CAA Validation and Benchmark Experiments for Airframe Noise: Needs, Challenges and Near Term Prospects

David P. Lockard

NASA Langley Research Center, Hampton, VA

Outline

- **Verification vs Validation**
- **Examples from the CFD community**
  - Benchmarking turbulence models
  - CFDVAL2004 – Flow Control Workshop
    - ERCOFTAC Workshop on LES of Turbulence, Acoustics, Combustion
  - AIAA CFD Drag Prediction Workshops
- **Examples from the CAA community**
- **Challenges for CAA**
- **Benchmark problems**
  - AFN Workshop on Benchmark Problems

Verification and Validation

- **Prediction problem**
  - Experimental testing of the real configuration is too costly or infeasible
  - Prediction is based on mathematical + numerical models
  - Computation provides the quantitative data of interest on which a decision is made
- **Mathematical model**
  - Structure: type of equations and functional relations between input and output
  - Data: parameters values or ranges (coefficients, boundary conditions, geometry, ...) in the model
- **Computational model**
  - Numerical approximation of the mathematical model

Verification and Validation

- **Mathematical models transform inputs into the prediction of the quantity of interest**
  - Prediction = Mathematical Model(inputs)
  - Flow solution = Navier-Stokes(Mach, Re, Pr, BC, IC, …)
- **Numerical models add another transformation between inputs and outputs**
- **Models can also map uncertainty ranges for input data into uncertainty sets for the output**
  - Sensitivity can be important but is rarely addressed

Verification and Validation

- **Verification and Validation concerns the reliability of computational models**
  - mathematical models + numerical simulations
- **Aims to determine whether an important or critical decision can be based on the outcome of computational models**

- **ASME Guide to V&V, 2006**
- **AIAA Guide to V&V, 1998 (under revision)**

Verification and Validation

- **Verification: The process of determining that a computational model accurately represents the underlying mathematical model and its solution**

Verification: Are we solving the equations correctly?

- **Validation: The process of determining the degree to which a model is an accurate representation of the real world [physics] for the perspective of the intended uses of the model**

Validation: Are we solving the correct equations?

Verification and Validation

- **Verification includes:**
  - Code Verification: correctness of code implementation; check with exact solutions; etc...
  - Solution Verification: analysis of the numerical method, convergence, a-posteriori error estimation for the desired output, etc...
- **Verification should come before validation**

- **Validation implies comparison with experiments**
- **Experimental measurements should be verified, too.**

Verification and Validation

- **Calibration experiments**
  - Simple experiments to identify some of the input data of the mathematical model
  - Simpler than the prediction problem and could be described by simpler mathematical models
    - i.e. Calibrate turbulence model parameters via flat plate boundary layer or decaying isotropic turbulence
- **Validation experiments**
  - Often easier than the “real” prediction problem but related and experimental measurements can be obtained
    - i.e. Tandem cylinders instead of landing gear
- **Comparisons between computational models and experiments is based on a suitable validation metric**
  - Model rejected if it fails to meet a priori tolerances
  - Experiments, metrics, and tolerances must be relevant

Examples from CFD

Turbulence Modeling Benchmarking

Turbulence Modeling Benchmarking

- **Turbulence modeling working group established**
  - Under Fluid Dynamics Technical Committee
  - Current active members:
    - Brian Smith (LMCO)
    - Chris Rumsey, Dennis Yoder, Nick Georgiadis (NASA)
    - Bora Suzen (NDSU)
    - George Huang (Wright State)
    - Hassan Hassan (NCSU)
    - Philippe Spalart (Boeing)
    - Won-Wook Kim (P&W)

- **NASA website established**
  - http://turbmodels.larc.nasa.gov
  - A resource for finding and verifying turbulence models

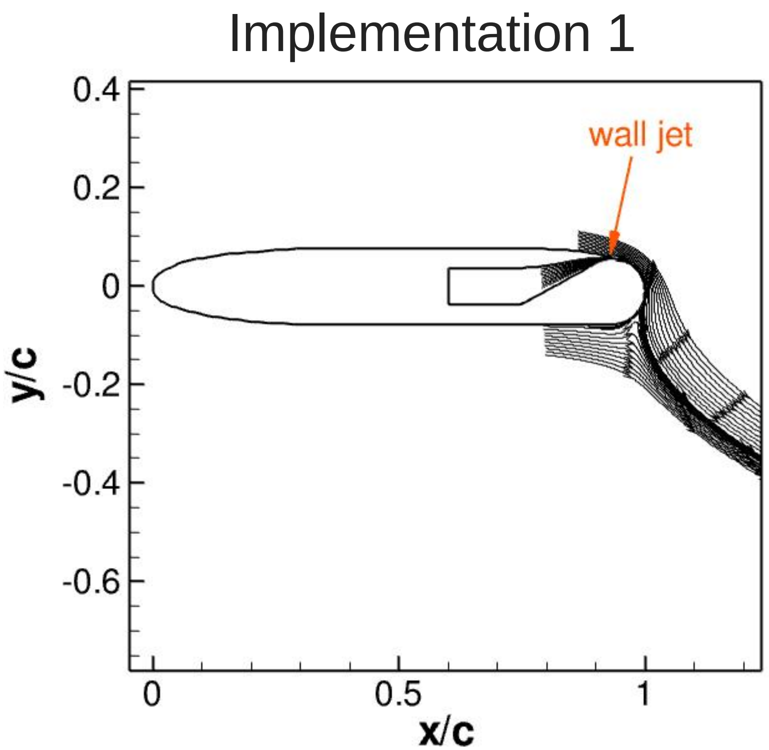
Turbulence Modeling Benchmarking

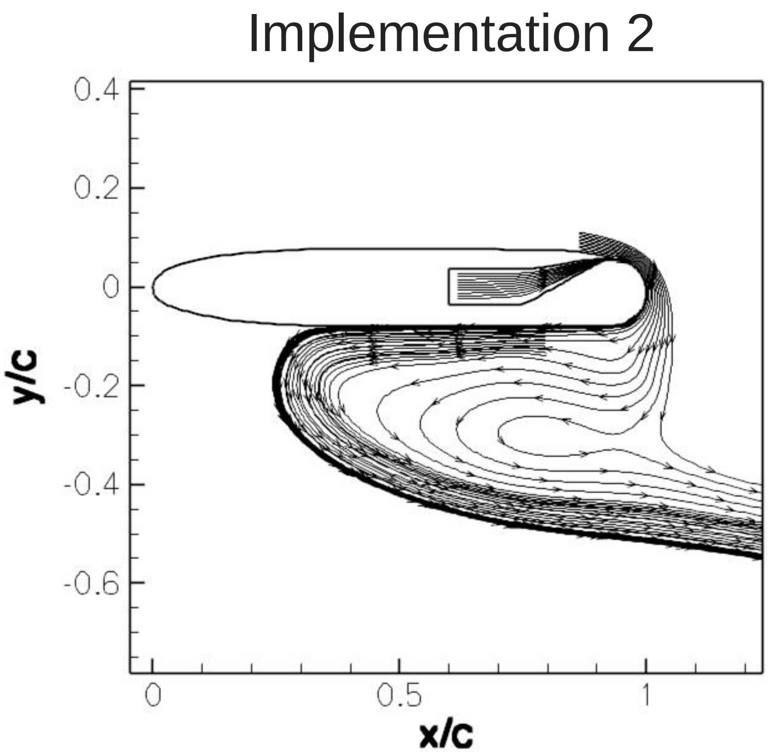
- **Need for improved turbulence modeling “usage” practices in the CFD community**
  - Inconsistencies in model formulation or implementation in different codes make it difficult to draw firm conclusions from multi-code CFD studies
  - Naming conventions and processes do not insure model implementation consistency
    - i.e. SA, SA-Ia, SA-noft2, SA-RC, SA-Catris, SA-Edwards, SA-fv3, SA-salsa

- **Desire to avoid difficulties & inconsistencies that can occur when attempting to implement models from papers/reports**

Example Difficulties

"Same" turbulence model - different results!

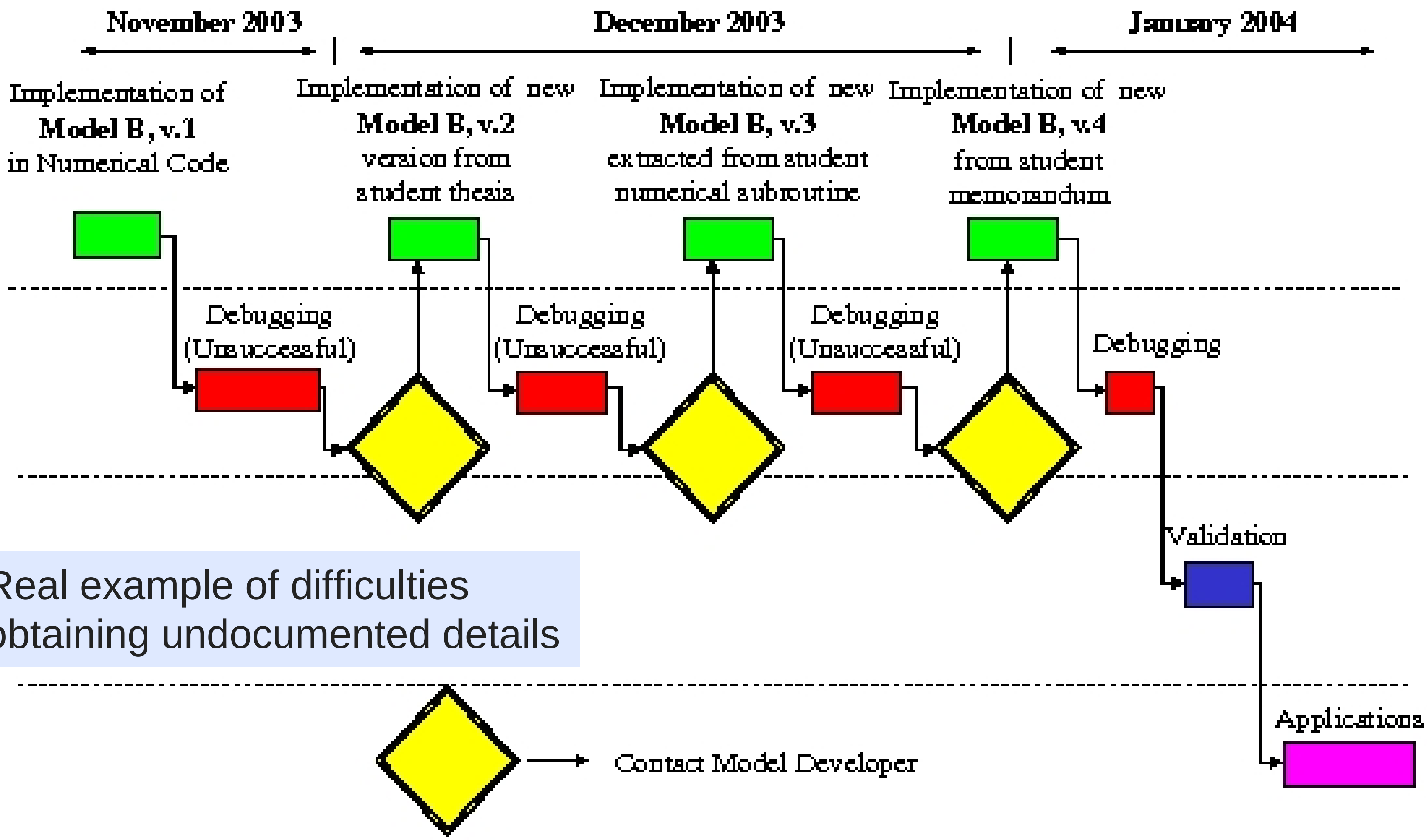




Sensitive cases can depend in part on model implementation differences (2004 NASA/ONR Circulation Control Workshop)

