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Second Workshop on Integration of EFD and CFD

Validation and Minimizing CFD Uncertainty for Commercial Aircraft Applications – The Integration of EFD and CFD

Edward N. Tinoco

Boeing Commercial Airplanes

Seattle, Washington, USA

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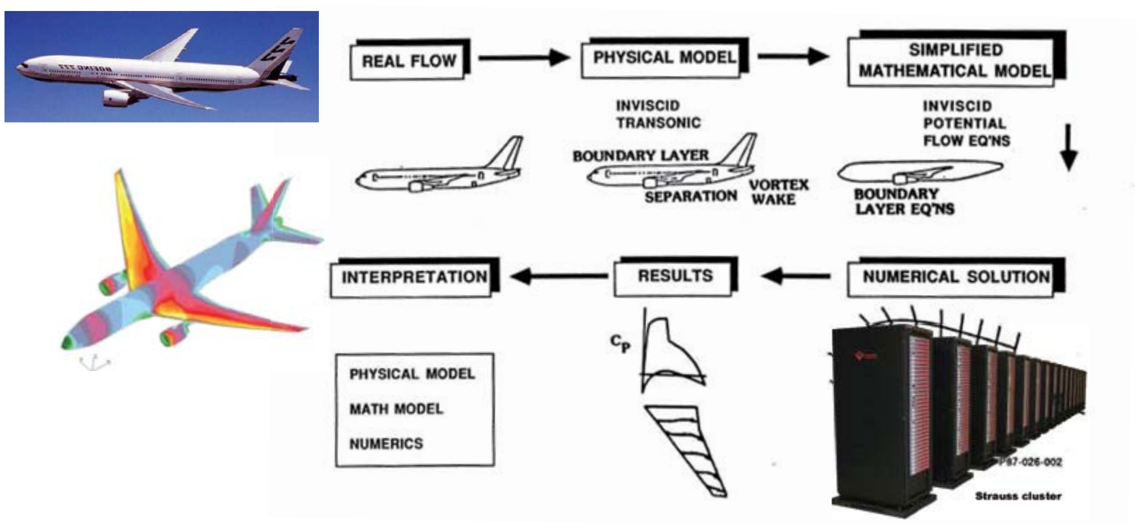
- **Scope: Validation experiences presented are limited to the application of Computational Fluid Dynamics (CFD) to high-speed (transonic) commercial transport vehicles**

Computational Fluid Dynamics



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Outline

- Scope: Validation experiences limited to high-speed (transonic) commercial transport vehicles
- Motivation
- Validation for an Intended Purpose
  - Codes - CFD
  - Knowing the test data - EFD
  - Adventures in validation
- Minimizing CFD Uncertainty
- Case Study – 3rd Drag Prediction Workshop
- Concluding Remarks

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Motivation

To get value out of CFD you must get CFD into the Product.

- CFD must get into the hands of the engineers responsible for the development of the product.
- CFD must be predictive
  - – Predictive results must be timely.
  - – Predictive results must be consistent
- Management must believe in the use of CFD.
  - – Makes economic sense.
  - – Usable by the engineers on the project.
  - – Confidence that both CFD and Users are validated.

