  - 2-D hill: Improved
  - Axisymmetric transonic bump (ATB): No change
  - 2-D diffuser (see paper): No change
  - 2-D backward facing step (2DBFS): Worse
  - 2-D mixing layer (2DML): Much Worse

- Summary: this fix can help for separated flows, but depends on the case
- Particularly hurts 2DML

EASM separation fix

- Described in CTR Proceedings of the Summer Program 2012, pp. 273-282

$$\cancel{\frac{Db_{ij}}{Dt}} - \frac{1}{2k}\left(D_{ij} \cancel{- \frac{\tau_{ij}}{k}} D\right) = -b_{ij}\frac{\varepsilon}{k}\left(\frac{P}{\varepsilon}-1\right) - \frac{2}{3}S_{ij} - \left(b_{ik}S_{kj} + S_{ik}b_{kj} - \frac{2}{3}b_{mn}S_{mn}\delta_{ij}\right)$$

$$+\left(b_{ik}W_{kj} - W_{ik}b_{kj}\right) + \frac{\boxed{\pi_{ij}}}{2k}$$

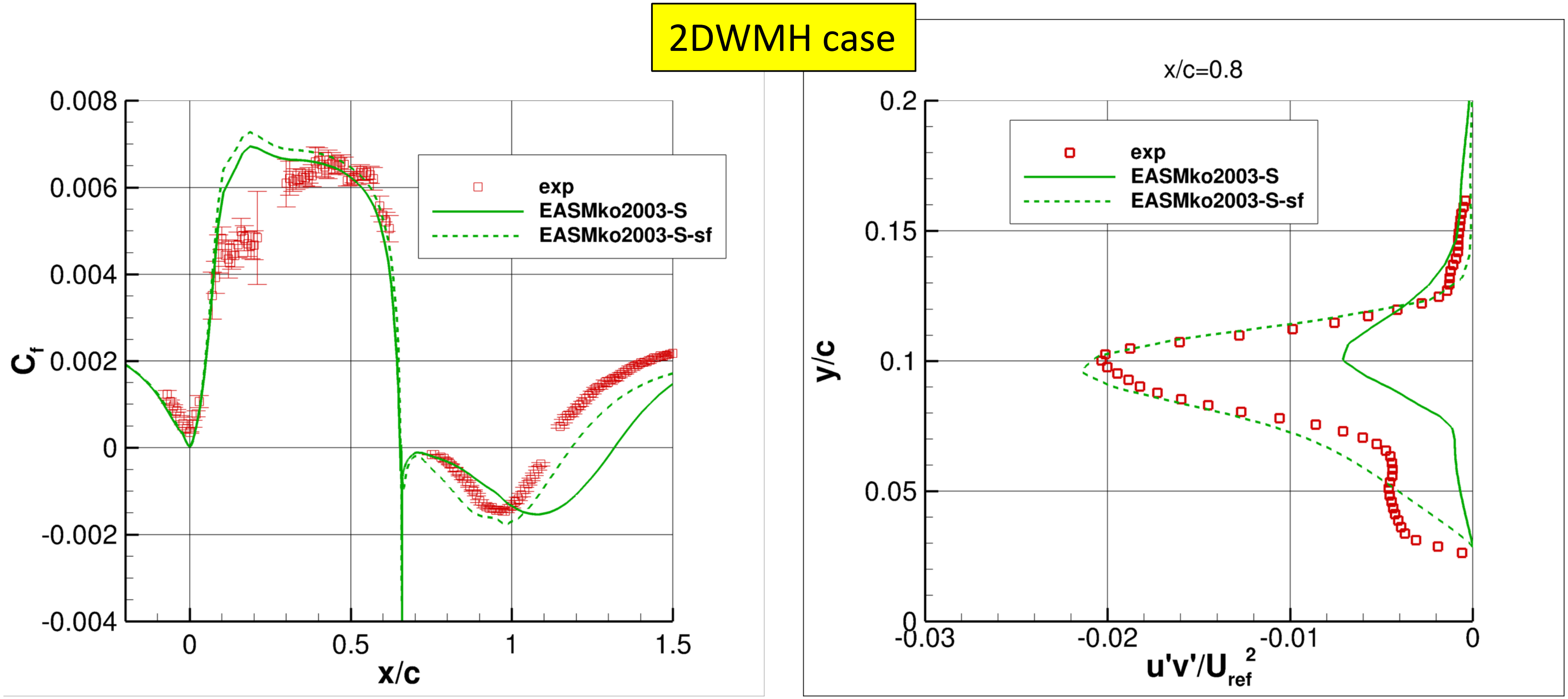
Pressure-strain model

EASM is derived from transport equation for Reynolds stress anisotropy tensor b_{ij} (assuming isotropic dissipation rate). Assuming turbulence is at equilibrium and that anisotropy of turbulent transport and viscous diffusion is proportional to anisotropy of Reynolds stresses: get implicit algebraic equation. Get explicit closed-form analytic solution using 3 basis tensors (exact for 2-D, approximate for 3-D), in conjunction with a linear pressure-strain model.

One of the pressure-strain constant coefficients is modified to be a function of local P/e

EASM separation fix

2DWMH case



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EASMko2003-S	-1.9%	19.8%	52.9%	-64.5%
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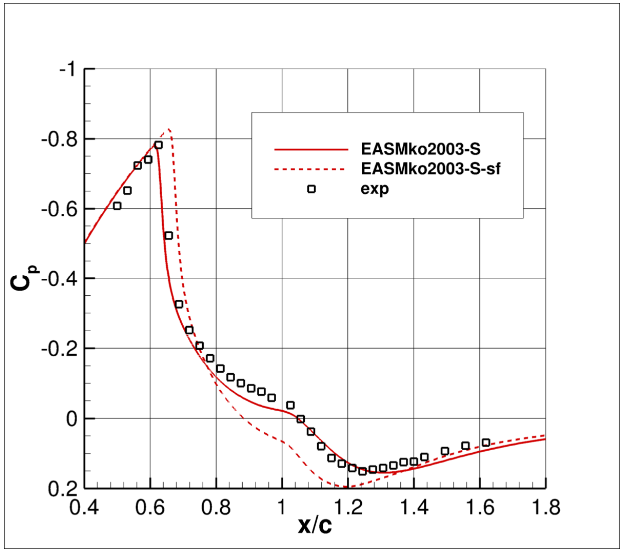
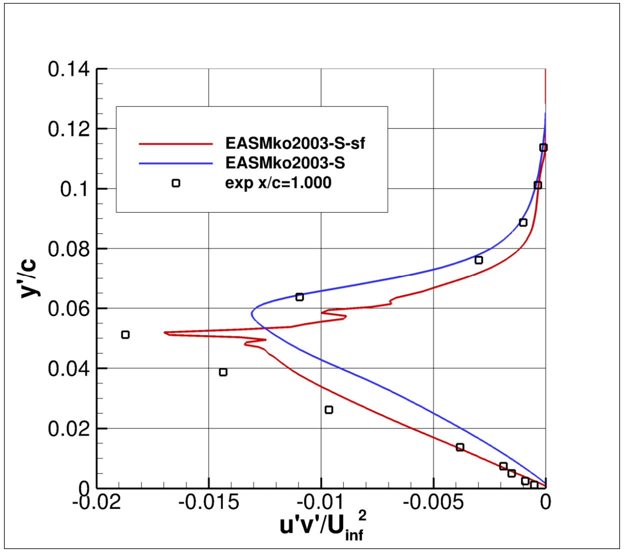
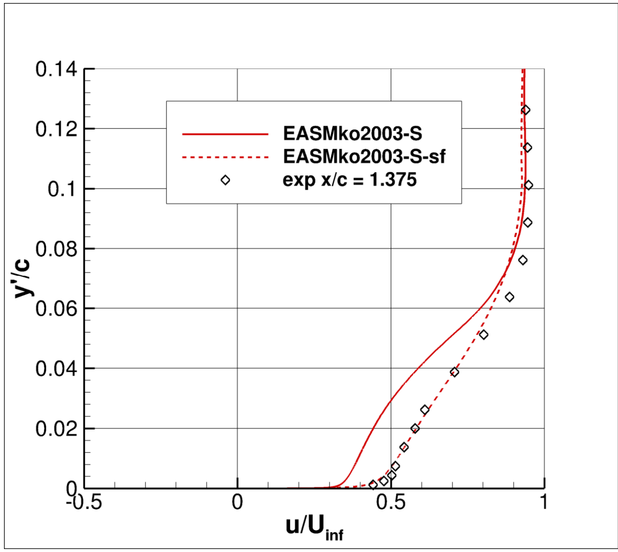
EASMko2003-S-sf for ATB case

ATB case







	Separation error	Reattachment error	Bubble length error	Peak u'v' error at x=1.0
EASMko2003-S	-6.6%	4.5%	23.9%	-31.1%
EASMko2003-S-sf	-2.1%	-0.6%	2.1%	-11.2%

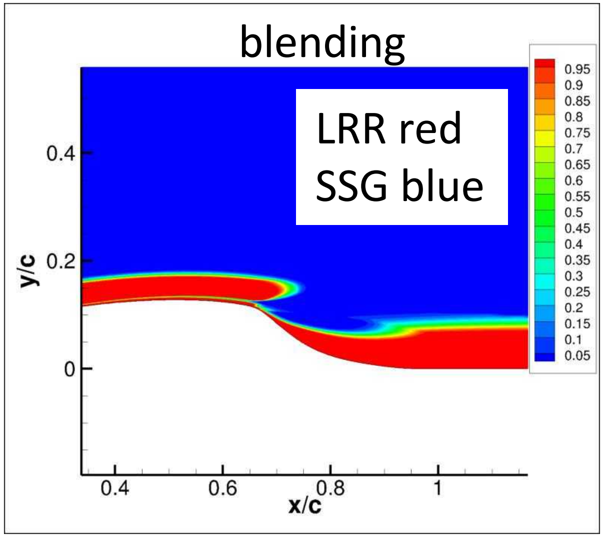
EASM separation fix

- EASM fix improves results for NASA hump (2DWMH)
- Axisymmetric transonic bump (ATB): In some ways Improved, in some ways Worse
- Other results (not shown here):
  - 2-D Rounded backstep (see paper): Improved
  - 2-D Backward facing step (2DBFS): Improved
  - 2-D mixing layer (2DML): Improved

- Summary: this fix can help for separated flows, but depends on the case

RSM separation fix

- RSM stress-omega version SSG/LRR-RSM-w2012 has been verified in multiple codes
- It blends the LRR and SSG pressure-strain models