Example Difficulties

Record of attempted implementation of someone else's turbulence model



Real example of difficulties obtaining undocumented details

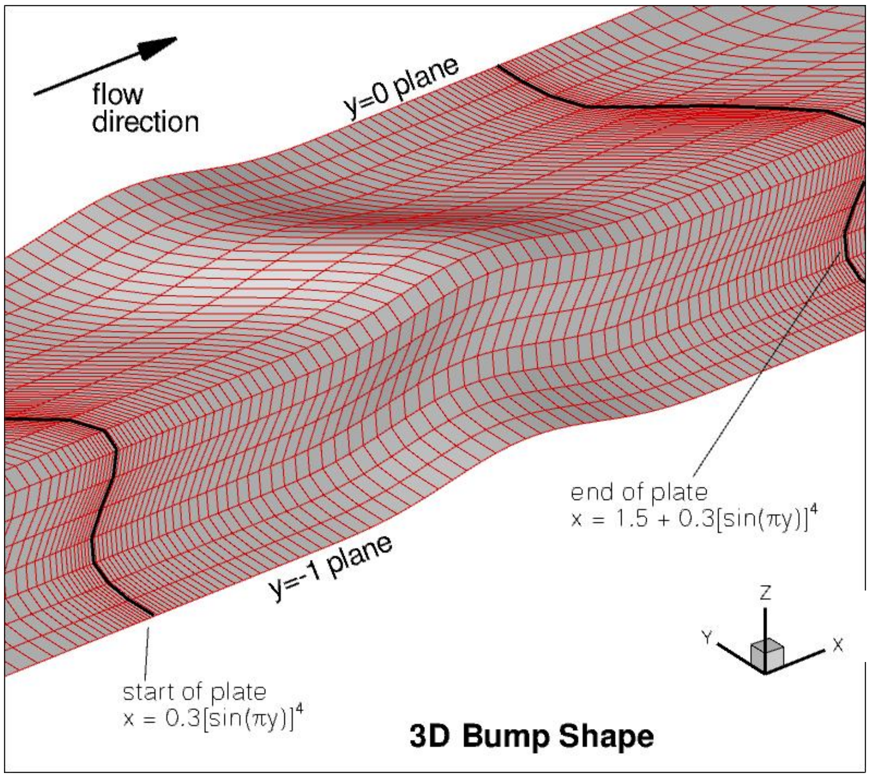
from Viti et al, Computers & Fluids 36 (2007) 1373-1383

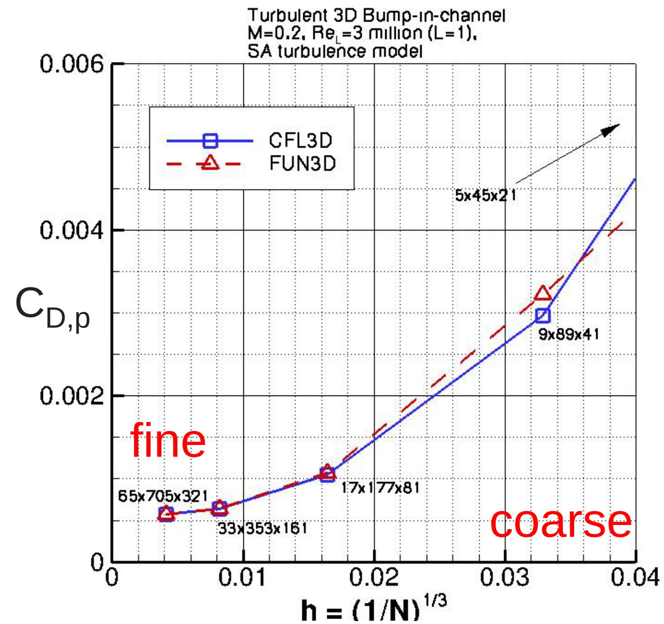
Verification cases and grids

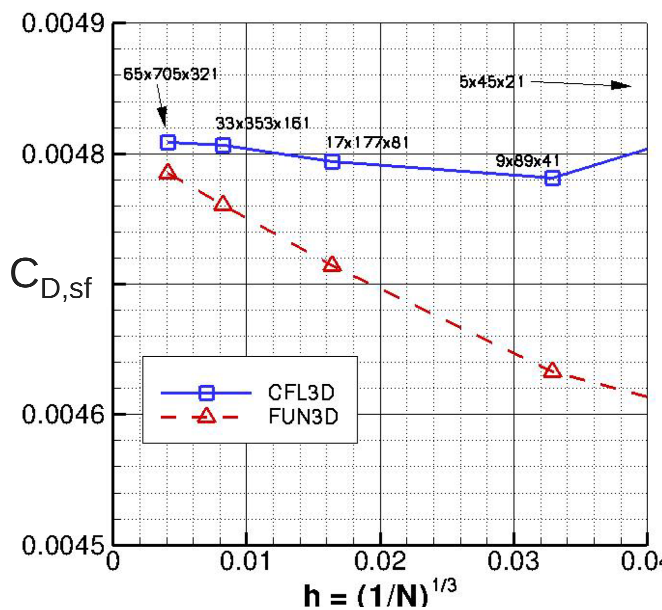
- **How to achieve <u>consistency</u> in turbulence model implementation?**
  - Decided to create series of “verification cases”
  - Show how 2 or more independent codes with the same turbulence model go to the same result as grid is refined
  - Provide grids for others to use
  - Provide solutions for others to compare against
  - Simple, analytically-defined geometries, no separation, easy to converge
- **Current verification cases:**
  - 2D zero pressure gradient (ZPG) flat plate
  - 2D planar shear
  - 2D bump in channel
  - 3D bump in channel

3D Bump-in-channel

- **Sequence of 5 grids of the same family**
  - 65x705x321 (finest), 5x45x21 cells (coarsest)







Manufactured Solutions

- **In method of manufactured solution (MMS), analytical source terms are added to the mathematical model**
  - Choose a solution and use a symbolic manipulator to calculate all the derivatives in your equations. Result is the source term.
  - i.e., you know precisely what the error is because you know the exact answer
  - Solution should approach exact solution with design-order accuracy as grid is refined

- **From “Workshop on CFD Uncertainty Analysis” series (three held)**
  - Manufactured solutions for various turbulence models
  - Manufactured Fortran function files, courtesy Luis Eca, IST (Lisbon)
    - Spalart-Allmaras (SA-noft2), Menter one-equation, Menter BSL, standard k-epsilon, Chien k-epsilon, TNT k-omega

Turbulence Benchmarking: Future Expansion

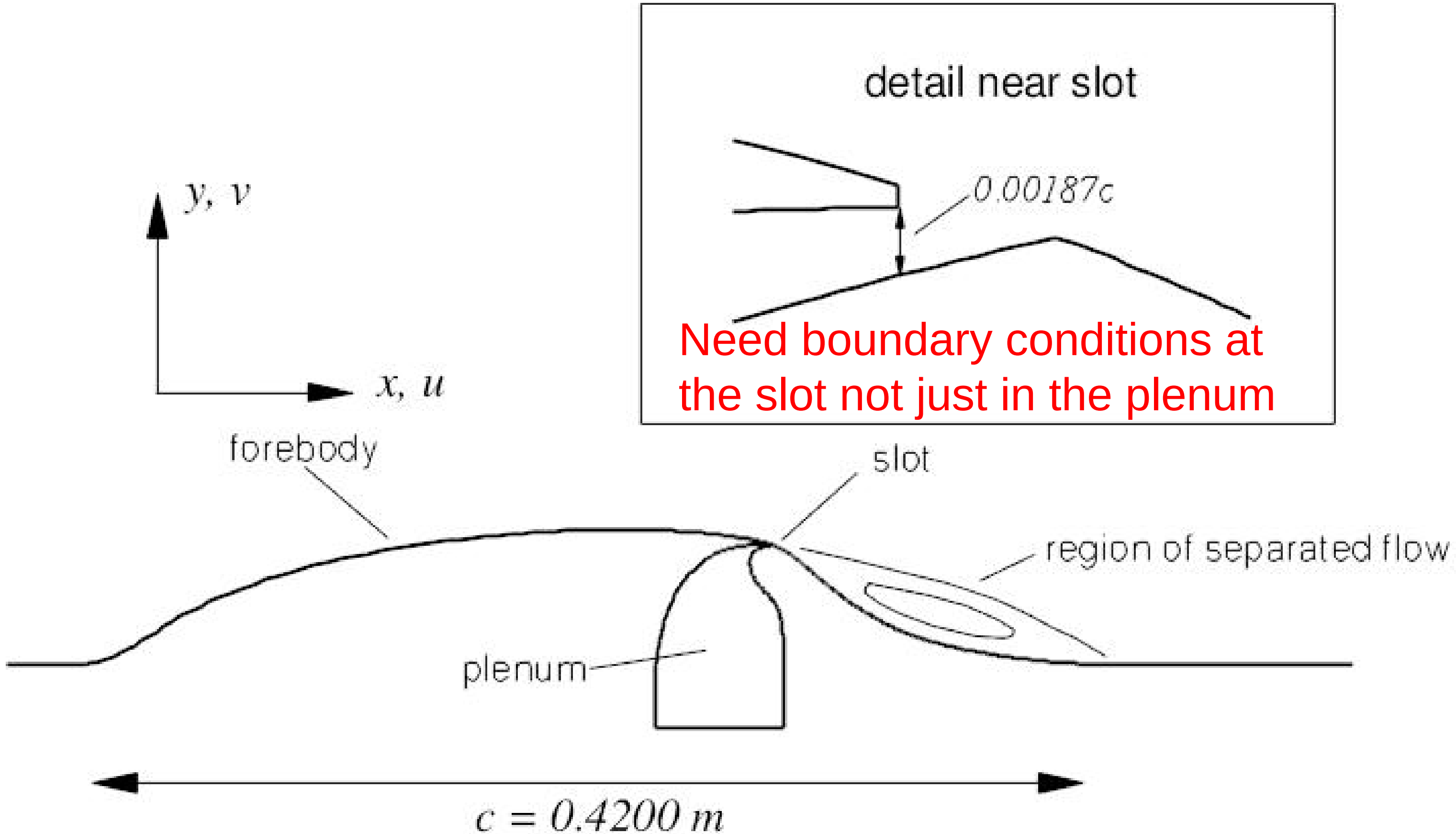
- **Suite of basic validation cases**
  - Choose small suite of 5 or so representative simple cases
  - Possibilities:
    - flat plate (law-of-the-wall theory, direct simulations, etc.)
    - axisymmetric bump (Bachalo & Johnson)
    - backward-facing step (Driver & Seegmiller)
    - separated NACA 4412 airfoil (Coles & Wadcock)
    - free shear layer / mixing layer (various experiments)
    - airfoil wake flow (Nakayama)
  - Provide references or point to results for additional cases

This group is currently addressing verification on simple cases. Validation cases only proposed.