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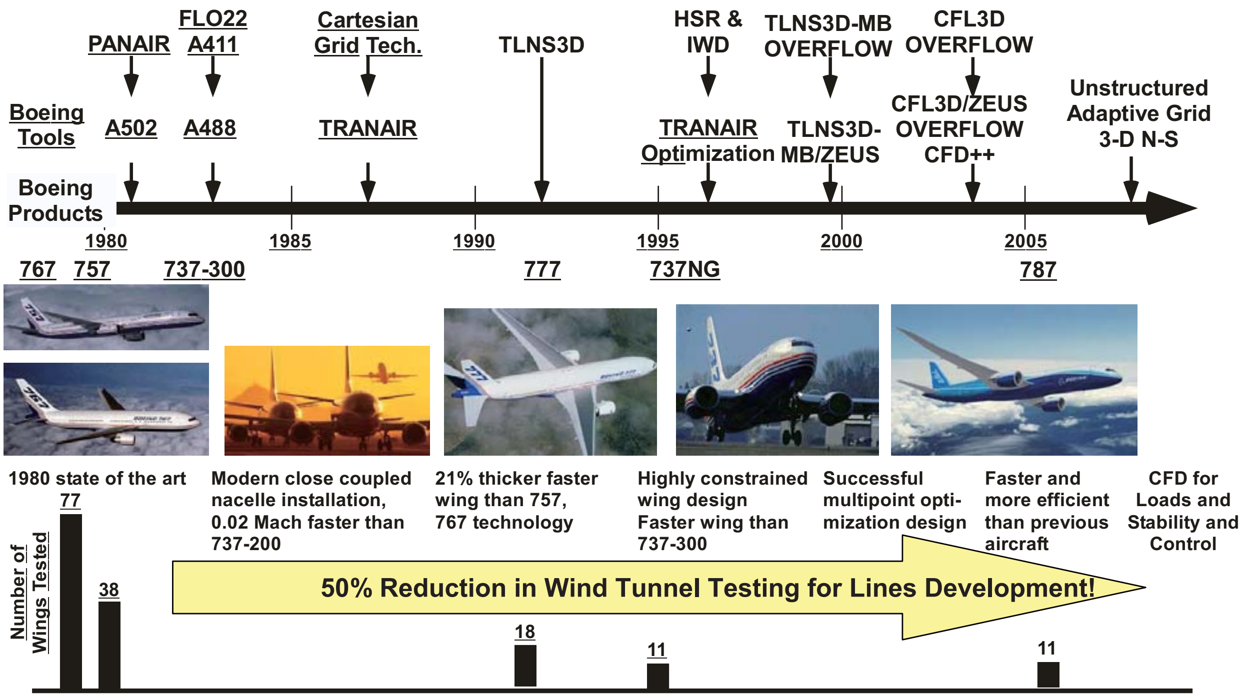
The Impact of CFD on Configuration Lines Development Wind Tunnel Testing



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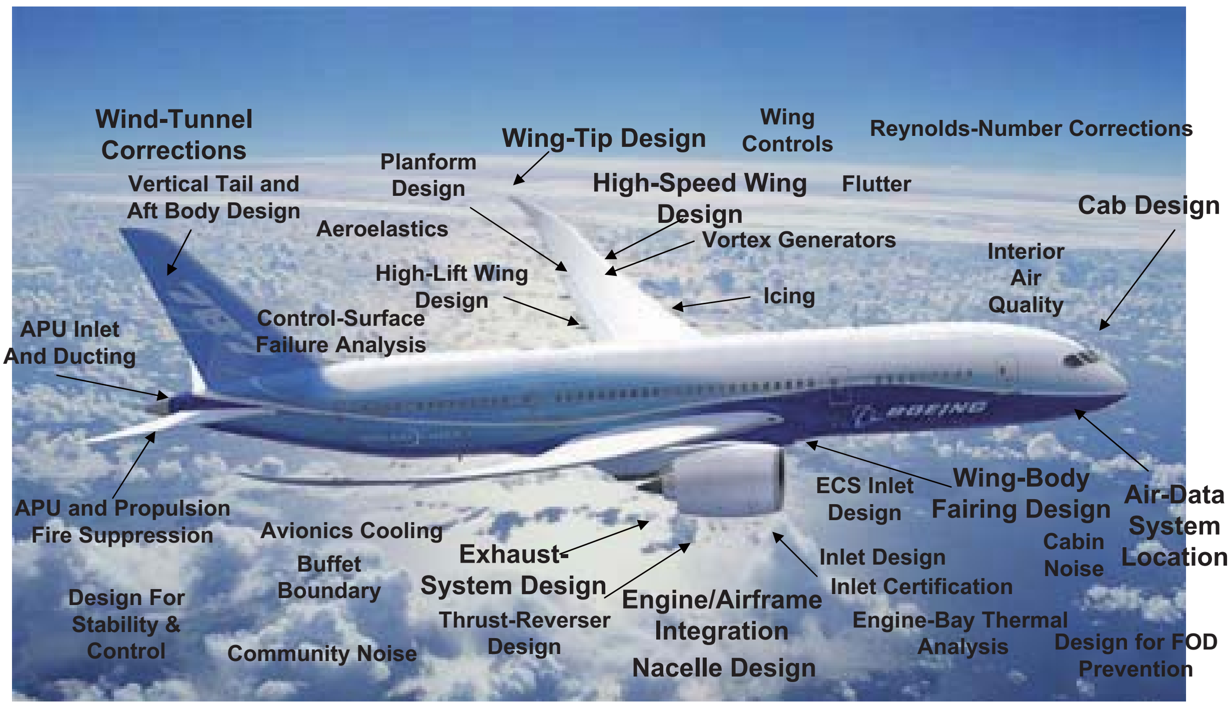
CFD Contributions to 787