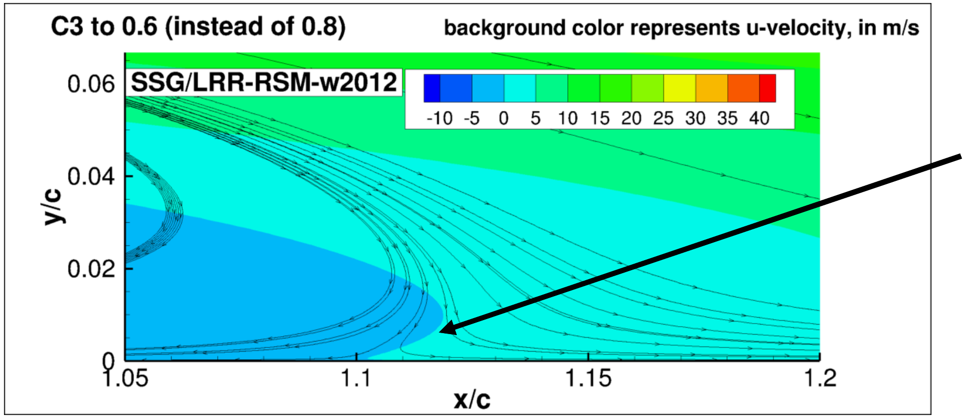
SSG pressure-strain model:

$$
\begin{aligned}
\rho\Pi_{ij} &= -\left(C_1\rho\varepsilon+\frac{1}{2}C_1^{*}\rho P_{kk}\right)b_{ij} \\
&+C_2\rho\varepsilon\left(b_{ik}b_{kj}-\frac{1}{3}b_{kl}b_{kl}\delta_{ij}\right) \\
&+(\boxed{C_3}-C_3^{*}\sqrt{b_{kl}b_{kl}})\rho k S_{ij}^{*} \\
&+C_4\rho k\left(b_{ik}S_{jk}+b_{jk}S_{ik}-\frac{2}{3}b_{kl}S_{kl}\delta_{ij}\right) \\
&+C_5\rho k\left(b_{ik}W_{jk}+b_{jk}W_{ik}\right)
\end{aligned}
$$

Same term altered in the 2012 CTR study. This constant has a large effect on RANS behavior in separated regions (nominal value=0.8)

RSM separation fix

- Changes to original model:
  - C_3 decreased to 0.53 in SSG model (leaving LRR alone), because blending function has LRR act near walls while SSG acts outside (including separated shear layer)
  - $C_1^{*(e)}=0$
  - Standard diffusion only (not generalized gradient)
  - Broader blending function (arg**2 instead of arg **4)
  - Yap correction⁺ added (to avoid backbending) at reattachment



⁺Yap correction described at http://www.cfd-online.com/Wiki/Yap_correction

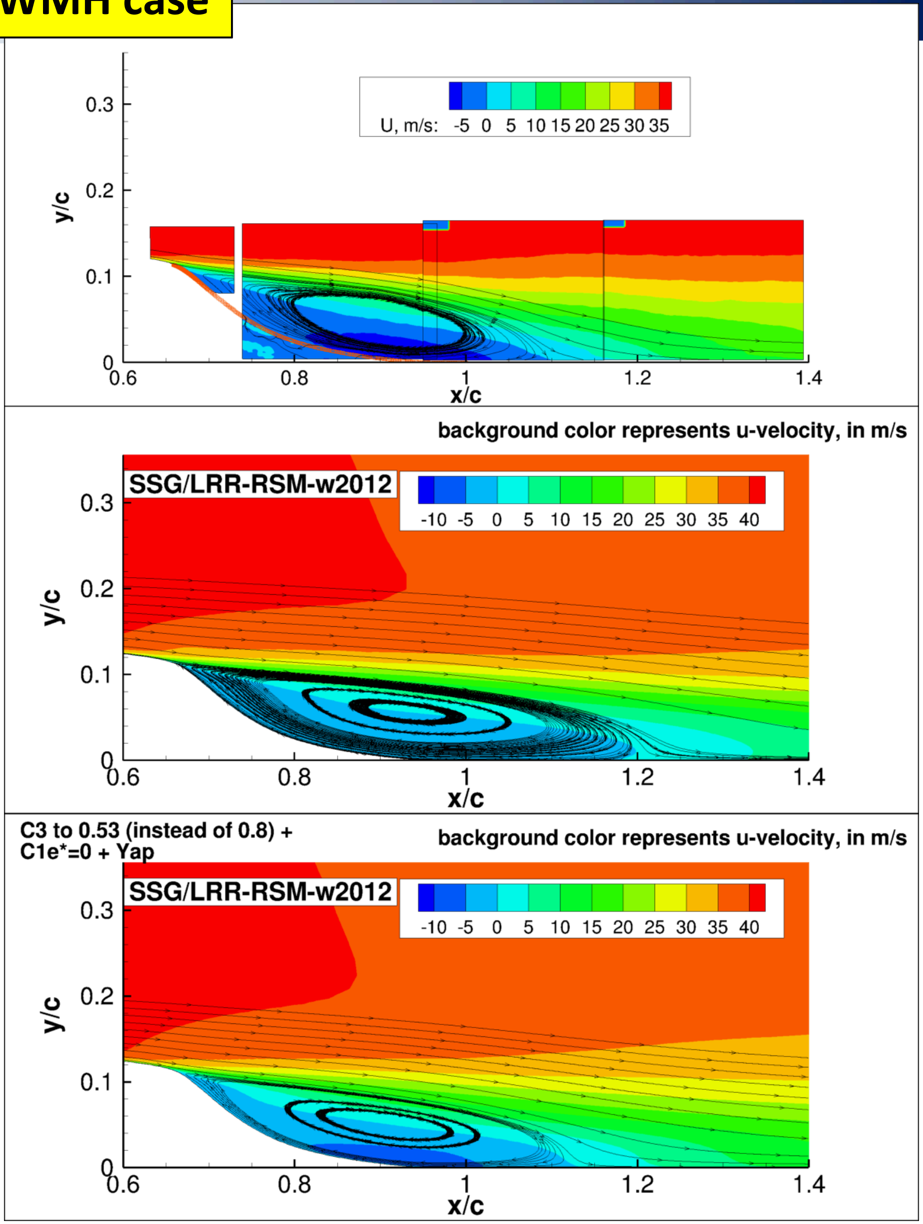
RSM separation fix

2DWMH case

experiment

Original RSM

New RSM



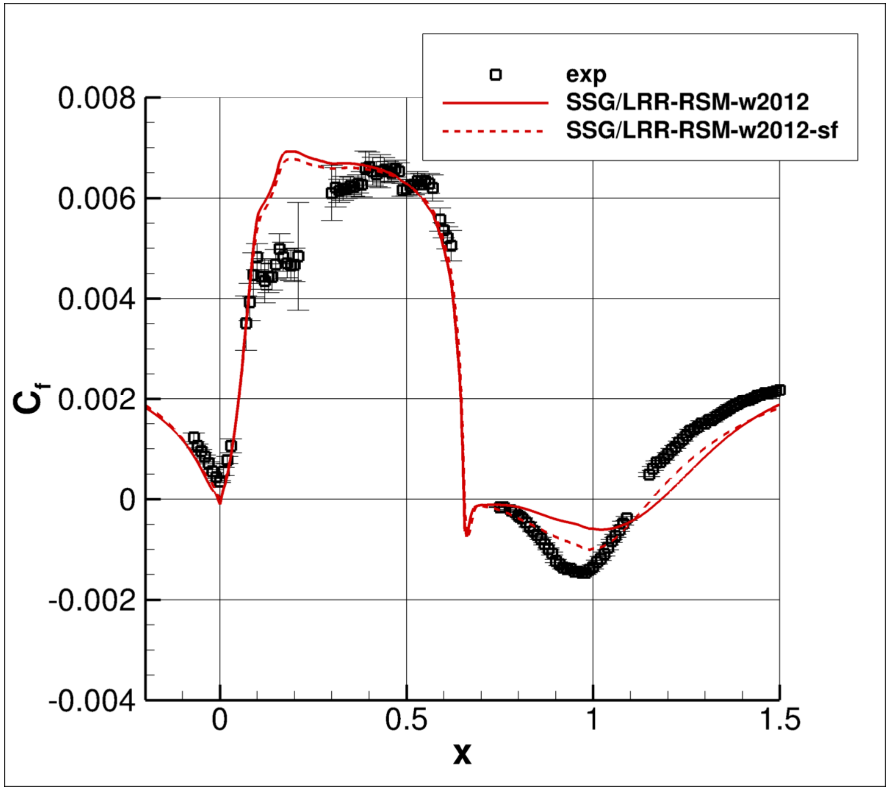
background color represents u-velocity, in m/s

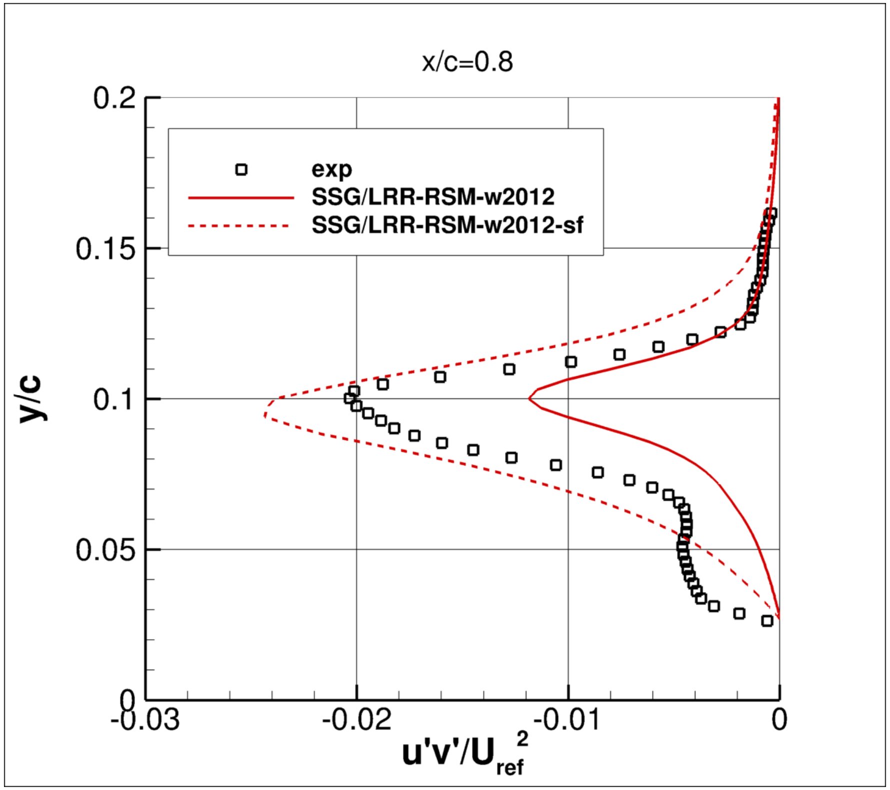
C3 to 0.53 (instead of 0.8) +
C1e*=0 + Yap

background color represents u-velocity, in m/s

RSM separation fix

2DWMH case





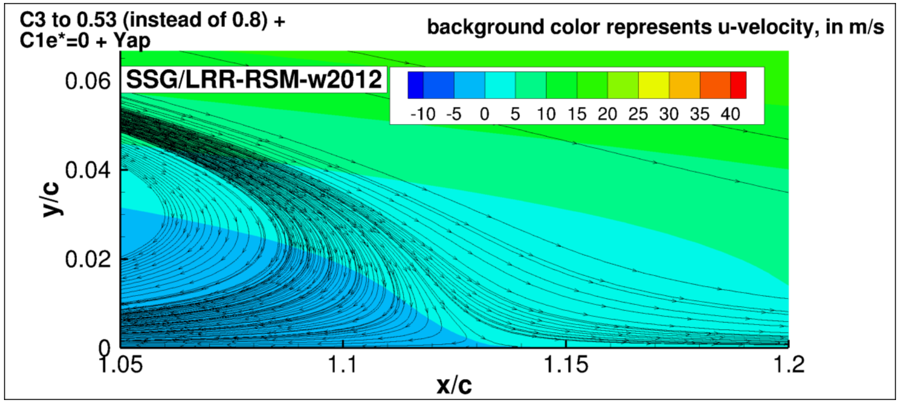
	Separation error	Reattachment error	Bubble length error	Peak u'v' error at x=0.8
SSG/LRR-RSM-w2012	-1.7%	7.5%	21.6%	-40.5%
SSG/LRR-RSM-w2012-sf	-1.5%	5.1%	15.1%	21.5%