Examples from CFD

CFDVAL2004 – *CFD Validation of Synthetic Jets and Turbulent Separation Control*

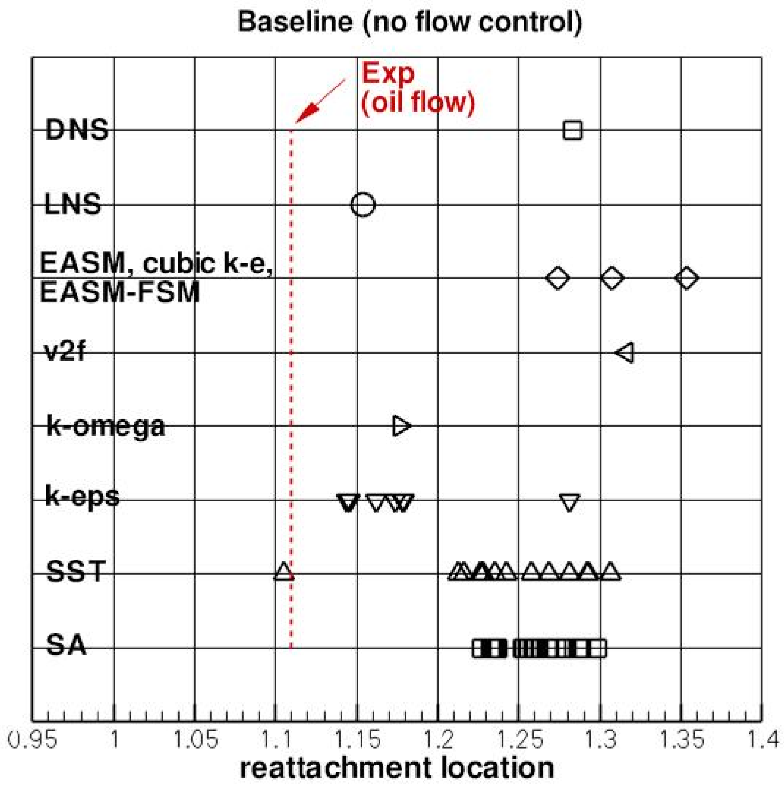
Case 3:Flow Over a Hump Model

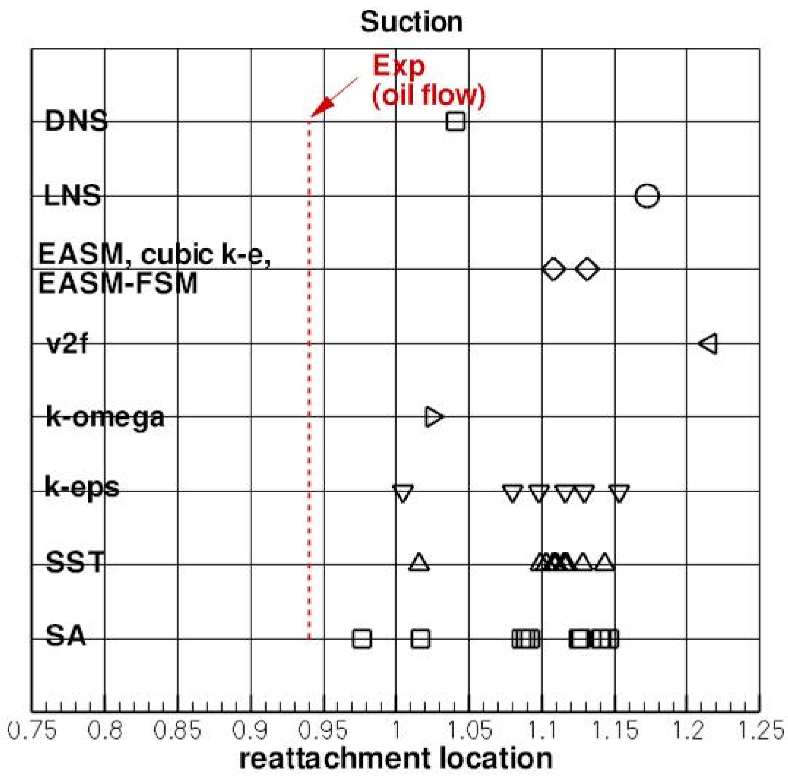


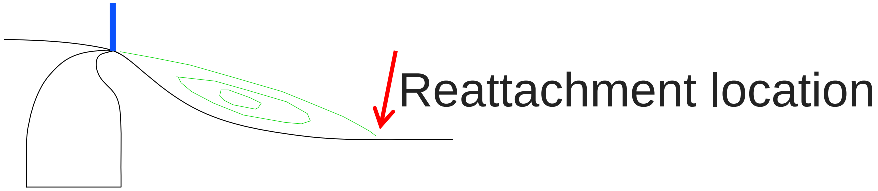
- Based on earlier experiment by Seifert & Pack (AIAA J, Vol. 40, No. 7, 2002, pp. 1363-1372)

- Also used in subsequent 11th & 12th ERCOFTAC/IAHR Workshops on Refined Turbulence Modeling

Hump Model: Reattachment Location







- **Eddy viscosity underpredicted in separated shear layer region**
  - Improved solutions from LES in subsequent years

CFDVAL: Lessons Learned

- **Flow field may have been partially laminar or transitional**
  - Causes greater uncertainty in experimental results and greater scatter in CFD
- **CFD Codes should employ the same BCs**
  - Insuring that CFD has the same boundary conditions as experiment is necessary, but can be very difficult
  - Need extremely well-documented BCs, especially with flow-control
  - Measured velocity profiles are particularly helpful
- **Grid and temporal refinement studies must be performed**
  - Running on the same grid can be particularly helpful, as it removes one of the variables when trying to compare turbulence models, codes, etc.

Experiments intended for CFD validation

- **CFD Needs thorough assessment of two-dimensionality if dataset is intended for 2-D computations**
  - Spanwise correlation should be known
- **CFD needs accurate assessment of as-built shape, including model and tunnel details**
- **Use of multiple measurement techniques (e.g., LDV and PIV to measure the same thing) are very useful and can reveal that experimental uncertainty can be high for certain flow fields**

Experiments intended for CFD validation

- **Use of both high resolution and low resolution PIV to measure the same thing is useful for assessing experimental uncertainty**
- **The more details given, the better for CFD validation, because the biggest challenge is to get CFD to run the "same problem" as experiment**
  - Thorough documentation of freestream conditions (both upstream and downstream), conditions in jet plenum, etc.
  - Details of forcing mechanisms (mechanical? electrical? frequencies? modes?)
  - Velocity and turbulence profiles at multiple stations, and especially at flow-control locations

Examples from CFD

Drag Prediction Workshops

Drag Prediction Workshops

- **AIAA Applied Aerodynamics Technical Committee has sponsored a series of workshops for transonic cruise drag prediction of subsonic transports:**

1. Assess the state-of-the-art computational methods as practical aerodynamics tools for aircraft force and moment prediction of industry relevant geometries

2. Provide an impartial forum for evaluating the effectiveness of existing computer codes and modeling techniques using Navier-Stokes solvers

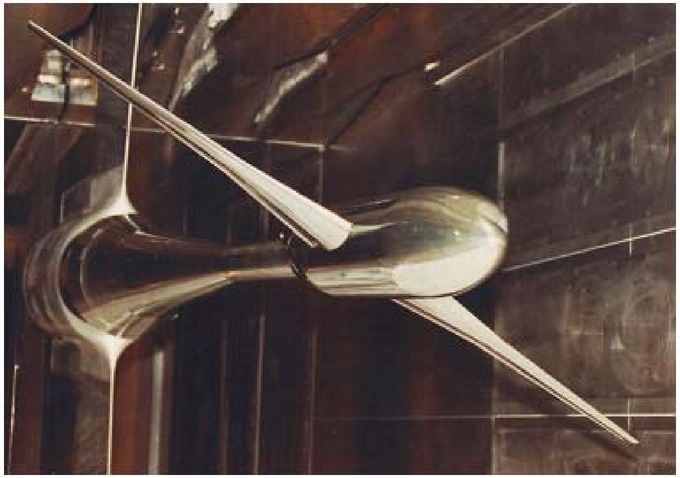
3. Identify areas needing additional research and development

DPW: Background

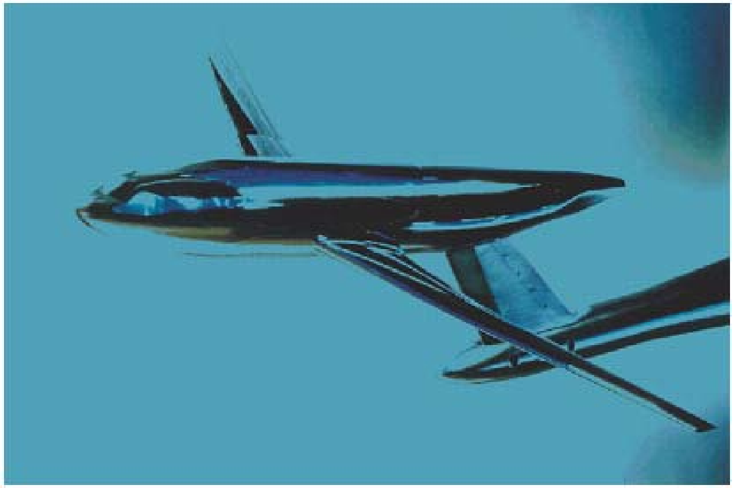
- **DPW-I: Anaheim CA, June 2001**
  - DLR-F4 Commercial Transport Wing-Body
  - Cruise Polar, Drag Rise
  - Experimental data from 3 facilities
- **DPW-II: Orlando FL, June 2003**
  - DLR-F6 Commercial Transport Wing-Body + Pylon-Nacelle
  - Cruise Polar, Drag Rise, grid convergence
  - Experimental data from 1 facility
- **DPW-III: San Francisco, CA, June 2006**
  - DLR-F6 Commercial Transport Wing-Body + FX2B Fairing, Wing
  - Cruise Polar, Drag Rise, grid convergence
  - Blind test - No experimental data at time of workshop
- **DPW-IV: San Antonio, TX, June 2009**
  - NASA Common Research Model – Blind test
  - Cruise Polar, Drag Rise, grid convergence

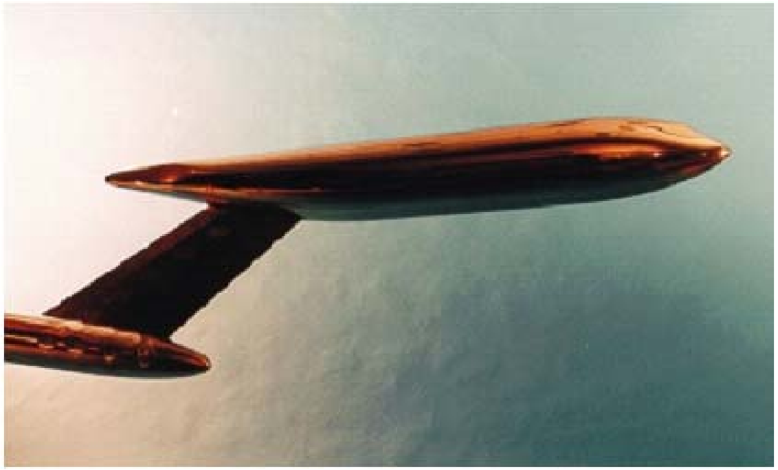
ETW Reference Model (DLR-F4)

From J. Quest



- **ETW model**
  - ~22.5% larger than used at DRA, NLR, & ONERA
- **Multiple mounts**
  - Similar to those used in other WT
  - Typical differences between tunnels



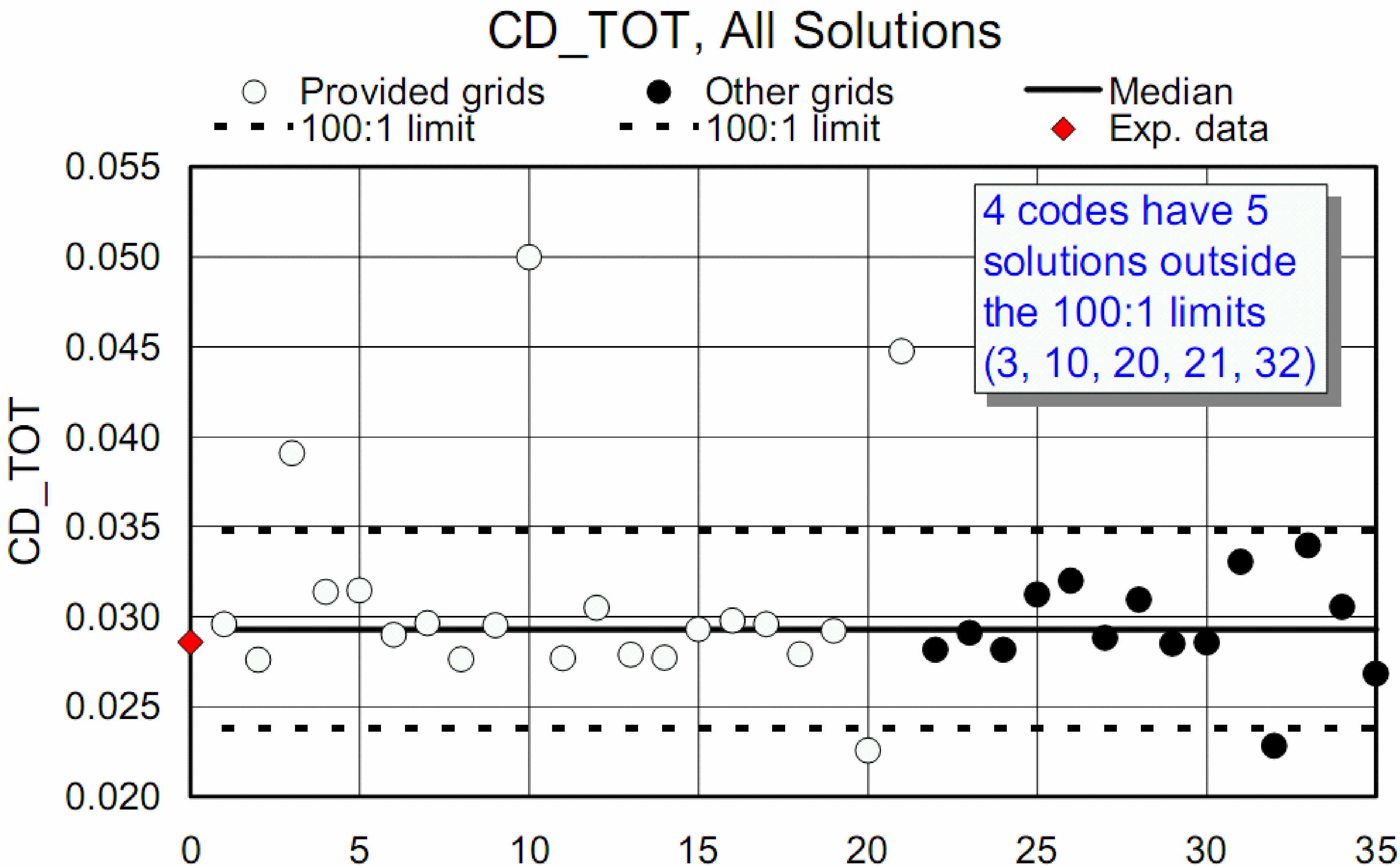


DPW I: Experimental Observations

- **One model - Three facilities**
- **Good agreement from facility to facility is challenging**
  - Facility differences, including model mounting
  - Instrumentation differences
  - Data acquisition, reduction, and “correction” differences
  - Repeatability of “unchanged” items
- **Model part fit, transition grit application, filler, etc.**