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Use of CFD and therefore the Need for Validation has been driven by "Desperation"

- Not being able to meet high-speed drag design goals by traditional "cut & try" wing design in 1980's led to "inverse design" via pressure matching
  - Need - Validated accuracy of wing pressure distribution prediction
  - Used on 777 and Next-Generation 737
- Not being able to meet high-speed drag design goals by "inverse design" wing design on 4-engine airplane in 1990's led to "optimization" drag design
  - Need – Validated prediction accuracy of configuration drag increments due to small geometry perturbations
  - Used on Sonic Cruiser, 787, 747-8
- Increased market pressure to reduce airplane development cycle time
  - Need – Validation of prediction accuracy of CFD for Loads and S&C
  - Used on 787 and 747-8

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Verification, Validation, Calibration, and Certification?

From a recent update from the AIAA committee on Standards for computational fluid dynamics we see *verification and validation of CFD codes and calculations as the process of determining the level of confidence that can be placed in the resulting CFD data where:*

Verification: The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.

Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

These are necessary first steps leading to:

Validation for Intended Purpose

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Validation for Intended Purpose

- Instill "user confidence" that the "CFD processes" can deliver solutions that are "good enough".
- "Good enough" depends on intended use and is in the eyes of the user.
- "Good enough" is frequently measured with respect to test data that has itself been deemed "good enough"
  - CFD should not exactly match test – both have different limitations
  - Matching data at 2 or 3 conditions is inadequate/misleading
  - Need trends over multiple conditions and configurations
- CFD code <u>by itself</u> can never be validated for an intended purpose
  - Too many variables – user accessible "knobs"
  - Grids – too much dependence
- "CFD process" from lofts, grid generation, solver, post-processing, etc. must be focus of establishing "user confidence" in being "good enough"

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Computational Methods
(addressed in this presentation)

TRANAIR
- Full Potential with directly coupled Boundary Layer
- Cartesian solution adaptive grid
- Drela lag-dissipation turbulence model
- Multi-point design/optimization

Navier-Stokes Codes
- CFL3D – Structured Multiblock Grid
- TLNS3D - Structured Multiblock Grid - Thin Layer
- OVERFLOW – Overset Grid

N-S Turbulence Models
- S-A Spalart-Allmaras
- Menter's k-w SST

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Knowing the Test Data

Neither wind tunnel nor flight test data can be considered an absolute against which to compare CFD for validation.

Flight Test Uncertainties
- Flight Conditions – Mach number, angle of attack, slideslip calibrations. Ability to hold conditions in flight.
- Forces – No direct measurements, inferred from flight characteristics, fuel burn.
- Pressures – limited in number, subject to significant instrumentation lag.
- Shape – Aircraft aeroelastics, control surface deflections.

Wind Tunnel Test Uncertainties
- Better control and measurement of flight conditions, forces, pressures, shape, etc. but:
  – Generally at much lower Reynolds number than full scale flight
  – Must be corrected for significant wall and mounting system effects to represent "free-air". Complete corrections not practical.
- Better statistical evaluation
  – Short term and long term repeats within a test entry
  – Test to test repeats
  – Tunnel to tunnel repeats

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Wind Tunnel Data Corrections

Clear tunnel flow conditions are subject to small variations in pressure and flow direction. The introduction of the wind tunnel model further disturbs these quantities away from “free-air”.