would be higher if no backbending

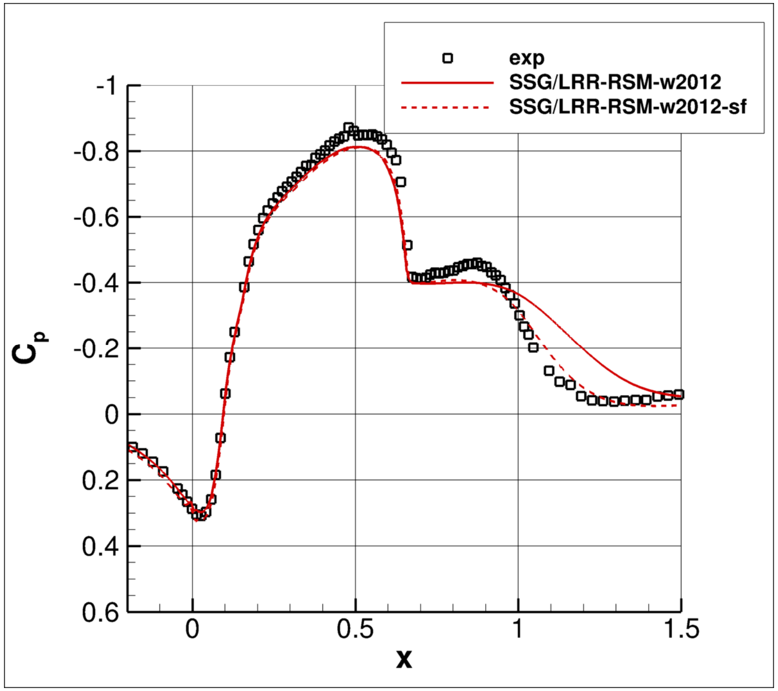
RSM separation fix

2DWMH case

- More turbulence in separated shear layer
- Deeper C_f in separated region (closer to exp)
- Backbending at reattachment has been eliminated


C3 to 0.53 (instead of 0.8) + C1e*=0 + Yap

background color represents u-velocity, in m/s

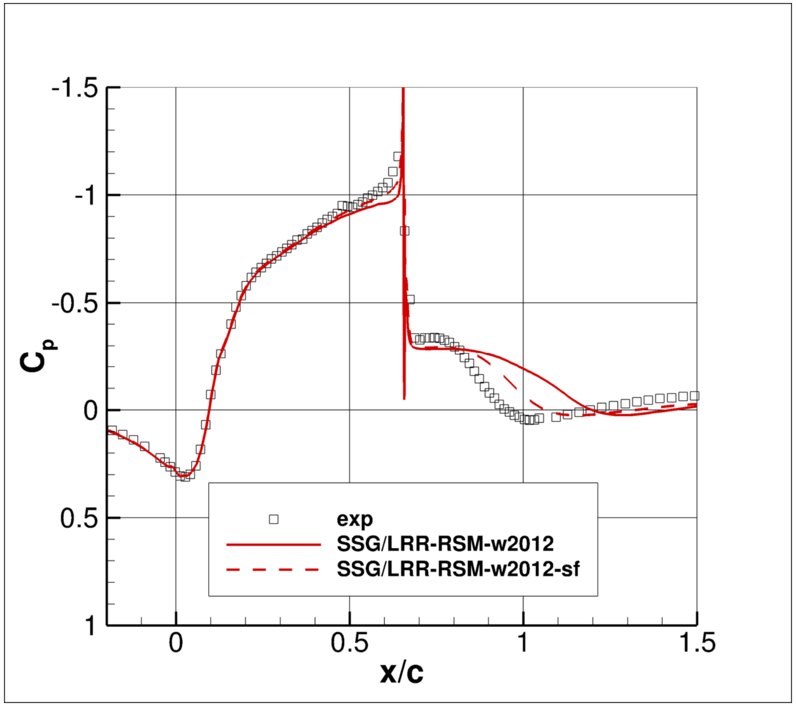


C_p much improved

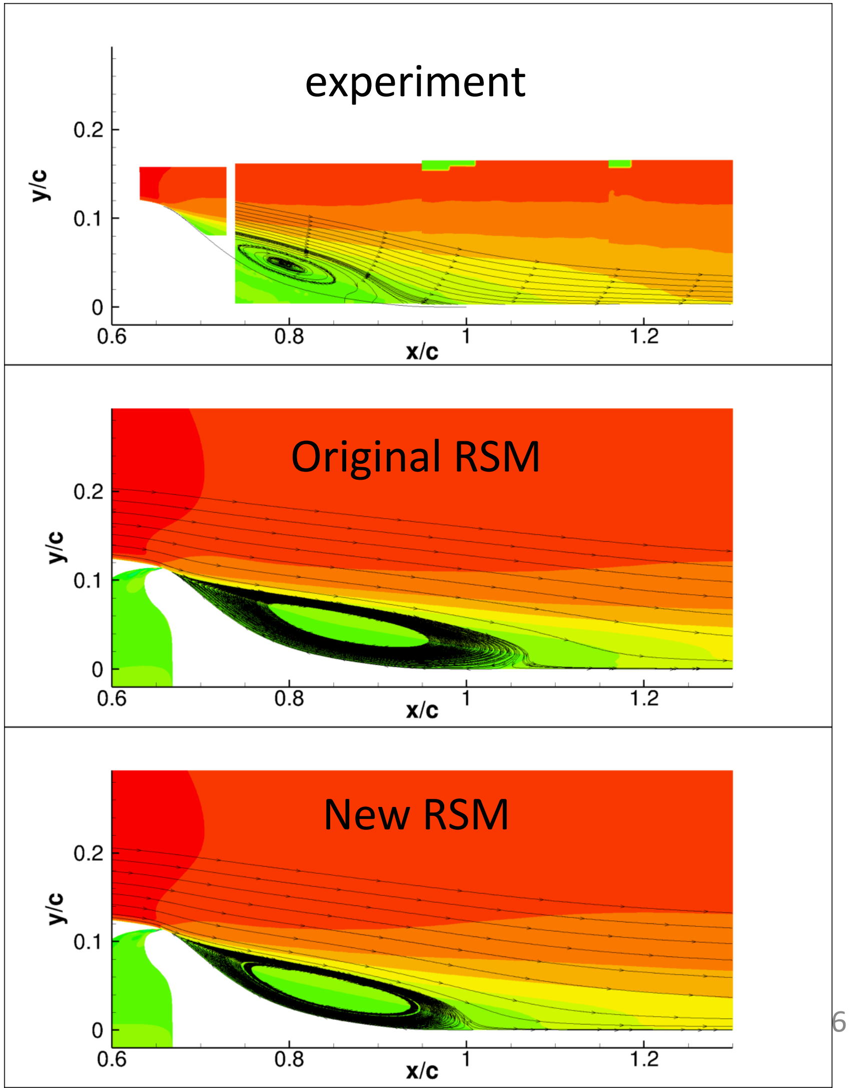
RSM separation fix

2DWMH suction case

- Improves NASA Hump *suction* case also

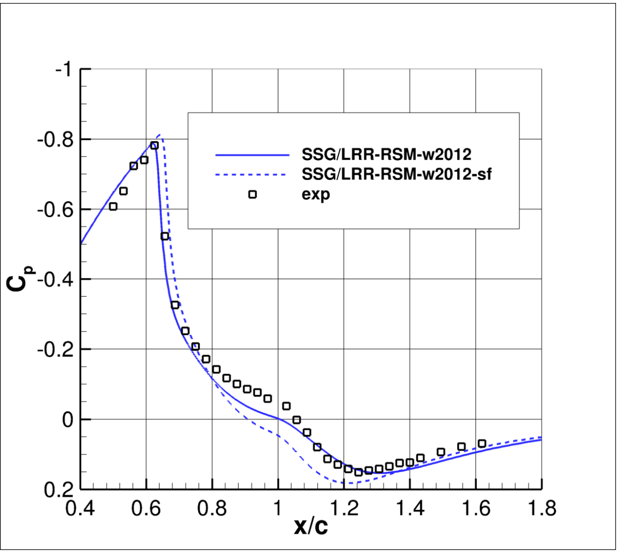


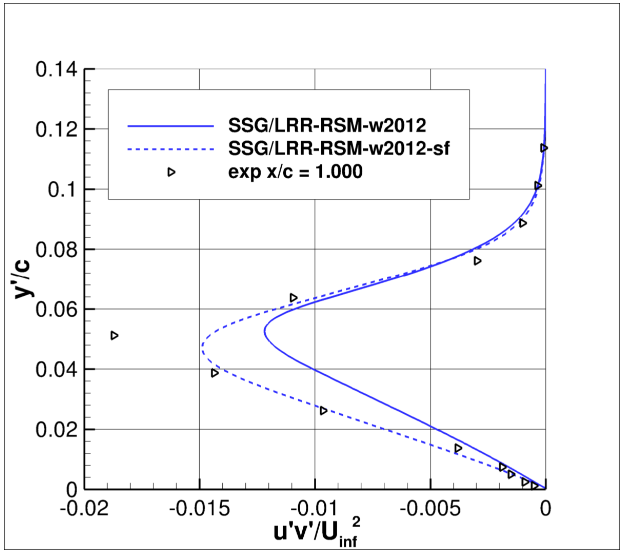
although bubble is still too large!