- **General agreement between facilities reasonable, but still considerable scatter in the data**

DPW I: All Total Drag Solutions at CL=0.5, M=0.75



1 drag count = 0.0001

Designers want results within ½ drag count

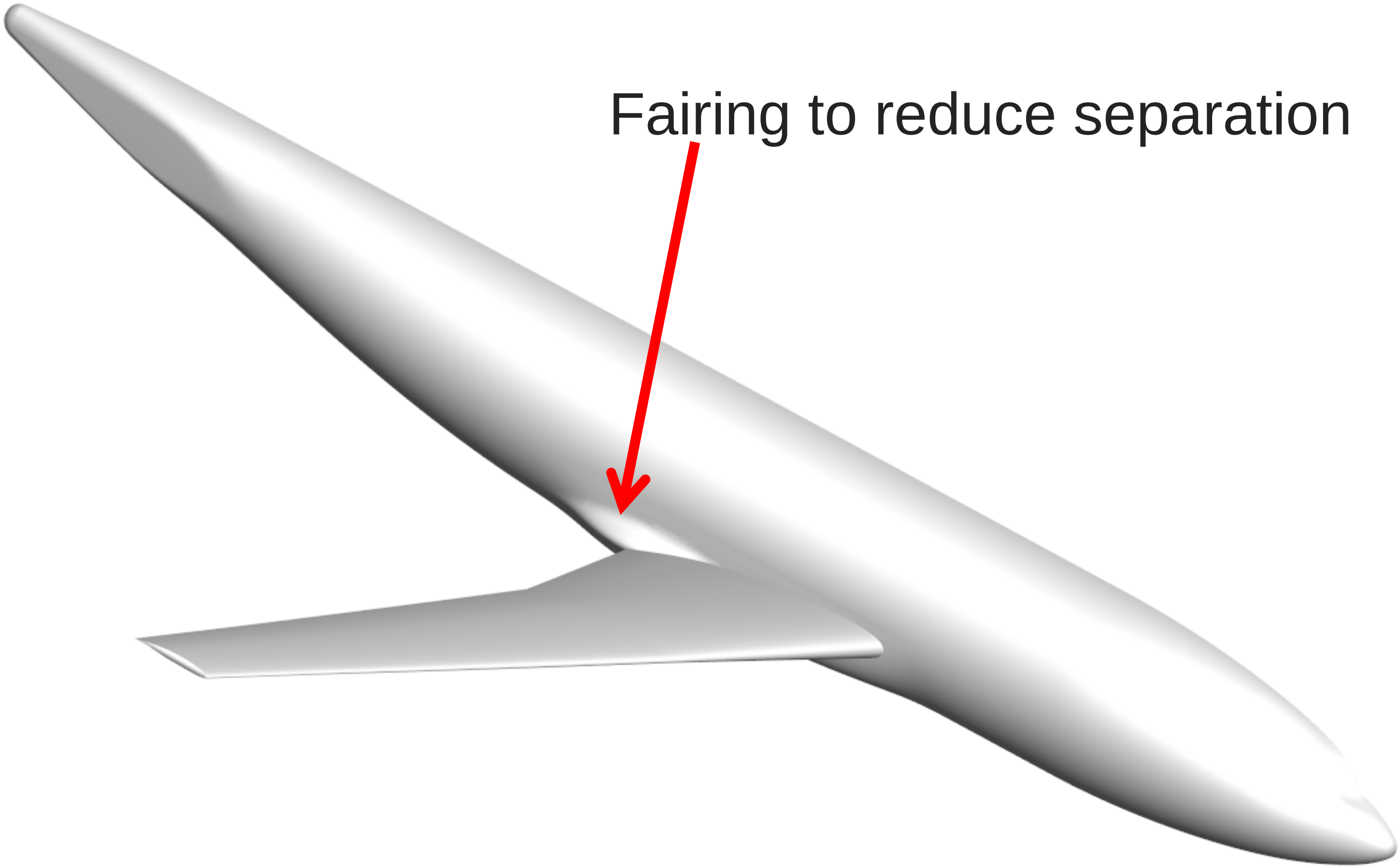
DPW I : Analysis of Solutions

- **Using the median to estimate the location and the median absolute deviation or average absolute deviation to estimate the scale allowed us to discern the outlier solutions without losing the meaning of the comparable core solution values.**
  - Assumes core is "correct"
- **There does seem to be a credible CFD true value and standard deviation. Whether these numbers are durable can only be seen by repeating this exercise.**
- **It appears that we need some set of best practices and quantitative sanity checks to avoid outliers. The continued existence of such outliers would force us to accept much bigger numbers for the scatter.**

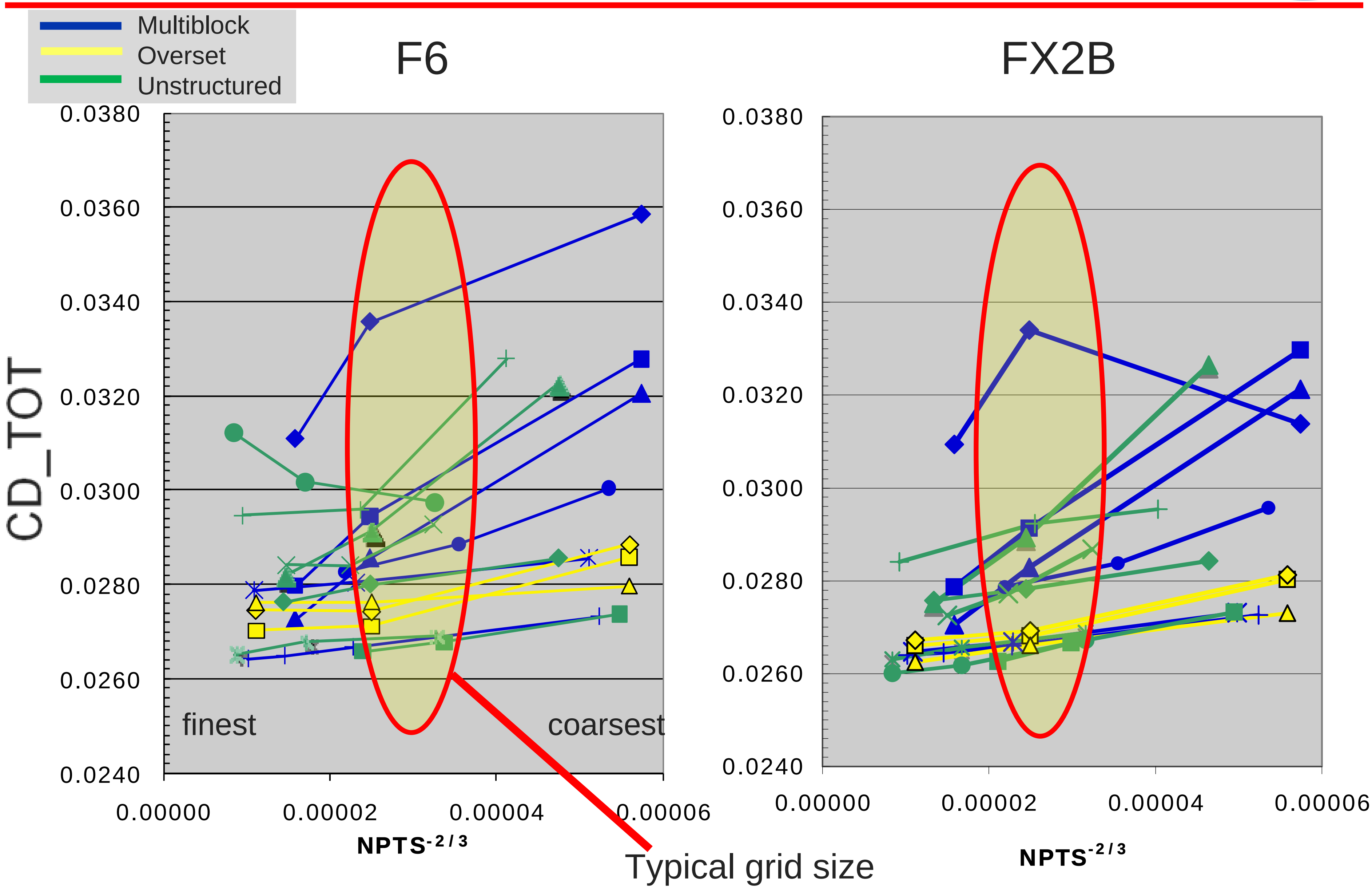
DPW I

- **The scatter for the core solutions is much too large for acceptable validation**
  - 100 drag counts in “core” solutions
    - ±5 drag counts of variation between experiments, ½ desired
- **Comparing CFD solutions to each other, in a collective sense, for diverse codes, grids, turbulence models, and observers, is probably the best way to determine the best practices needed to reduce the scatter to acceptable levels**

DPWIII Case 1: DLR-F6 with FX2B



DPW III - Nested CD_TOT



DPWIII Concluding Remarks

- **The Good News:**
  - **DPW-3 was a “blind test”, i.e. no experimental data existed to “guide” solutions. The results were about as good for the blind test as for DPW-2.**

- **The Less Good News:**
  - Have not demonstrated convergence of medians, spread or core interval for F6/FX2B despite increased grid sizes
  - F6 spread and core interval have not improved from DPW-2
  - FX2B spread and core interval are not substantially better than F6
  - DPW-W1 spread and core interval are not showing convergence
  - After 3 drag prediction workshops, grids remain a leading order issue

DPW Recommendations

- **We must generate grid families systematically rather than generate individual grids for convergence studies**
  - Grid generation software should automatically generate a family of grids for grid convergence studies

- **We must make a concerted effort to understand the differences in the codes and models**
  - No single main effect (grid, turbulence model, differencing, etc.) explained why some results were outliers

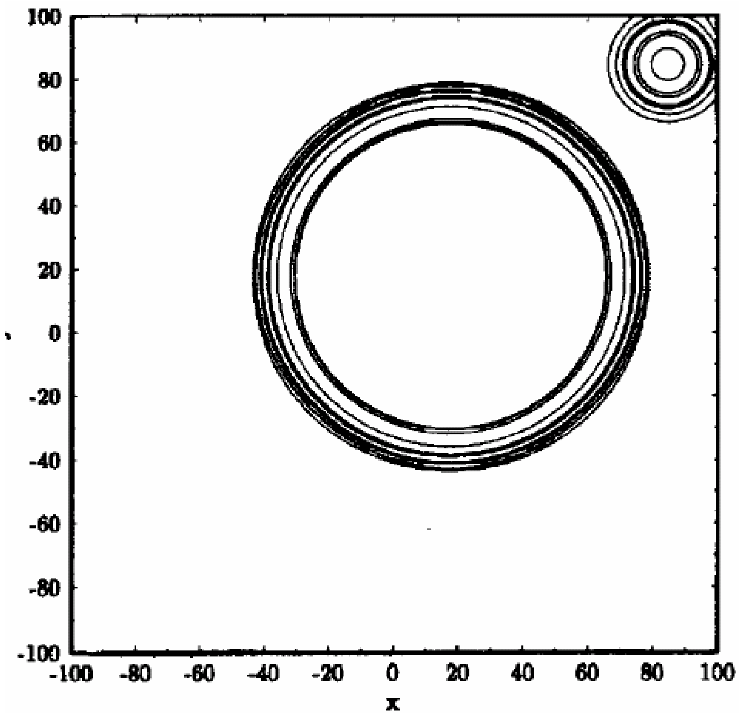
- **We must make a concerted effort to understand and improve the process**
  - Need to understand the effects of grid quality and grid resolution
    - Need metrics for grid quality and grid resolution
  - Need to re-evaluate best practices, e.g. for iterative convergence