- **Mach Number – Function of total and static pressure**
  - **Centerline pressure vs. static measurement**
  - **Static pressure change due to model presence – “Mach Blockage”**
- **Angle-of-Attack – A derived quantity – physical angle + corrections for:**
  - **Flow angularity – “Up-flow”**
  - **Lift interference – “δ_o” – Model to tunnel size, tunnel wall ventilation, Mach**
- **Drag – Measured force corrected for angle-of-attack, + corrections for:**
  - **Clear tunnel buoyancy**
  - **Solid blockage buoyancy**
  - **Internal cavity pressures**
  - **Normalized skin friction**
- **Tare and Interference – can effect all quantities, specific to model, tunnel, Mach number**

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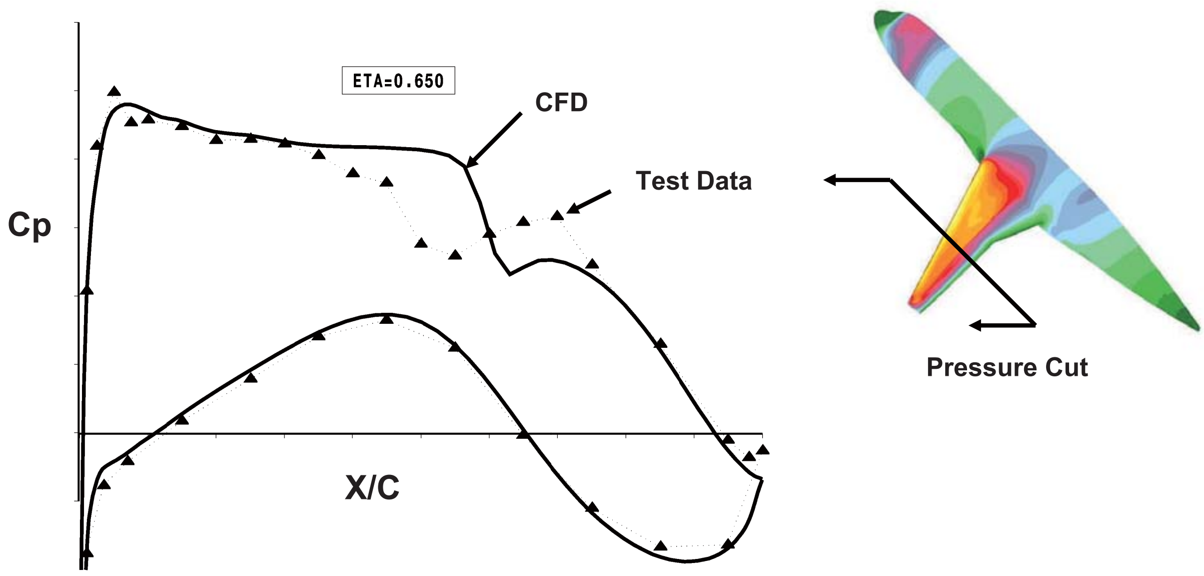
Poor Validation Choice

The CFD development team struggled for nearly a year trying to get better agreement with test data.