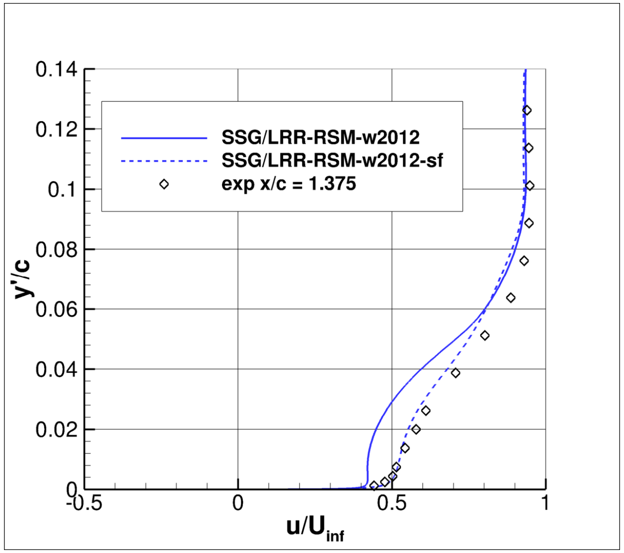


RSM separation fix

ATB case

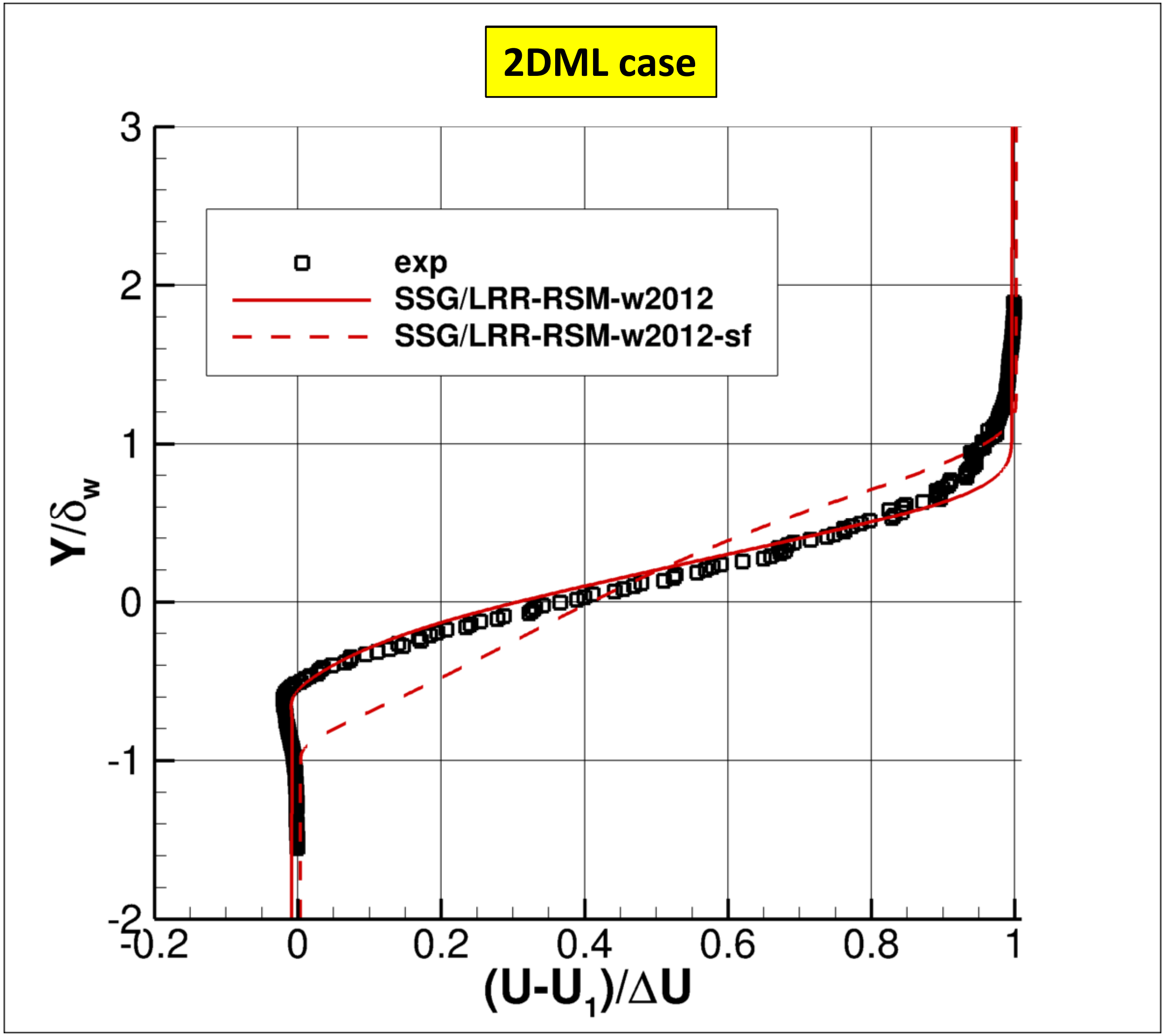






	Separation error	Reattachment error	Bubble length error	Peak u'v' error at x=1.0
SSG/LRR-RSM-w2012	-5.0%	-2.5%	1.9%	-35.8%
SSG/LRR-RSM-w2012-sf	-2.9%	-1.8%	0.1%	-21.6%

SSG/LRR-RSM-w2012-sf for 2DML case



RSM separation fix

- RSM fix improves results for NASA hump (2DWMH)
- Axisymmetric transonic bump (ATB): In some ways Improved, in some ways Worse
- 2-D mixing layer (2DML): Much Worse
- Other results (not shown here):
  - 2-D backward facing step (2DBFS): In some ways Improved, in some ways Worse

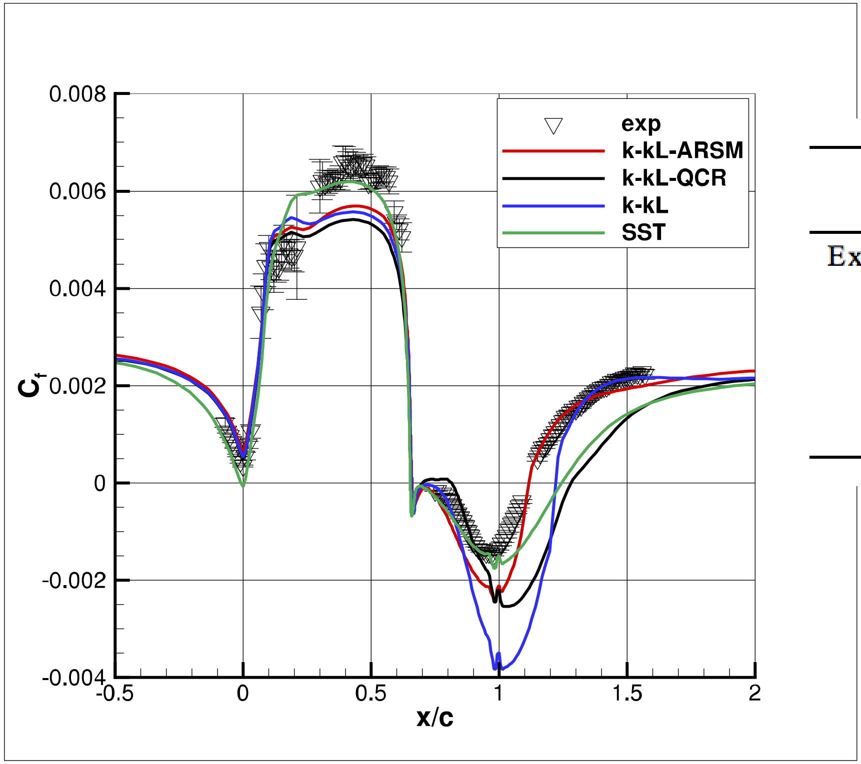
- Summary: this fix can help for separated flows, but depends on the case
- Particularly hurts 2DML

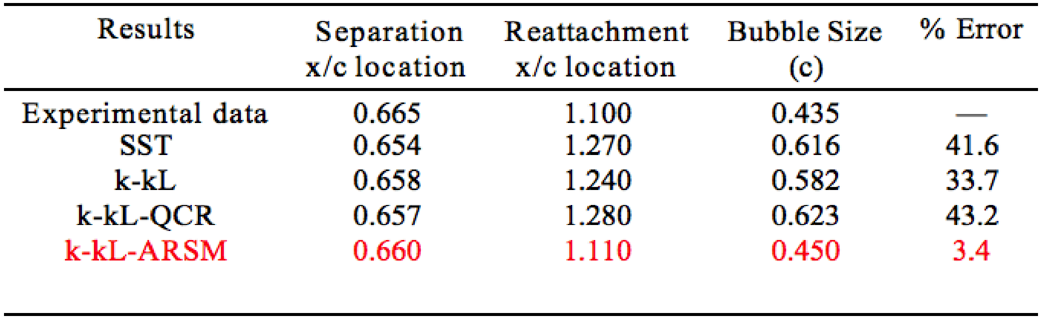
K-kL model variants

- Developed by Abdol-Hamid
  - Two-equation turbulence model formulation based on earlier work of Menter & Egorov (FTC 2010) and Smith (AIAA 2015-2922)
  - No blending functions
  - Simple wall BCs
  - Includes a von Karman length scale term in the production term of the kL equation
  - Linear k-kL-MEAH2015
    - NASA/TM-2015-218968
  - Nonlinear k-kL Algebraic Reynolds Stress Model (ARSM) k-kL-ARSM2018+J
    - NASA/TM-2018-219820
    - "+J" indicates jet/shear flow correction
  - (There are also QCR and RSM variants in development)

K-kL: 2-D NASA Hump Model

Baseline case: Typical RANS >35% error in bubble size





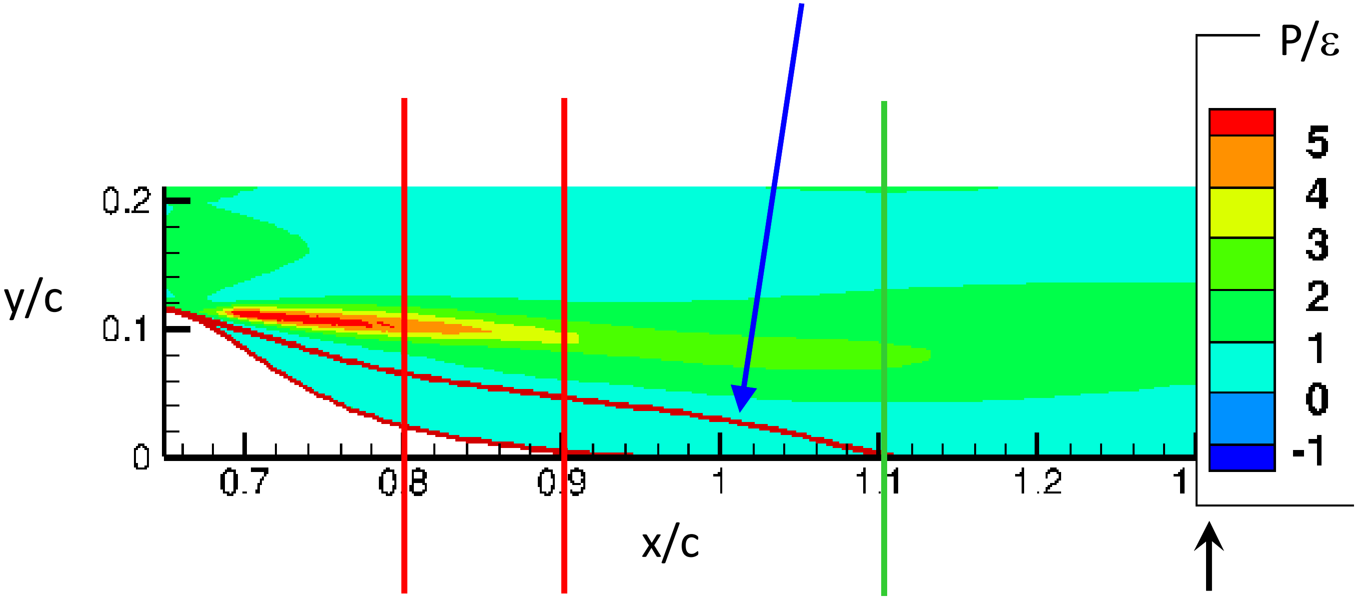
Results	Separation x/c location	Reattachment x/c location	Bubble Size (c)	% Error
Experimental data	0.665	1.100	0.435	—
SST	0.654	1.270	0.616	41.6
k-kL	0.658	1.240	0.582	33.7
k-kL-QCR	0.657	1.280	0.623	43.2
k-kL-ARSM	0.660	1.110	0.450	3.4

k-kL-ARSM gives only 3.4% error for the bubble length
(but underpredicts C_f for 0.25<x/c<0.6)

K-kL: 2-D NASA Hump Model

Why does k-kL-ARSM produce reasonable separated flow results?