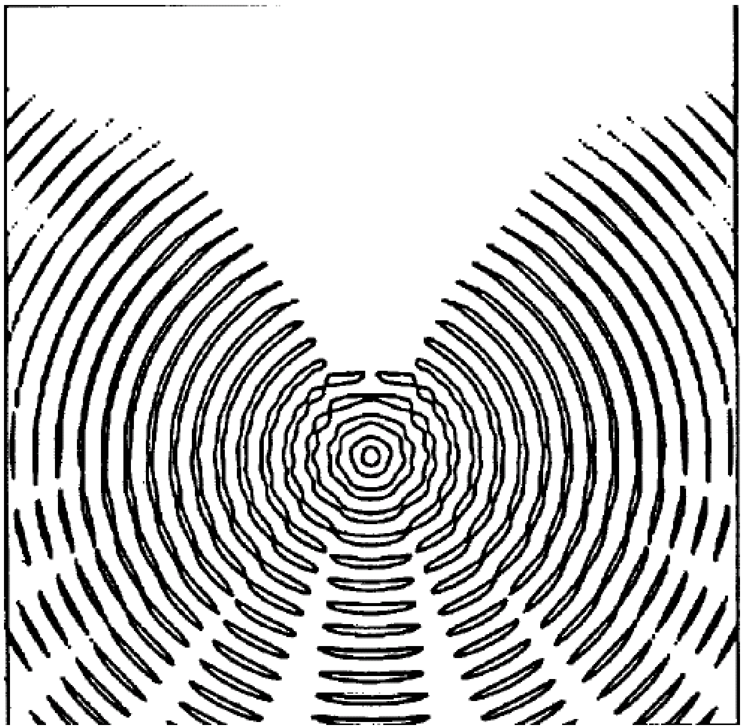
Examples from CAA

CAA Workshops

CAA Workshops

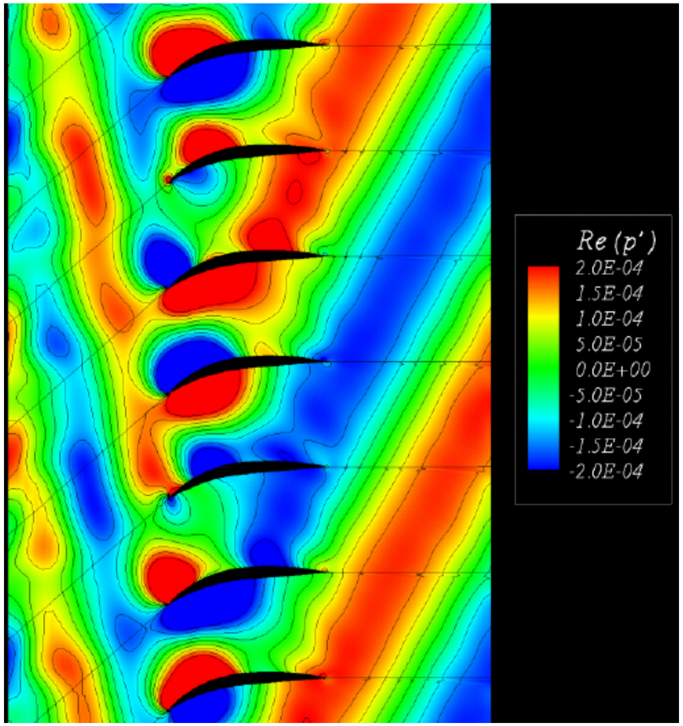
- **4 workshops from 1995 – 2004**
  - Focused on determining whether CFD could be used to calculate acoustic sources and wave propagation
    - Identified importance of low dissipation and dispersion
    - Problems with analytic solutions (verification studies)
      - Benchmark problems for the evaluation of new methods

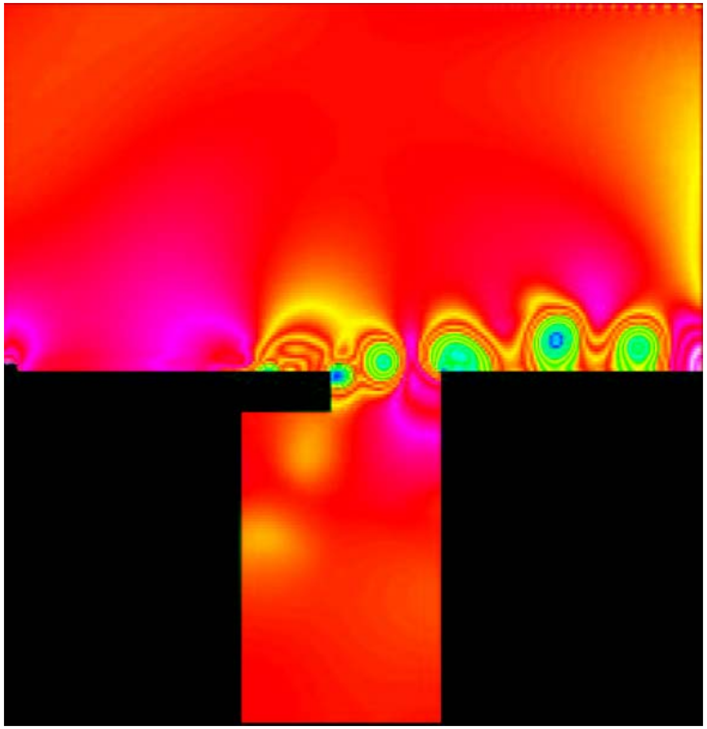




CAA Workshops

- **Test cases gradually increased in complexity**
  - Geometry
  - Physics (Navier-Stokes, turbulence)
  - Problem size
- **Problems of practical interest being addressed by 2004**
  - Experimental data for validation studies

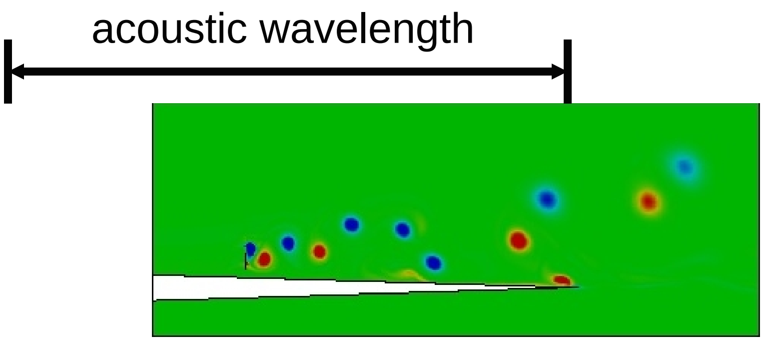




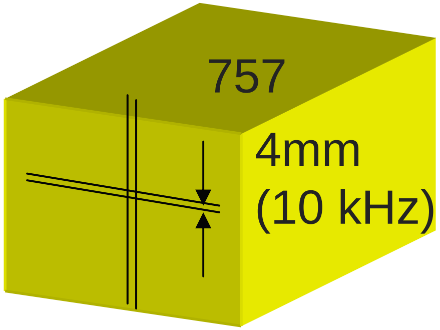
Unique Challenges for CAA

CAA Challenges: Spatial Scales

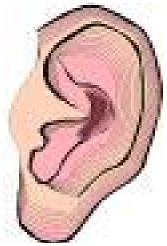
- **Spatial scale disparity**
  - Between geometry, flow structures, acoustics
  - Excessive number of grid points



- 10^{11} grid points needed to resolve the acoustics up to 10 kHz within a box surrounding a 757
  - 2.4 Terabytes to store the grid
  - Resolving turbulence scales in boundary layers increases the requirement

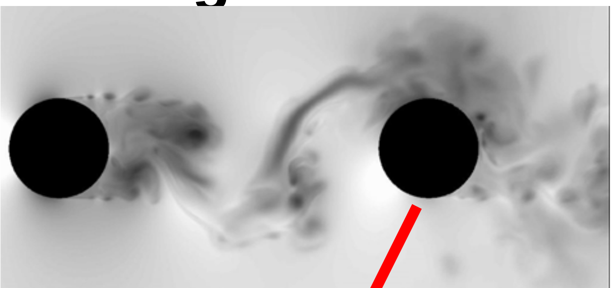


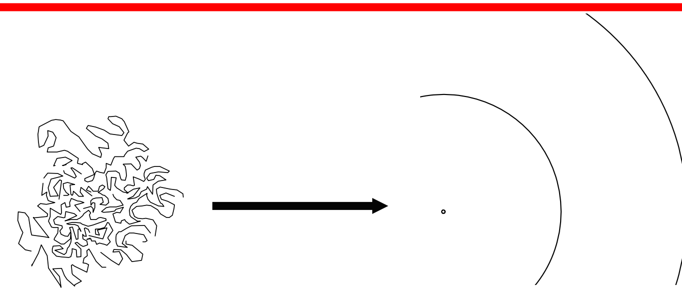
- 10^{13} grid points needed to extend the box to the ground (at certification height)
  - 240 Terabytes to store the grid