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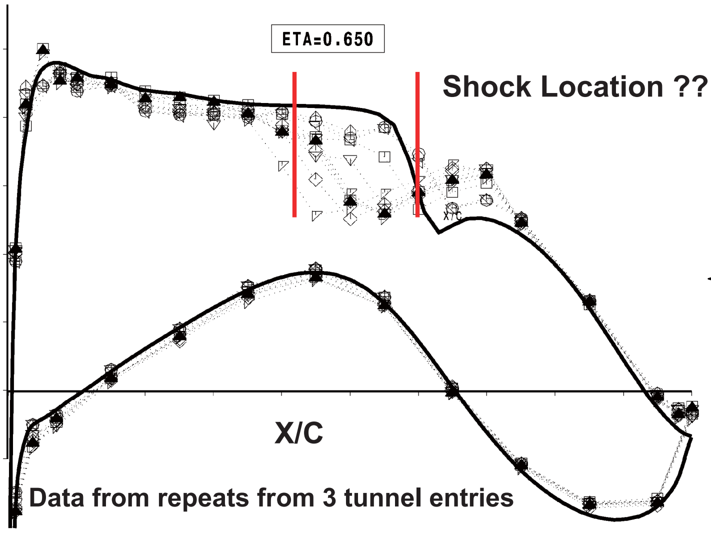
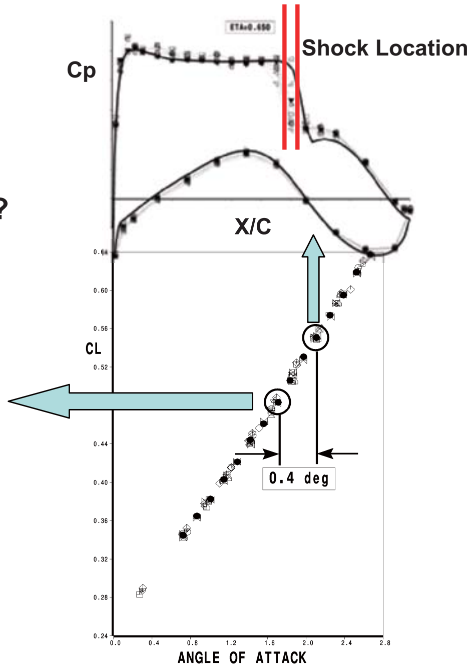
Poor Validation Choice

Extreme Sensitivity of Shock Location to Flow Conditions

Sensitivity of the shock location to exact Mach and angle of attack is very high at this condition - the correlation will be very poor.





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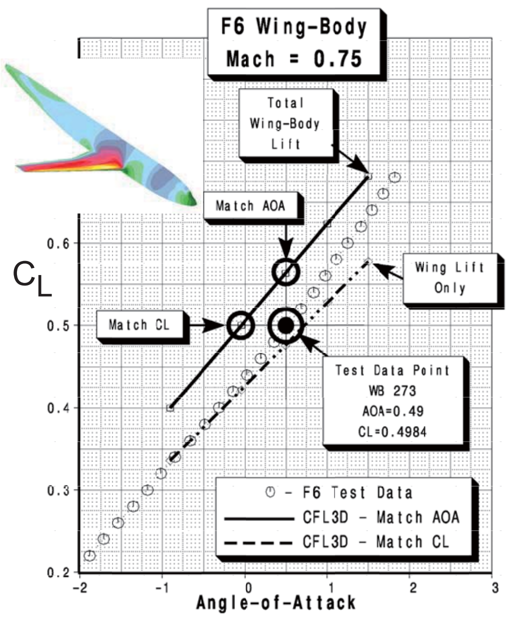
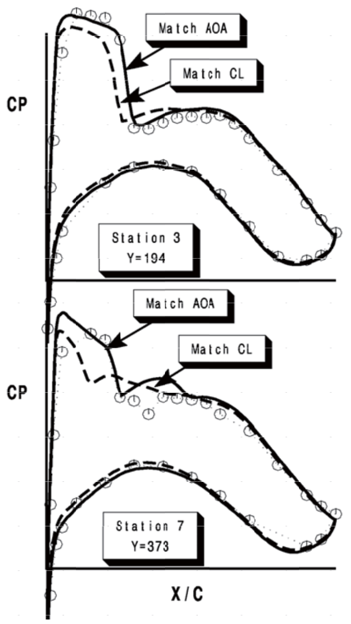
Inconsistency between forces and pressures

DLR F6 Wing-Body **Wing Cp's – Match α or CL?**





- Apparent wing pressure agreement at given angle of attack raises question about lift force.
- Not enough information available to determine why