Separation line



x/c=0.8 0.9 1.1 1.3

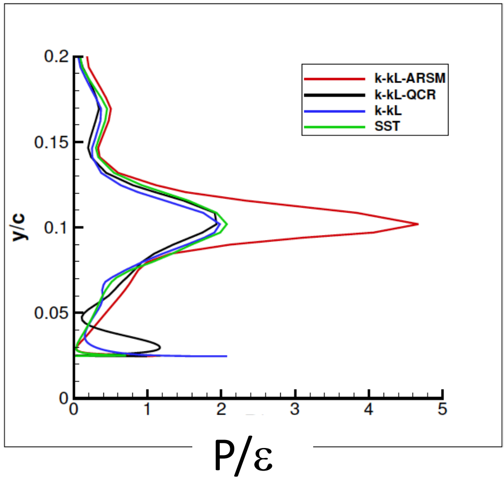
Separation locations

Attachment locations

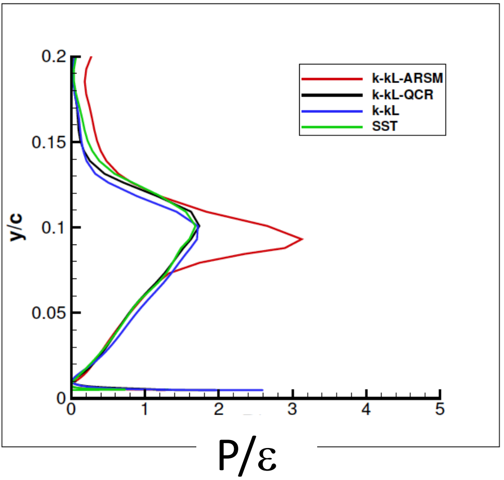
K-kL: 2-D NASA Hump Model

Why does k-kL-ARSM produce reasonable separated flow results?

x/c=0.8



x/c=0.9



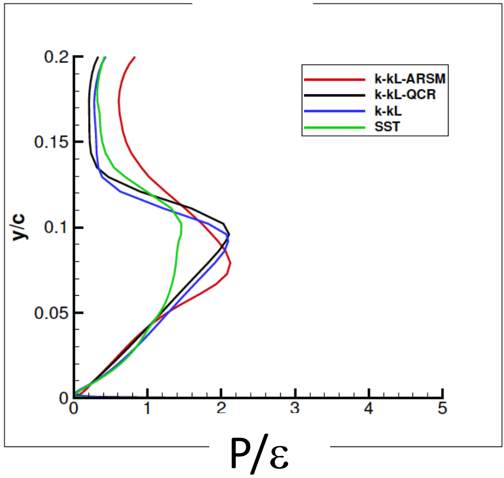
🟥 k-kL-ARSM

⬛ k-kL-QCR

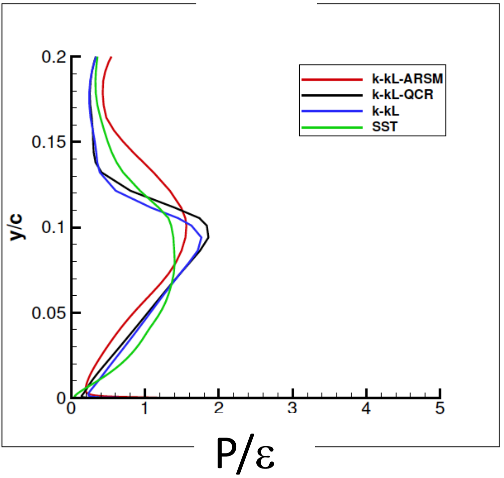
🟦 k-kL

🟩 SST

x/c=1.1



x/c=1.3



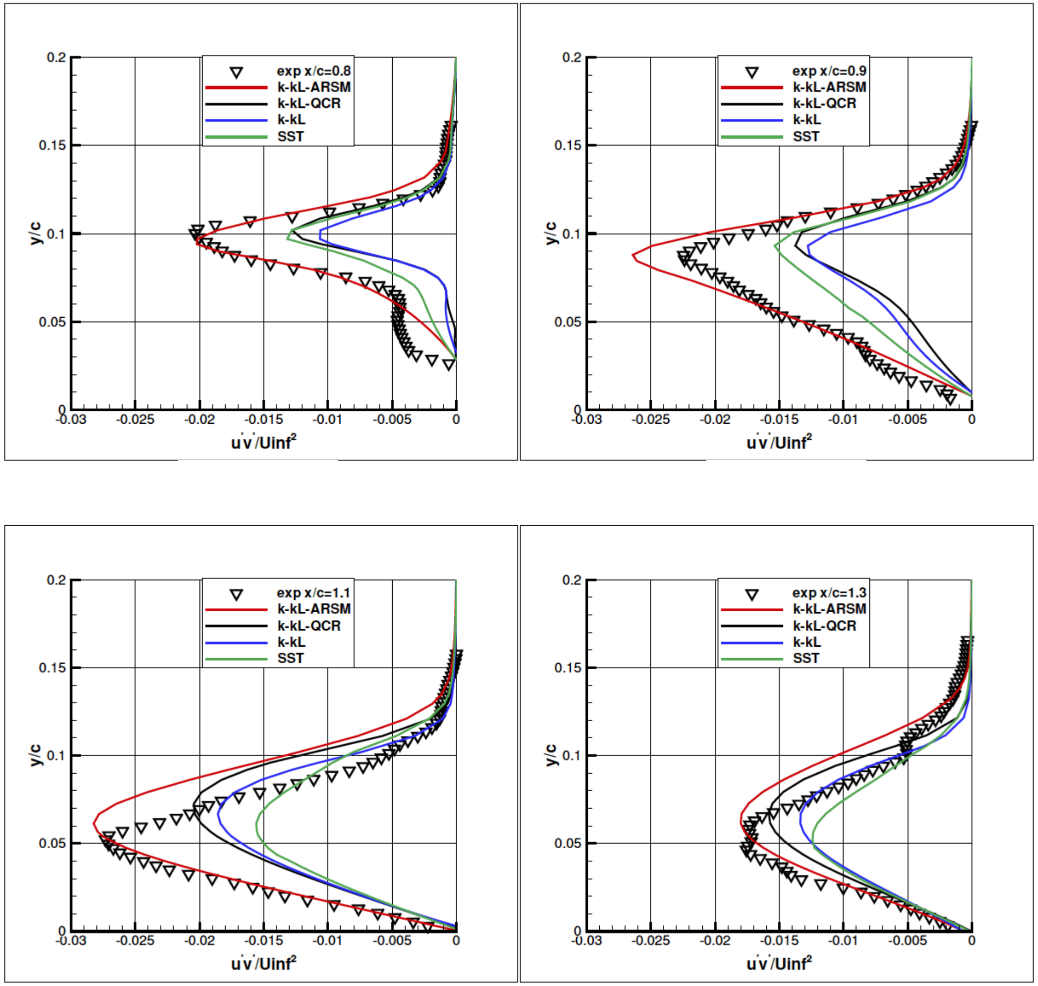
High P/ε in the separation region (similar to LES results)