CAA Challenges: Amplitude Disparity

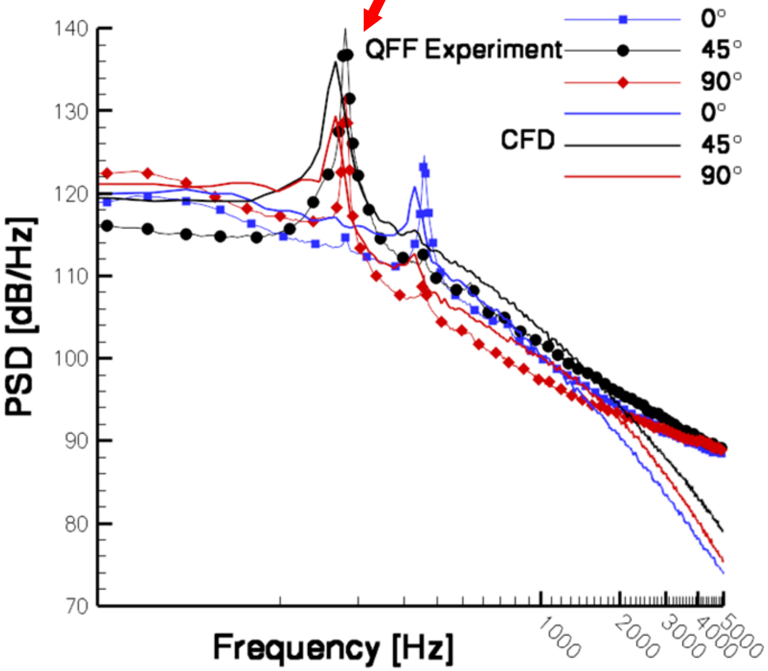
Need high accuracy over long distances



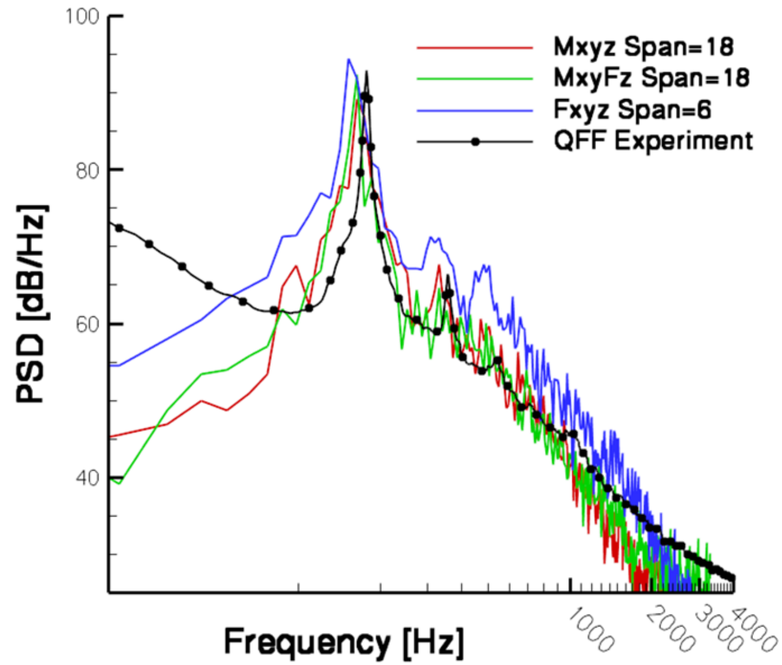


SPL on surface ~ 140 dB

SPL 16 diameters from model ~ 95 dB



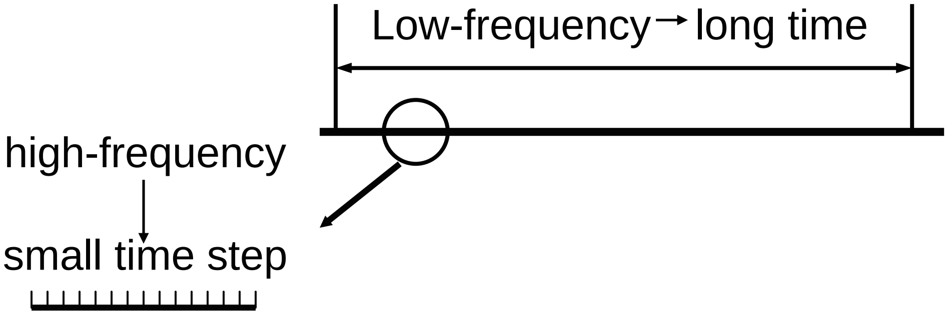
Surface Pressure

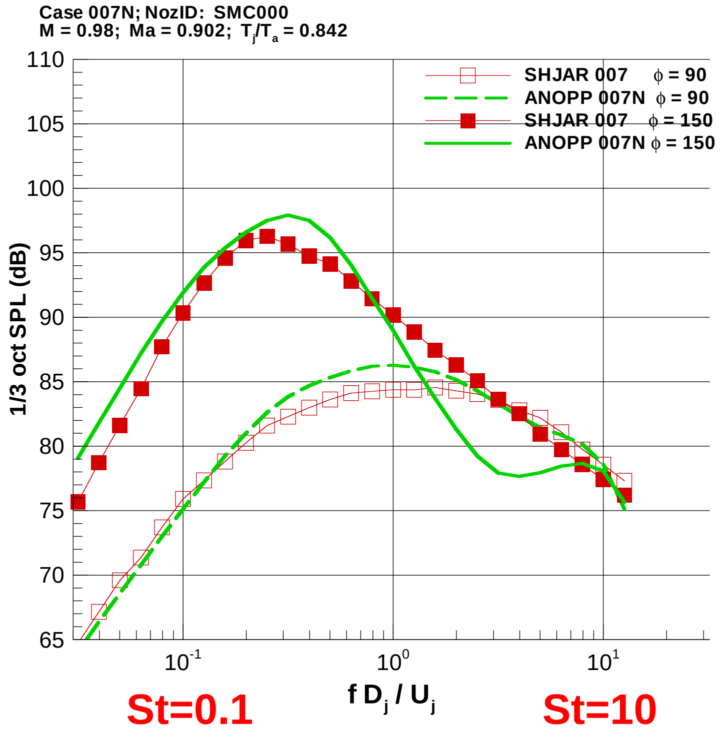


Acoustic Signal

CAA Challenges: Temporal Scales

- **Small time step**
- **Large number of time steps**

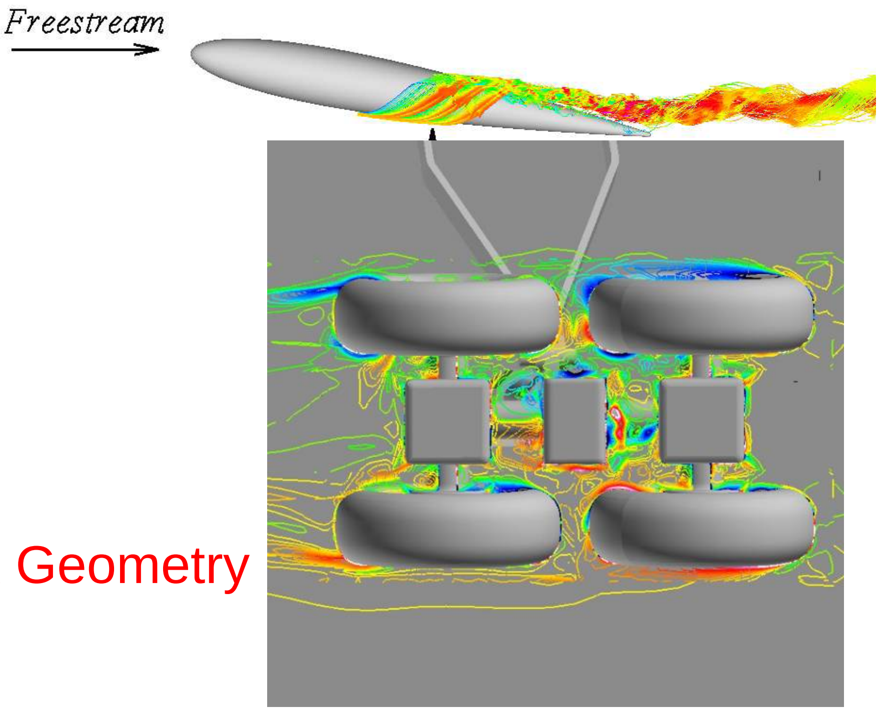




- Generally 2 orders of magnitude difference between min and max frequencies
- For random processes, would prefer to average at least 10 of the longest period
- May need 25 steps within the smallest period
- Time steps ~ (100) * (10) * 25 = 25,000 per realization
- Experimentalists average over hundreds of realizations

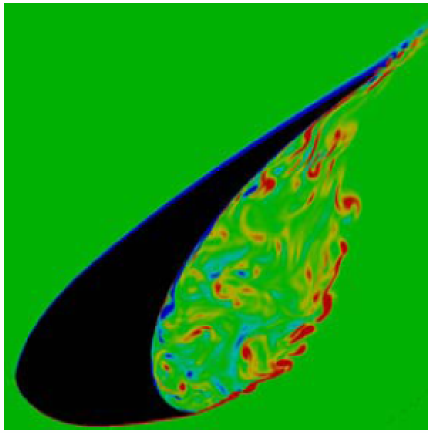
CAA Challenges: Complex Physics

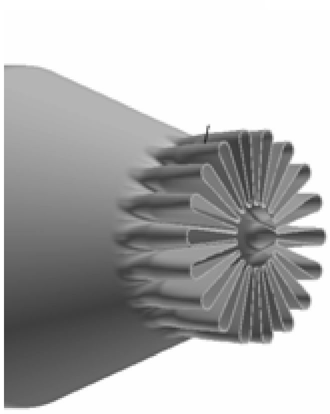
- **Physical mechanisms of noise generation**
  - **Pressure field around moving bodies**
  - **Wake interaction with surfaces**
  - **Feedback / resonance**
  - **Instability wave growth/decay**
  - **Shocks**
  - **Scattering**
  - **Turbulence**

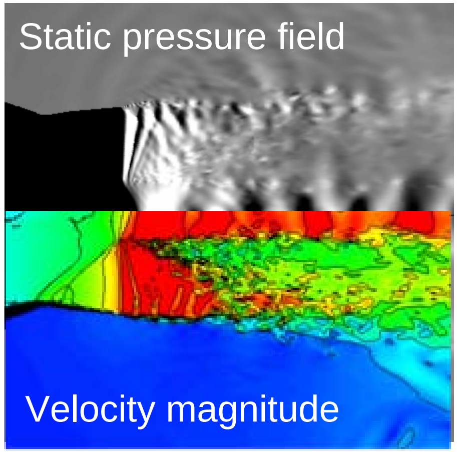


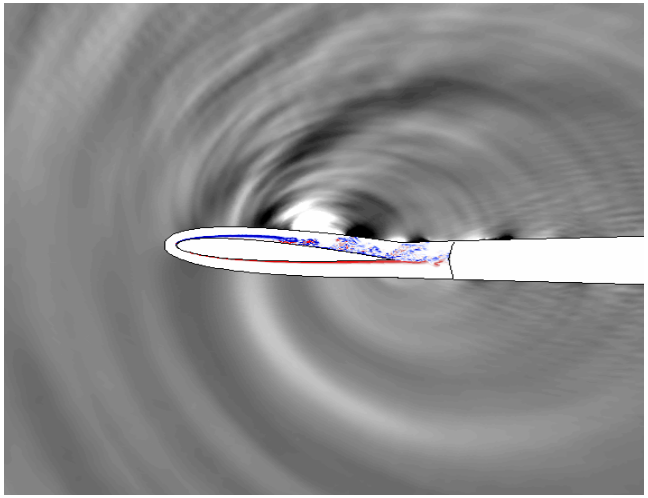
Complex Geometry

High-Re Flows









Airframe Noise Challenges

- **High Reynolds numbers**
  - Boundary layer state often plays an important role in the developing unsteadiness
- **Separation points on smooth bodies**
  - Transition models in CFD are rare
  - Effects of experimental transition strips can be difficult to simulate
- **Statistics**
  - Low Mach number flows require long runs to acquire statistically meaningful data
- **Complex geometry**
  - Need accurate and flexible solvers

The V&V Challenge

The CFD community has a longer history and less complicated physics, yet they are still formulating verification and validation cases and procedures.

Doing V&V correctly is difficult, but it is the appropriate path forward.

What Makes an Experiment a Benchmark?

Definition: a standardized problem or test that serves as a basis for evaluation or comparison (Merriam-Webster)

Benchmarks

- **Relevant**
  - Problem with physics related to the real problem
- **Confidence**
  - Must be earned, often over time
  - Group analysis very beneficial (i.e. workshops)
  - Experimental and computational cross examinations
- **Open and accessible data**
  - Non-proprietary and easily found
- **Well-defined geometry including model and tunnel details**
  - Includes boundary conditions

Benchmarks (continued)

- **Measurements of many quantities of interest**
  - Near field and far field
  - Steady (time-averaged) and unsteady
- **Experimental uncertainty quantified**
- Formal error analyses
- Multiple measurement techniques for the same quantity
- Testing in multiple facilities
- **Reynolds number effects quantified or minimized**
- Avoid transitional flows
- Document effects of transition strips
- **Thorough documentation of flow conditions (both upstream and downstream), conditions in plenum, etc.**
- Either avoid or thoroughly assess two dimensionality
  - Correlation/Coherence should be known