From the 2nd AIAA Drag Prediction Workshop

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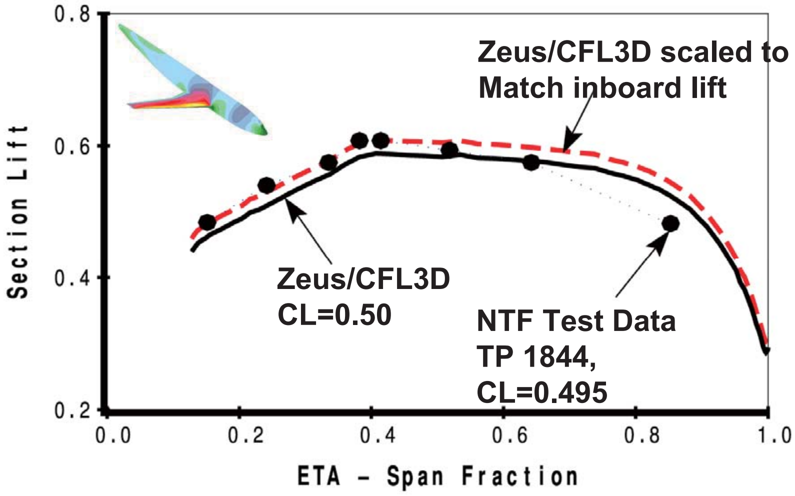
Inconsistency between forces and pressures

Probable cause – wrong wing twist in CFD model!



Increasing the nose down twist on the outboard part of the wing will result in a higher angle of attack when matching CL thereby better matching the wind tunnel force and pressure data.

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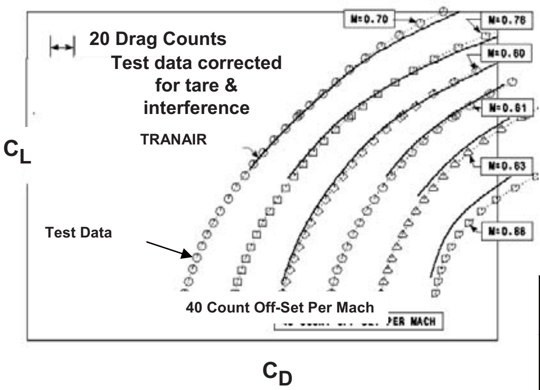
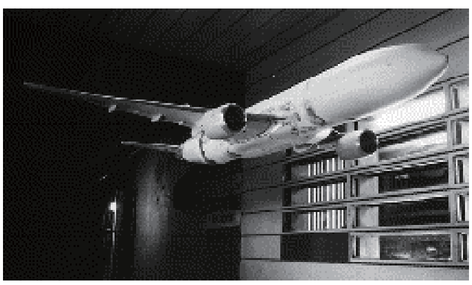
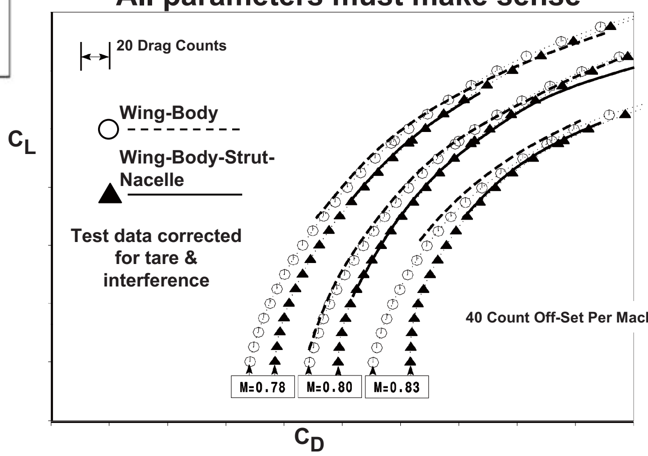
Validation for Drag



- A single drag tare added to all TRANAIR results
- Comparison made over a range of Mach and angle-of-attack
- Emphasis placed on incremental drag
- All parameters must make sense