K-kL: 2-D NASA Hump Model

Typical RANS turbulent shear stress too low

x/c=0.8

x/c=0.9



x/c=1.1

x/c=1.3

▽ exp

🟥 k-kL-ARSM

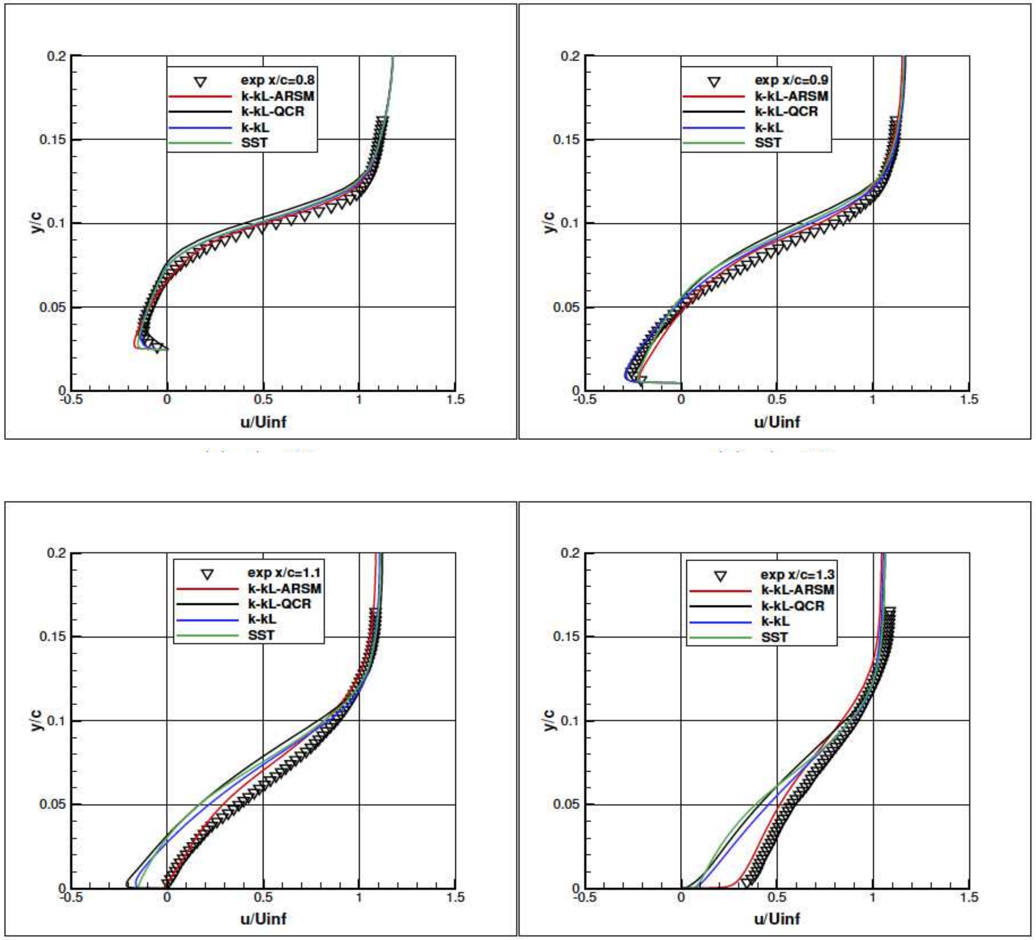
⬛ k-kL-QCR

🟦 k-kL

🟩 SST

K-kL-ARSM gives better prediction for magnitude of shear stress

K-kL: 2-D NASA Hump Model



x/c=0.8

x/c=0.9

x/c=1.1

x/c=1.3

▽ exp

k-kL-ARSM

k-kL-QCR

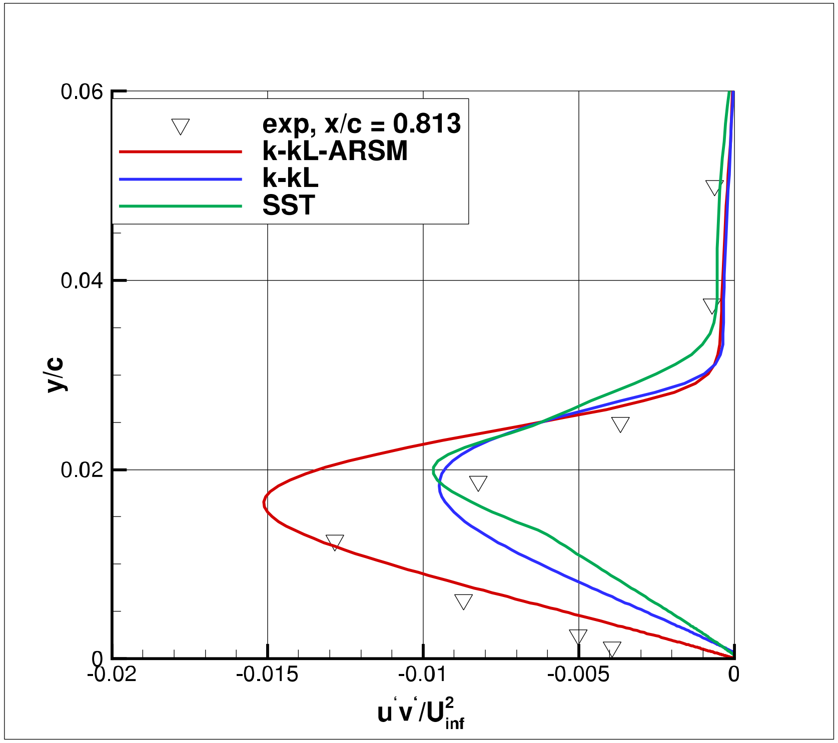
k-kL

SST

K-kL-ARSM gives better prediction of velocity profiles

K-kL: Axisymmetric Transonic Bump

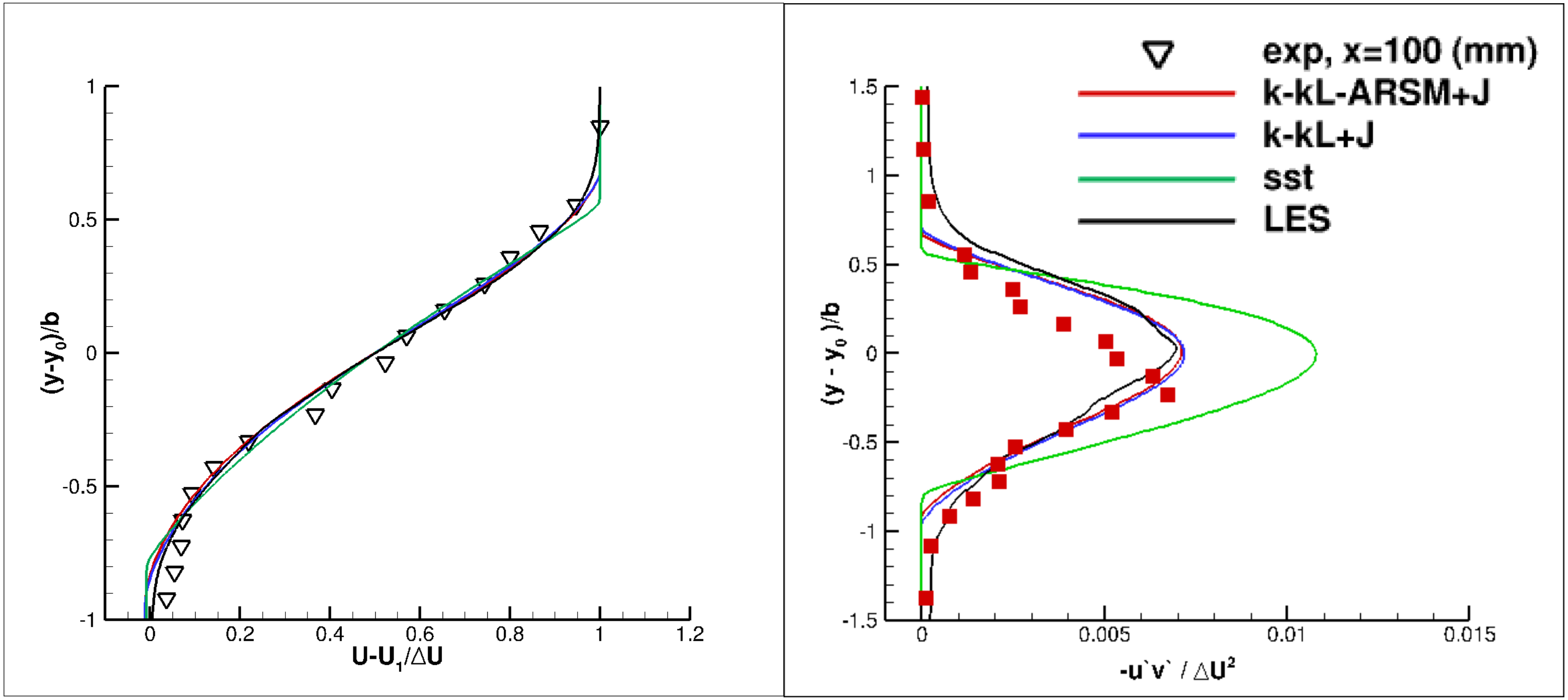
Baseline case: Typical RANS 20-30% error in bubble size



Results	Separation x/c location	Reattachment x/c location	Bubble Size (c)	% Error
Experimental data	0.700	1.100	0.400	—
SST	0.665	1.160	0.495	23.70
k-kL	0.669	1.120	0.451	12.70
k-kL-QCR	0.665	1.140	0.475	18.75
k-kL-ARSM	0.701	1.050	0.349	13.00

k-kL-ARSM gives 13% error for the bubble length

K-kL: Compressible Mixing Layer



k-kL-ARSM still performs well for mixing layers

Summary of RANS efforts

- “Separation fixes” have been developed for different RANS model types (linear eddy viscosity, EASM, RSM)
  - These fixes are specifically designed to increase the turbulence levels in the separated shear layer, but they do it in an *ad hoc* manner
  - Fixes are mostly tuned based on a few basic nominally 2D experiments or 2D simulations; significantly more testing would be required for 3D/complex cases
  - Consistency issues:
    - fixes do not necessarily help in all separated flow situations
    - difficult to improve all aspects of a case (get right answer for right reasons)
    - difficult to help flows that need it while not hurting other flows
  - As such, they do not necessarily improve the state of the art in a reliable and predictive sense
  - They may nonetheless serve as useful tools in the RANS arsenal
- New k-kL-ARSM performs well for separated flows tested
  - While not harming free mixing layers
  - It is undergoing further evaluation

Summary

- **RCA Research Portfolio**
    - ➢ Progress toward RCA research goals and CFD 2030 roadmap

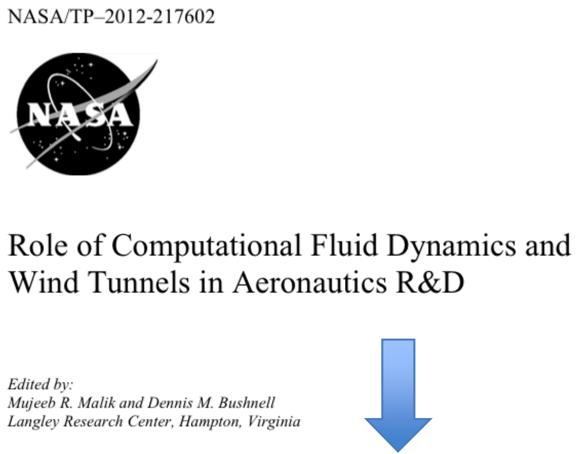
- **RCA 40% Technical Challenge**
    - – LES (including wall-resolved for walled flows) provided required improvement for all test cases
        - ▪ Computational cost is a challenge for practical applications
    - – Some wall-modelled and/or hybrid RANS/LES approaches provided required improvement for walled flows
        - ▪ Wall models/interface approaches need improvement
        - ▪ Best practices (e.g., grids, inflow) need to be established
    - – **RANS models (including RSM) could be "tuned" to meet the goal, but often at the expense of general capability**

Summary (cont'd)

- **The future of RANS?**
  - RANS will continue to be part of the computational toolbox, at least for external flows, owing to its significant cost advantage
  - But the open question remains: how much **research** effort should continue to be devoted to improving RANS for separated flows (and other specific needs)?
  - We still hold out hope that continued exploration of detailed flow physics for a variety of unit problems using DNS and LES will help point the way to improved RANS models
  - The Turbulence Modeling Resource (TMR) website and the AIAA Turbulence Model Benchmarking Working Group (TMBWG) are dedicated to:
    - Providing verification & validation cases for widely-used RANS models
    - Serving as a forum for new models and modeling ideas
    - More time should be spent seeking and collaboratively testing new RANS models for flows where most models currently fail
  - A "community of collaborators" is needed!

Backup slides

RCA Background

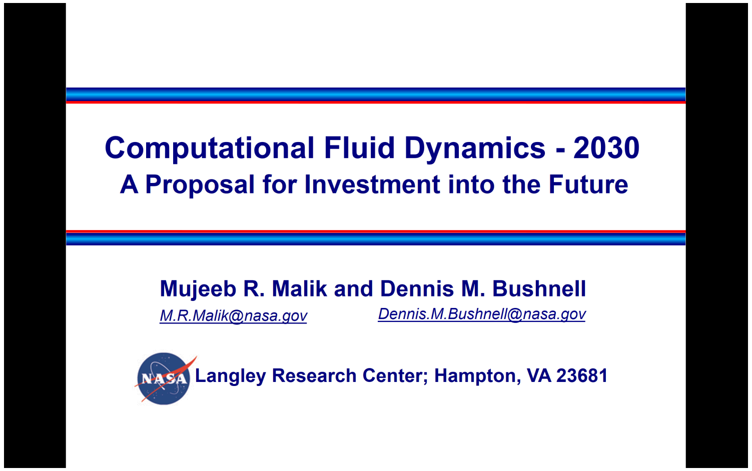


NASA/TP–2012-217602

Role of Computational Fluid Dynamics and Wind Tunnels in Aeronautics R&D

Edited by:
Mujeeb R. Malik and Dennis M. Bushnell
Langley Research Center, Hampton, Virginia

2010



Computational Fluid Dynamics - 2030
A Proposal for Investment into the Future

Mujeeb R. Malik and Dennis M. Bushnell
M.R.Malik@nasa.gov Dennis.M.Bushnell@nasa.gov

Langley Research Center; Hampton, VA 23681

"…Research is needed for the advancement of CFD algorithms with respect to accuracy, speed, and robustness, as well as in the development of advanced turbulence models."