Near-term Prospects

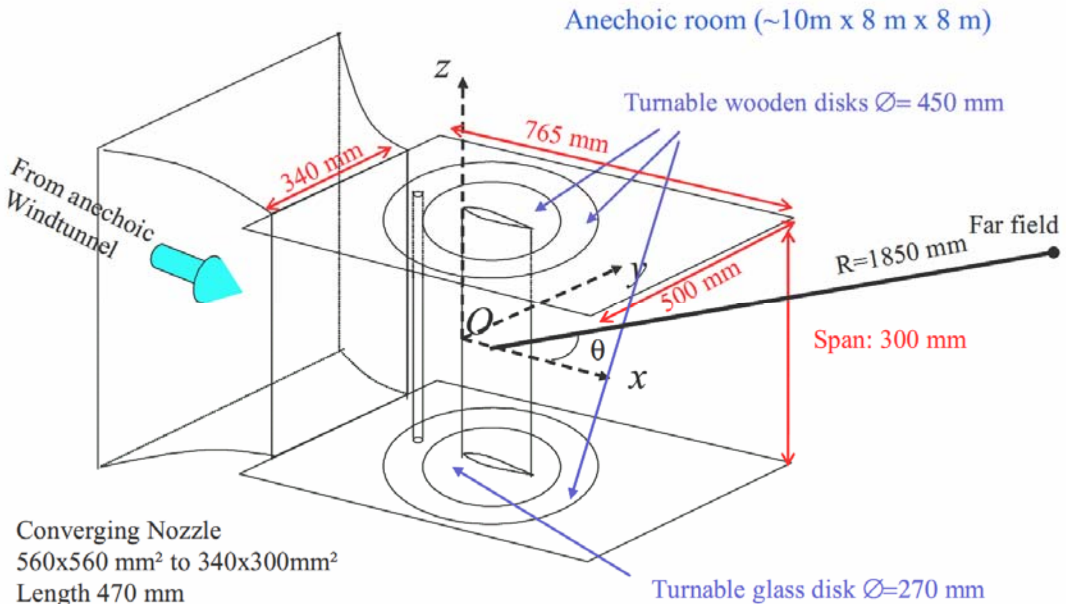
A few examples…

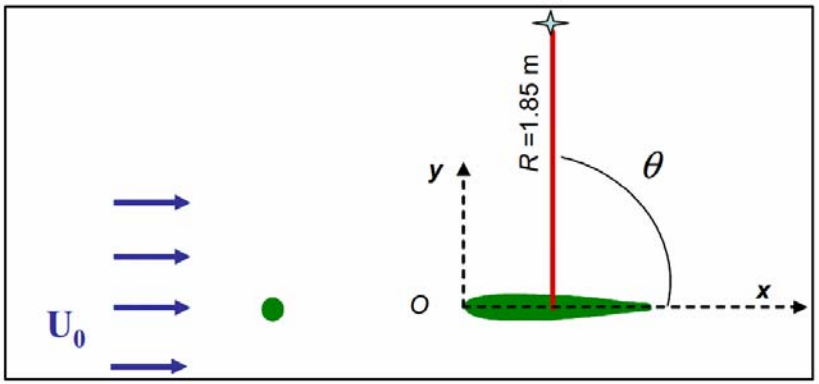
Rod-Airfoil

- Simulates turbomachinery Interactions

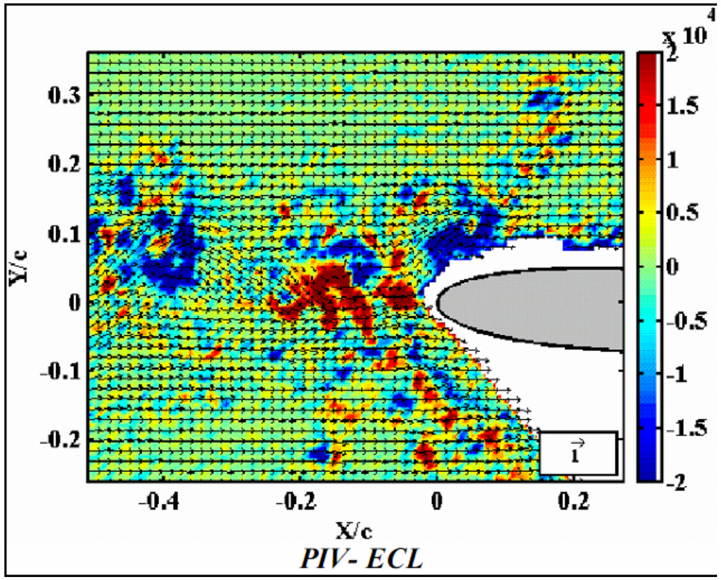
- Multiple measurements
    - Different tunnels

- Favorable comparisons between CAA and experiment



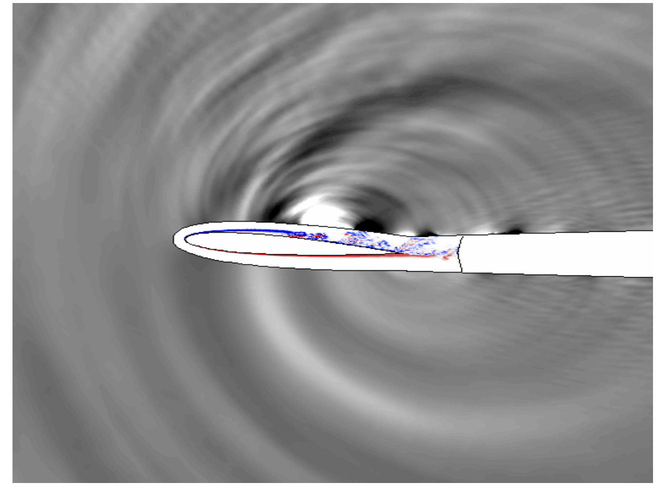


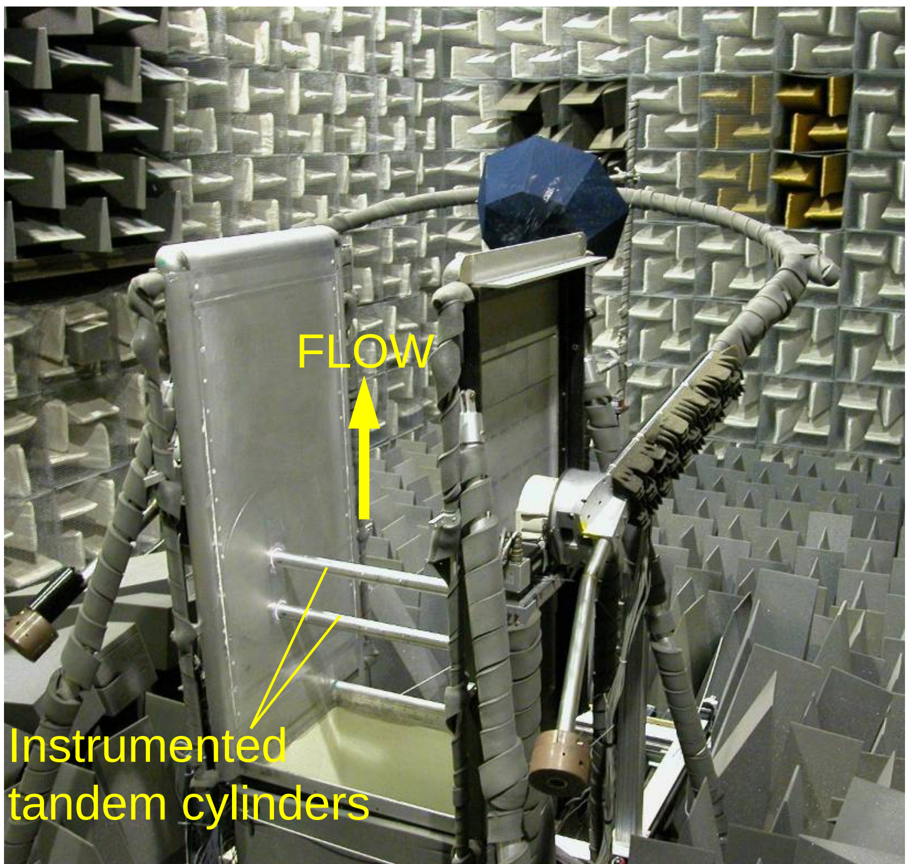
Jacob, et al. AIAA 2008-2899

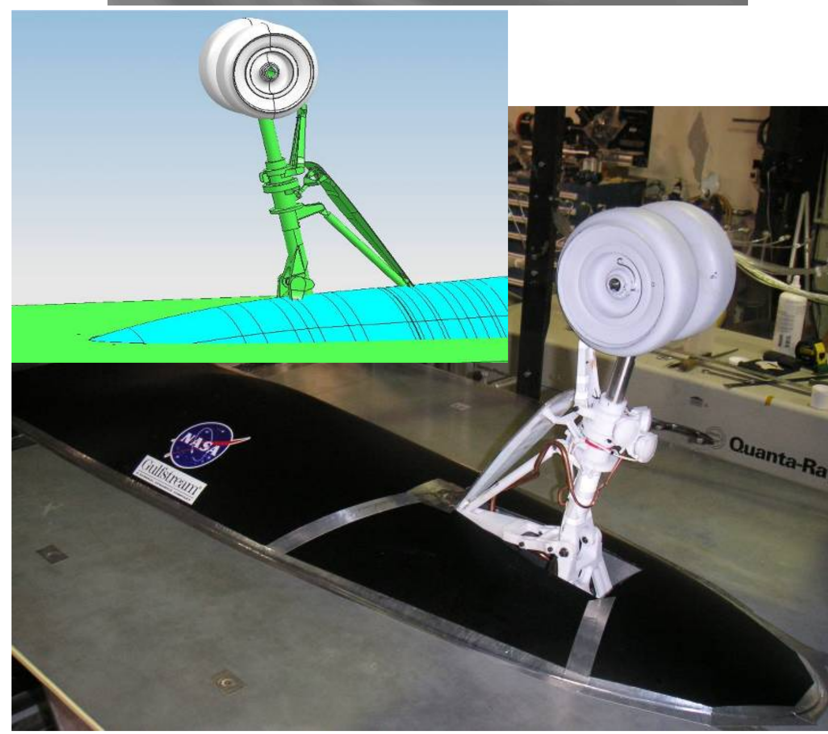


Workshop on AFN Benchmark Problems

- **2010 workshop**
  - Tandem cylinders
  - Trailing-edge scattering
  - Simplified landing gear (nose and main)





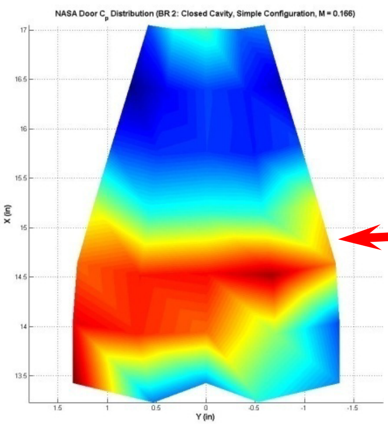


Nose Landing Gear
(Flow Field Measurements: LaRC BART)