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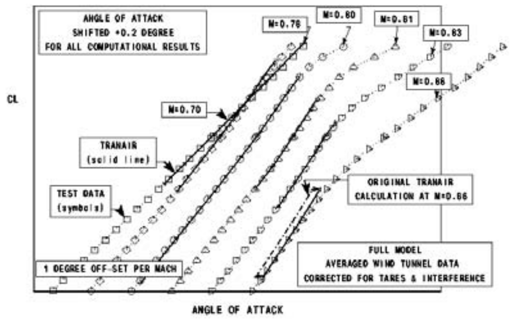
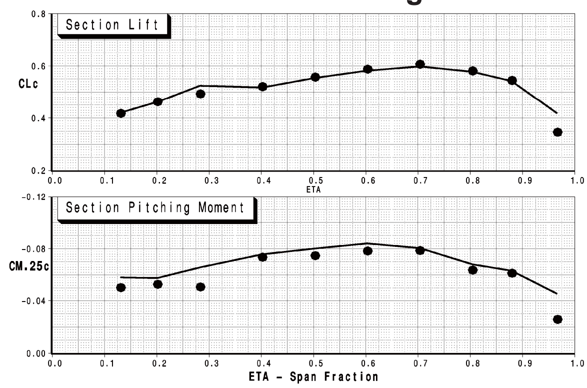
Validation Must Make Sense for all Parameters

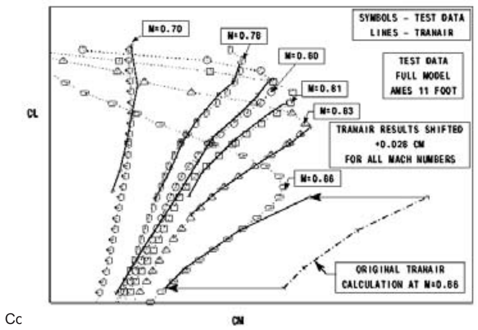
Total Lift



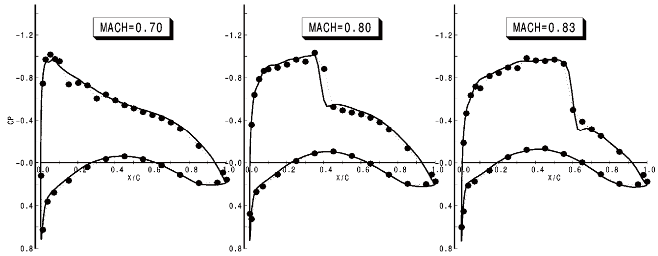
Section Lift and Pitching Moment



Total Pitching Moment



Pressure Distributions



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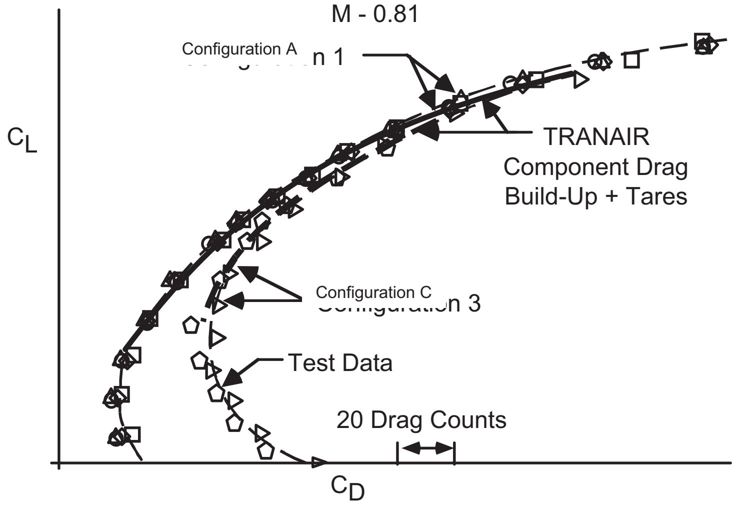
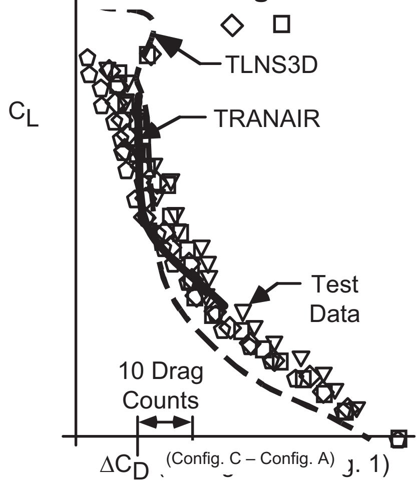
Code to Code, Code to Test Comparisons