Launch of RCA under SFW Project in 2012

CFD Vision 2030 Study NRA

RCA in new Aeronautical Sciences Project in 2013

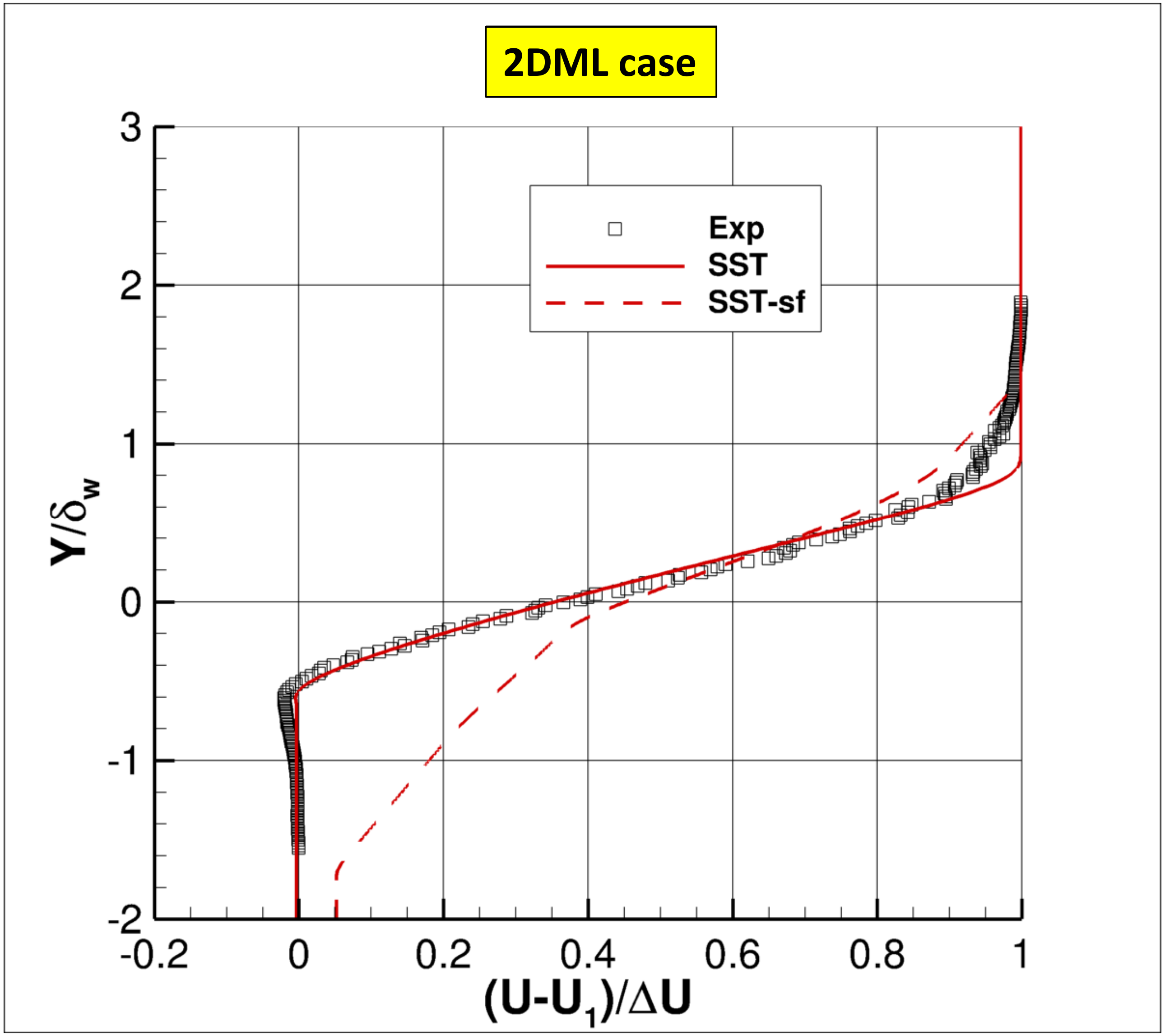
RCA Technical Challenge Defined

Aeronautical Sciences Project became T^3 under the new TAC Program in 2015

CFD Vision 2030 Recommendations

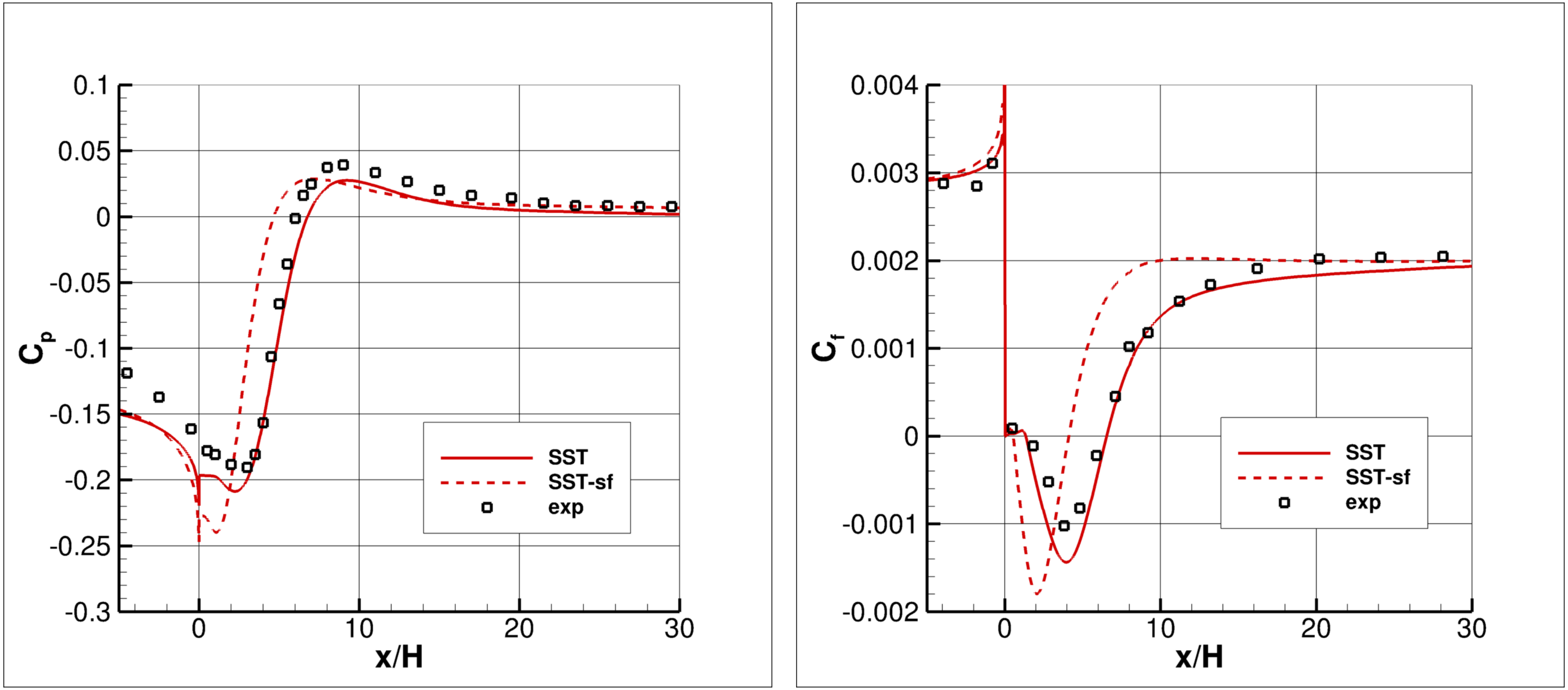
1. NASA should develop, fund and sustain a base research and technology (R/T) development program for simulation-based analysis and design technologies.
2. NASA should develop and maintain an integrated simulation and software development infrastructure to enable rapid CFD technology maturation.
3. HPC systems should be made available and utilized for large-scale CFD development and testing.
4. NASA should lead efforts to develop and execute integrated experimental testing and computational validation campaigns.
5. NASA should develop, foster, and leverage improved collaborations with key research partners and industrial stakeholders across disciplines within the broader scientific and engineering communities.
6. NASA should attract world-class engineers and scientists.