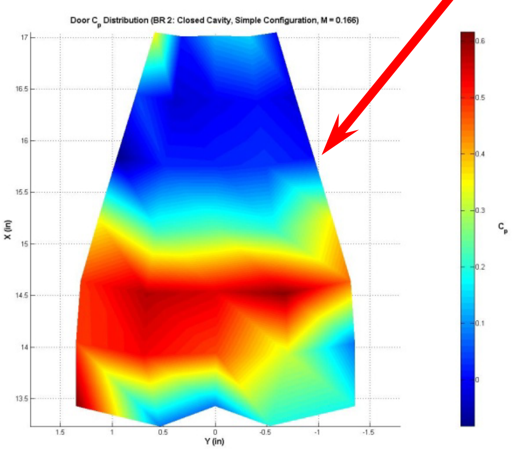
25% Scale G550 Nose Gear Model

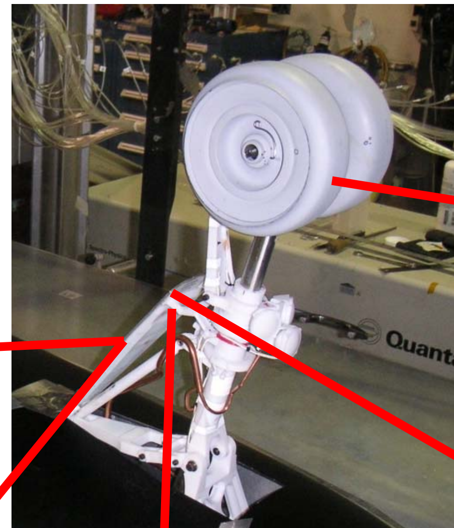
Door Cp

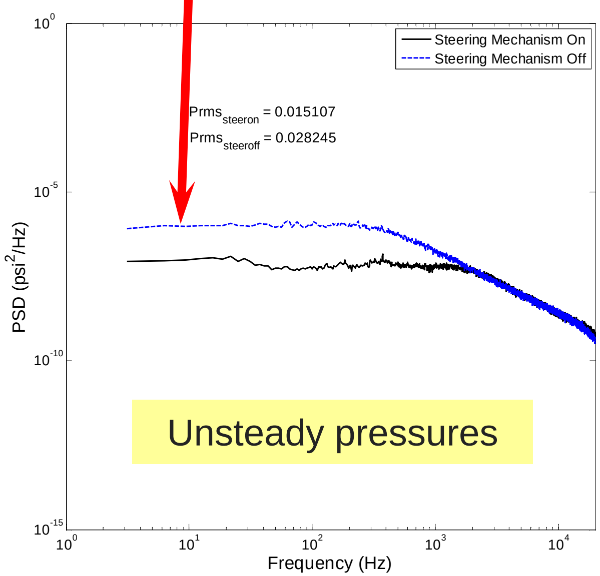
LaRC BART

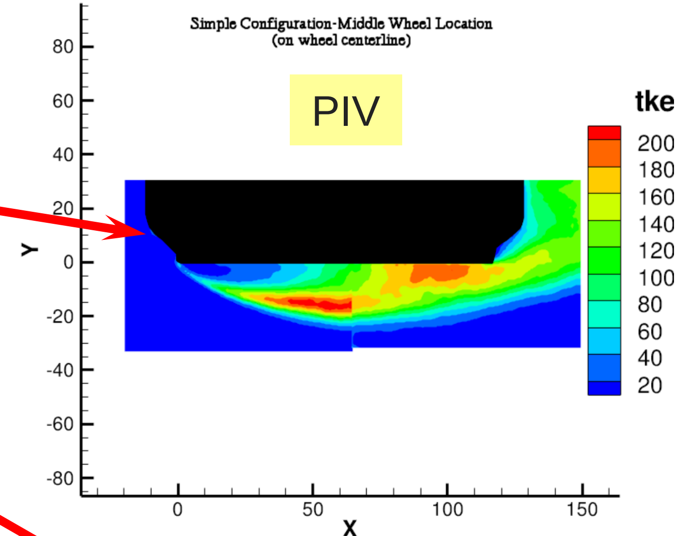


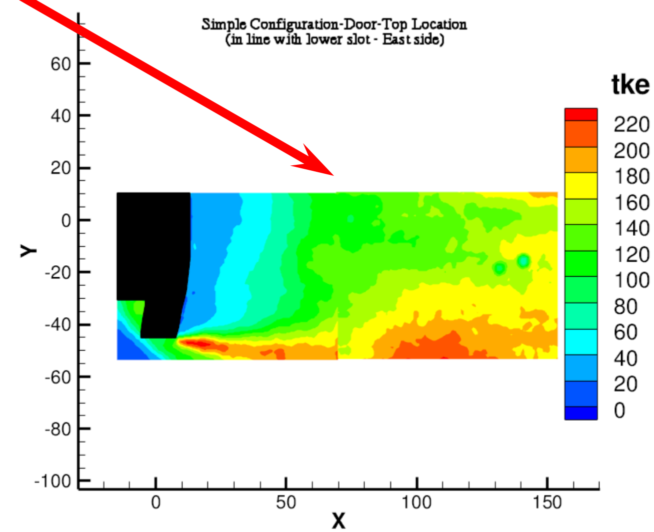
GAC/UFL



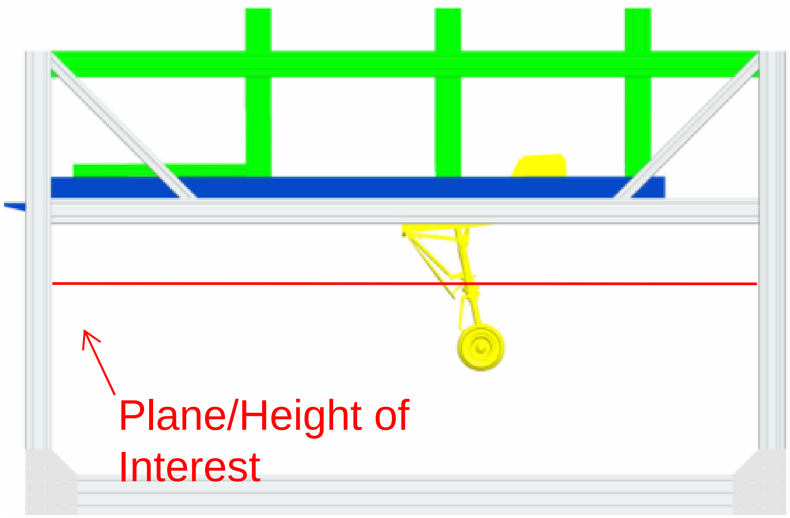


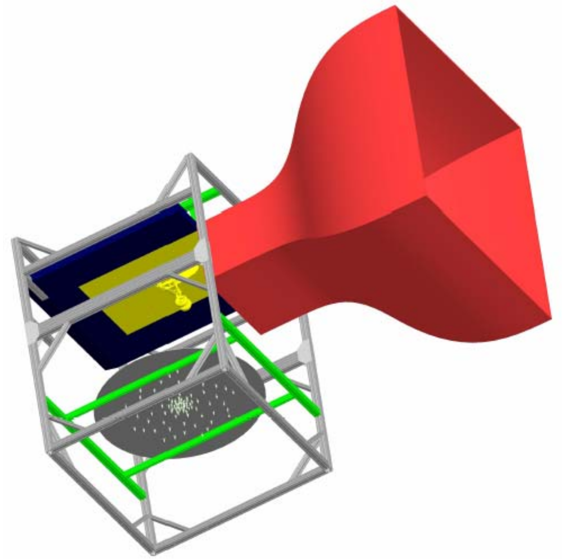




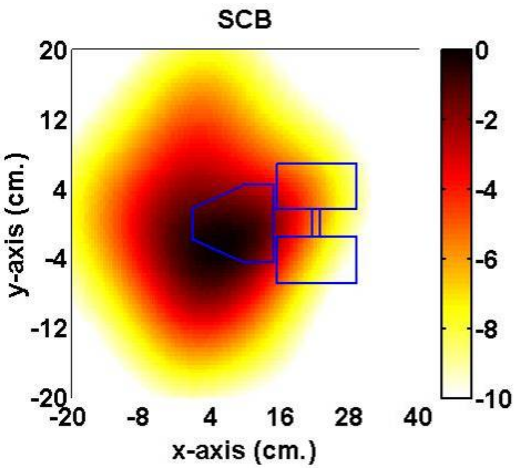


Nose Landing Gear
(Microphone Array Measurements: GAC/UFL Tunnel)





F_{focus} = 2 kHz



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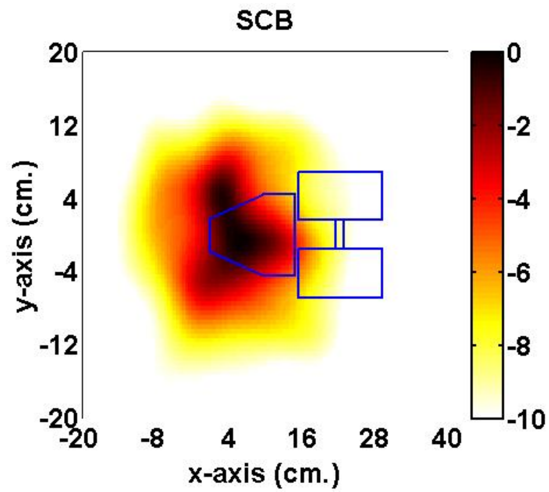
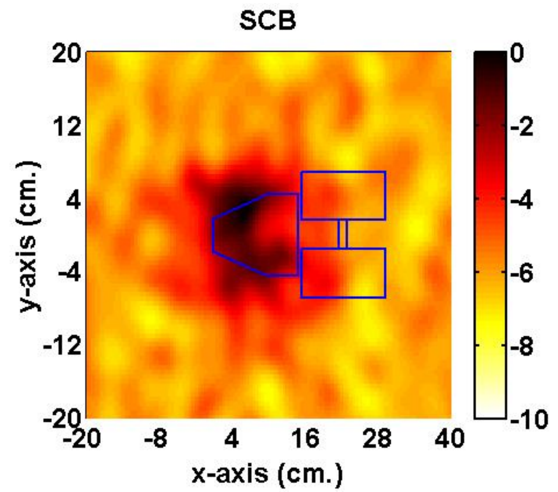


F_{focus} = 10 kHz



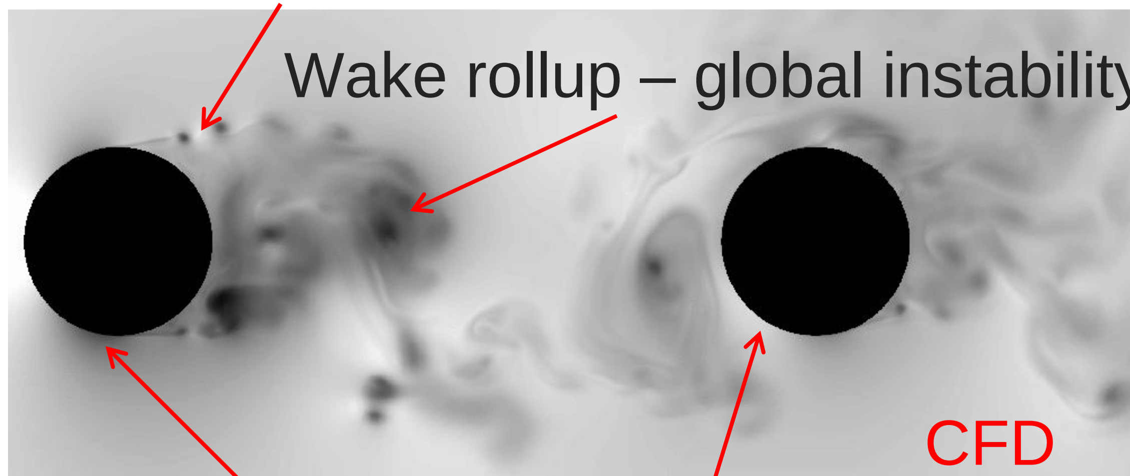
Tandem Cylinders: Physics

• Separation point determines trajectory of shear layer
• Flow separates past 90º on the upstream cylinder

• Trip used in experiments to fix the separation point

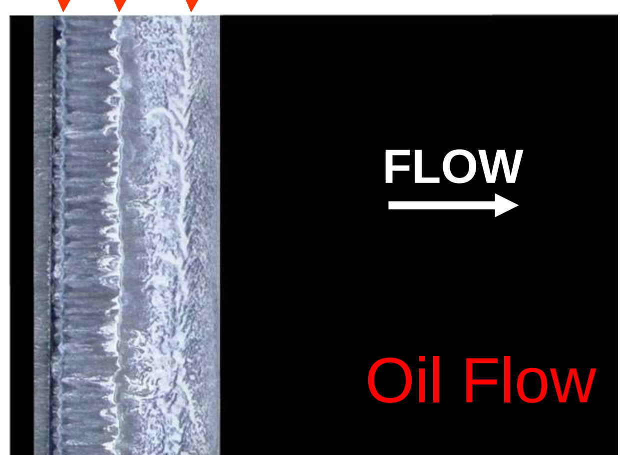
Character very different from laminar case

Kelvin-Helmholtz Instabilities



Turbulent boundary layers

T S R



Trip
Separation
Reattachment

Tandem Cylinders

- **The "Good"**
  - Relevant physics
  - Open and accessible
  - Multiple measurements
    - Surface Cp, rms Cp, spectra, oil flow, spanwise coherence
    - Off-surface near-field PIV, hot-wire, pressures
    - Radiated acoustics
  - Separation point fixed by transition strips
  - Tested in 2 facilities
    - Reasonable agreement
  - Several codes used to simulate the case
- **The "Bad"**
  - Transition strips create complications in modeling
  - 3D version of 2D problem
  - End effects undocumented
  - Some measurements only performed in 1 facility

Summary

- **The message from the CFD community**
  - Be complete in collecting data
  - Be thorough in analyzing solutions
  - Expect more variability in results than desired
    - Need standardization of nomenclature
    - Using common grids minimizes the scatter
      - Similar issues with time step?
    - Must work towards a way to quantify the error
      - Identification of true outliers and unique but correct solutions
  - Build trust through group exercises
    - Multiple measurements
    - Multiple facilities
    - Multiple codes

Summary (continued)

- **CAA benefitted in the establishment of many verification cases from the CAA workshops**
  - Can also use cases developed by the CFD community
  - Manufactured solutions may prove beneficial

- **Collective efforts should be useful for developing validation cases**
  - Confidence developed or problems identified more rapidly
  - Leverages different expertise
  - Helps distribute the expenses

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  - http://groups.google.com/group/afnworkshop_problem3
  - http://groups.google.com/group/afnworkshop_problem4
- **EU project NODESIM-CFD: Workshop on uncertainty quantification in CFD**
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- **ERCOFTAC CFD best practices**
  - http://www.ercoftac.org/index.php?id=77
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