SST-sf for 2DML case

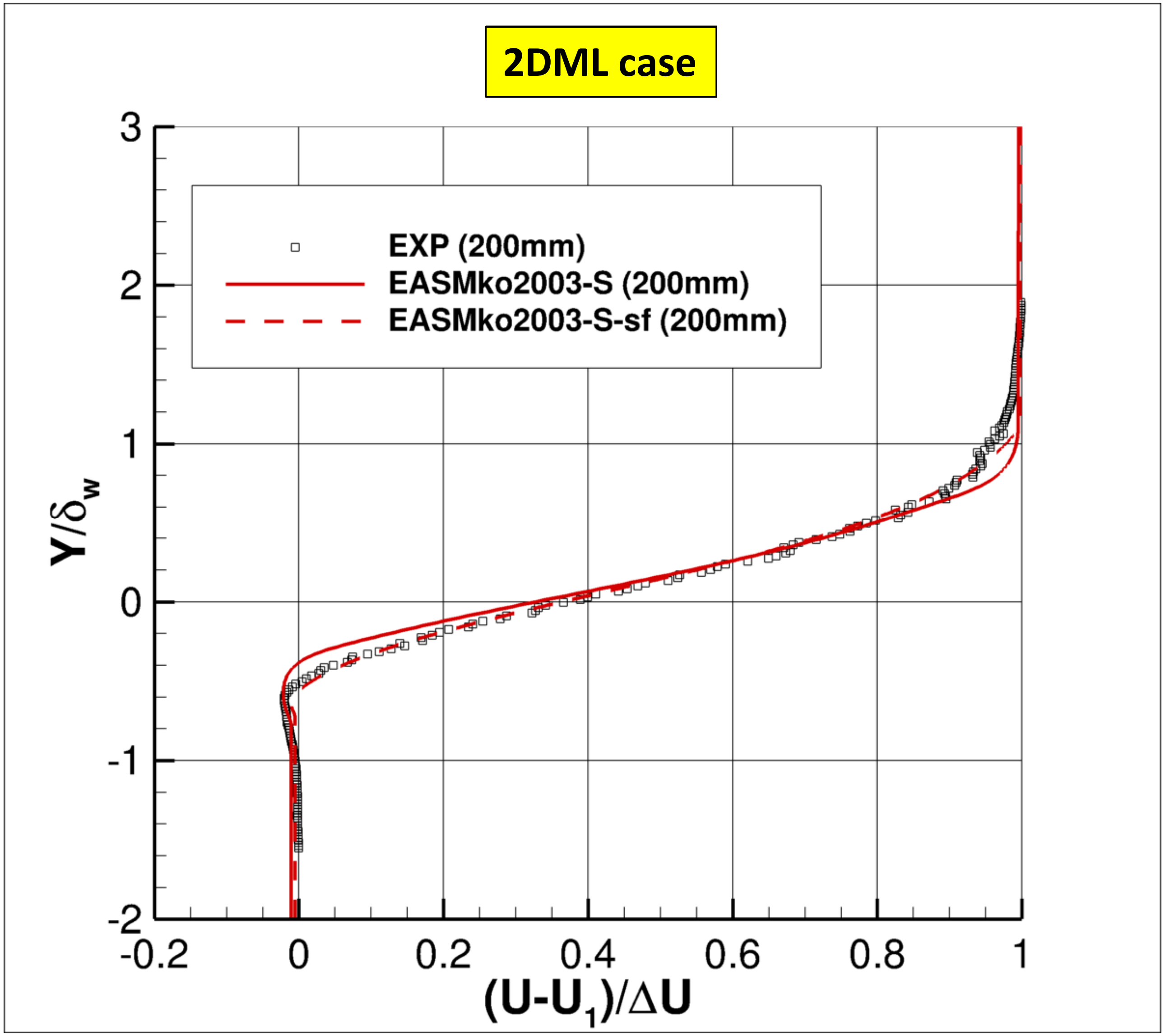


SST-sf for 2DBFS case

2DBFS case

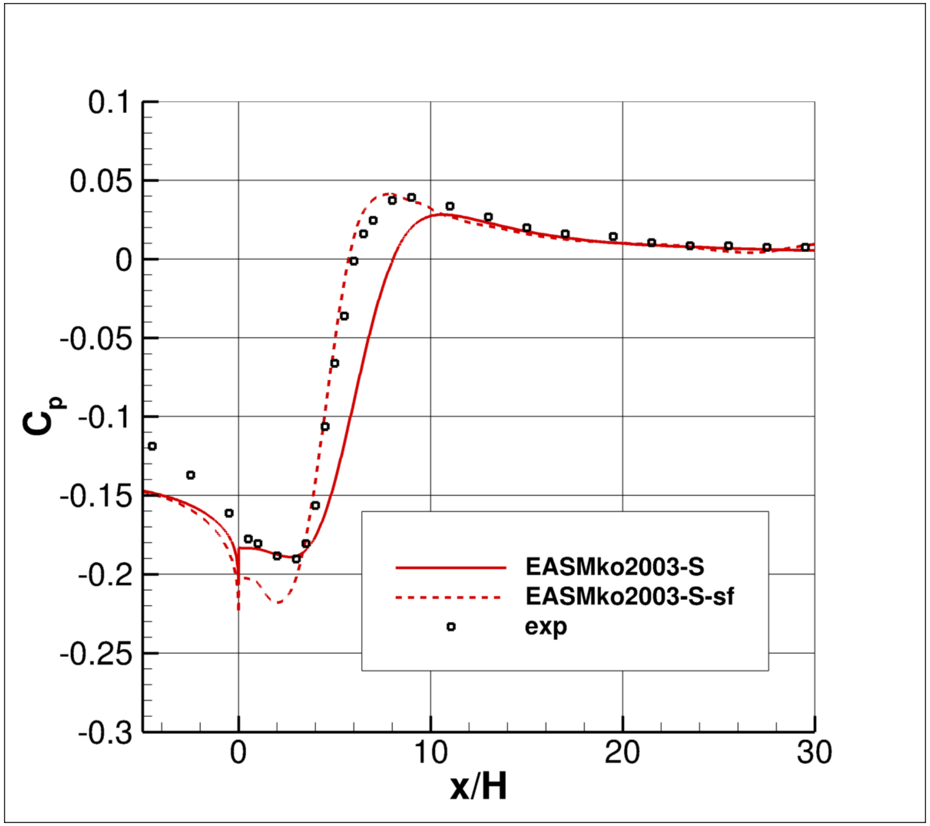


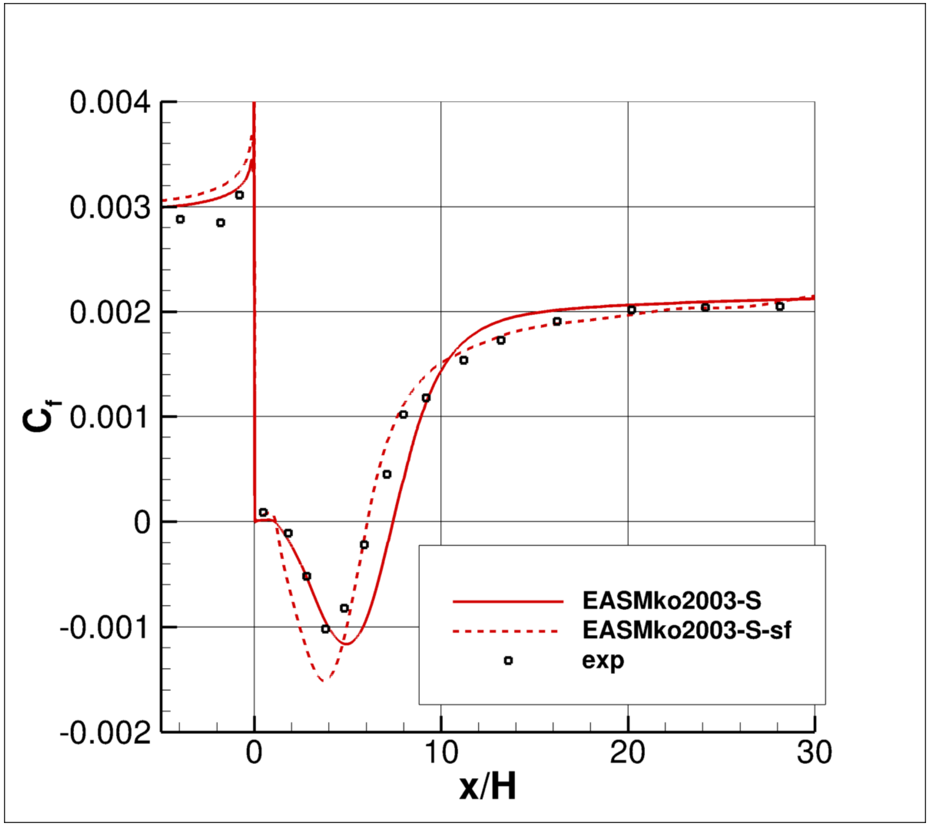
EASMko2003-S-sf for 2DML case



EASMko2003-S-sf for 2DBFS case

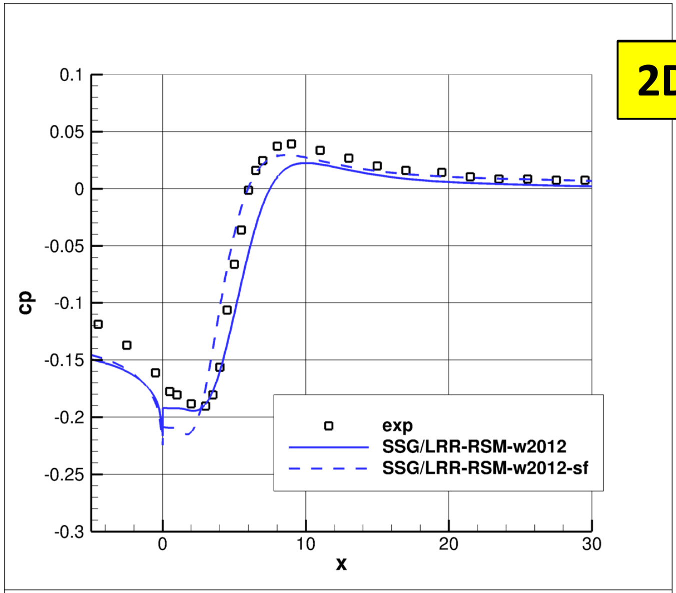
2DBFS case

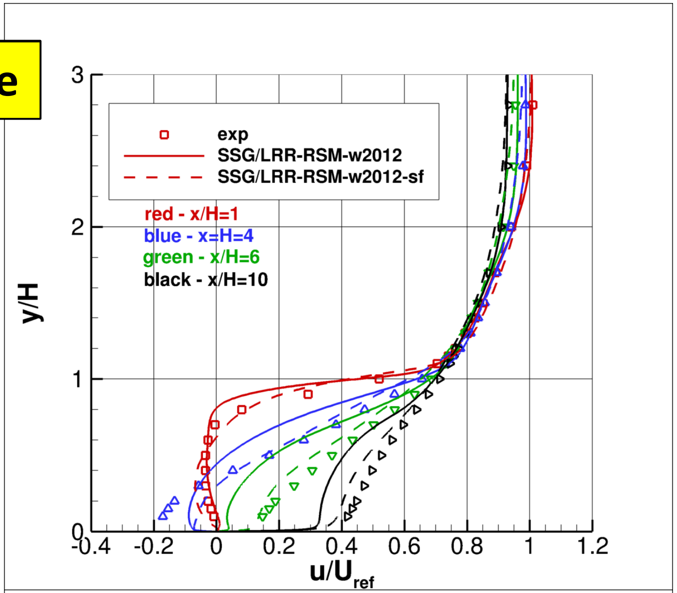


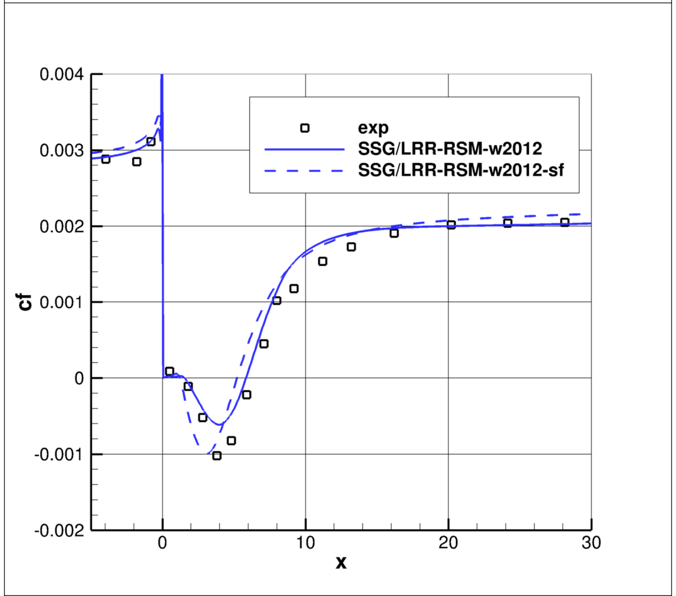


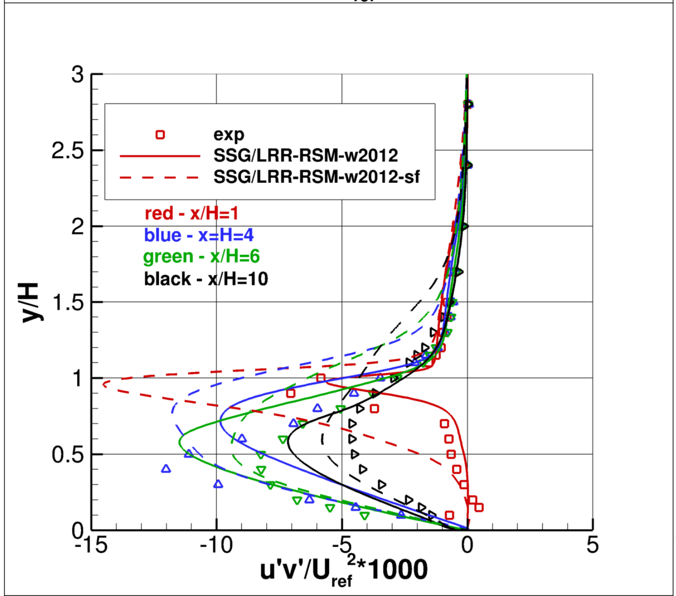
SSG/LRR-RSM-w2012-sf for 2DBFS case

2DBFS case









Final Note

- Perspectives from "Whither Turbulence? Turbulence at the Crossroads", Lecture Notes in Physics Vol. 357, ed: J. L. Lumley, Springer-Verlag, 1990
  - "DNS will be of growing importance in providing new insights in basic turbulence physics and guidance in turbulence modeling" (Reynolds)
  - "The great bulk of routine engineering calculations... always will be made with the most economical representations of the turbulence that provide adequate predictions, [so] it is important to continue the development of simpler turbulence models" (Reynolds)
  - "Second moment [models, i.e., RSM] give demonstrably superior predictive accuracy than any eddy-viscosity model... Only at the level of second-moment closure can one begin to see the interconnections with other approaches to representing turbulence. It is also a level at which one can discuss what is *left out* of the model. [RSMs are] likely to become increasingly employed between now and the turn of the century." (Launder)
  - "At the 10% level, the present state of the art [of RANS] looks quite good... At the 1% level it might be quite another story." (Roshko)