- Validation with multiple code adds to confidence
- A single drag tare added to results from each code
- Different levels predicted but same incremental delta

Wing-Body Drag Polars



Incremental Drag between Configurations



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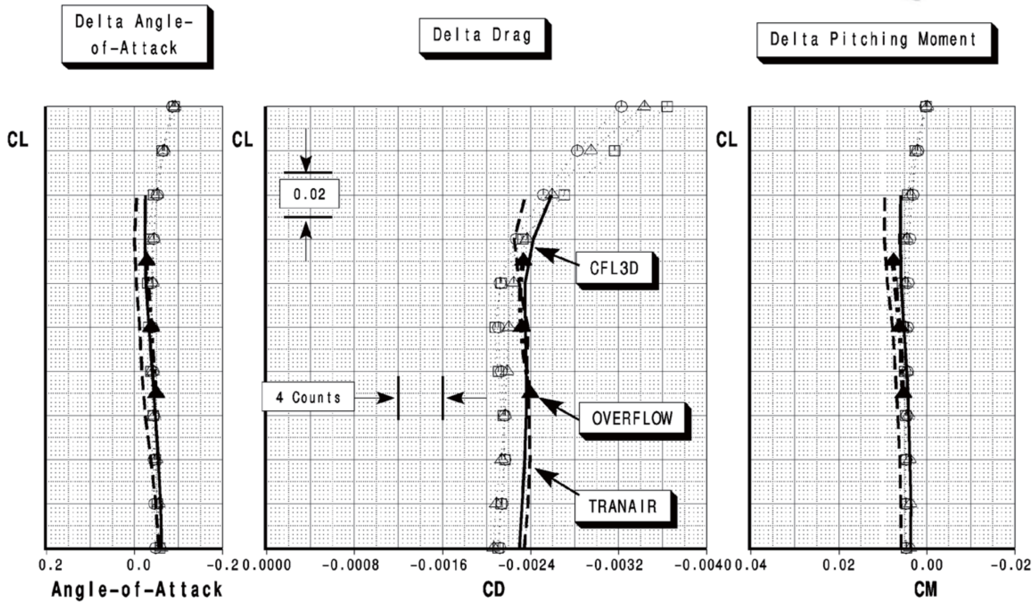
Code to Code, Code to Test Comparisons

- Validation with multiple code adds to confidence
- Consistent processes yield consistent results



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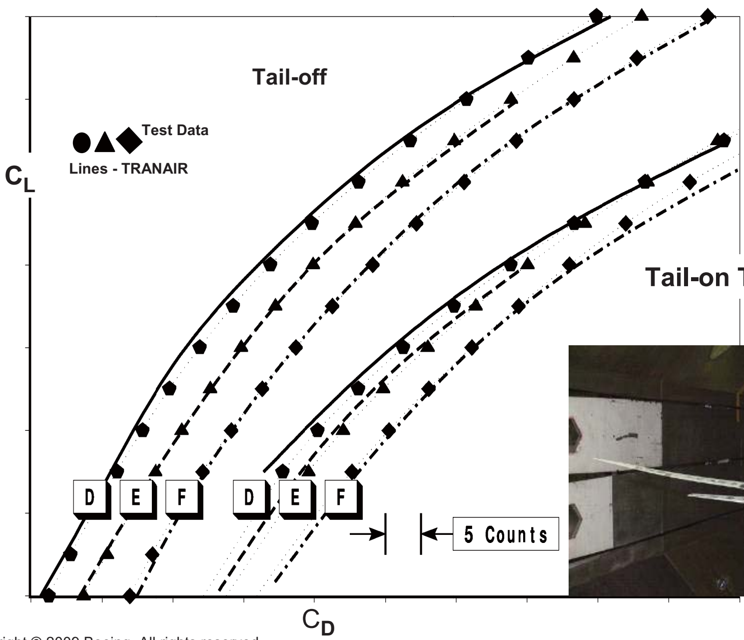
Consistency Builds Confidence in Validation

Predictive CFD – The bulk of these results were obtained pre-test!



- Single drag tare added to all results
- Consistent processes yield consistent results
- Consistent results build confidence

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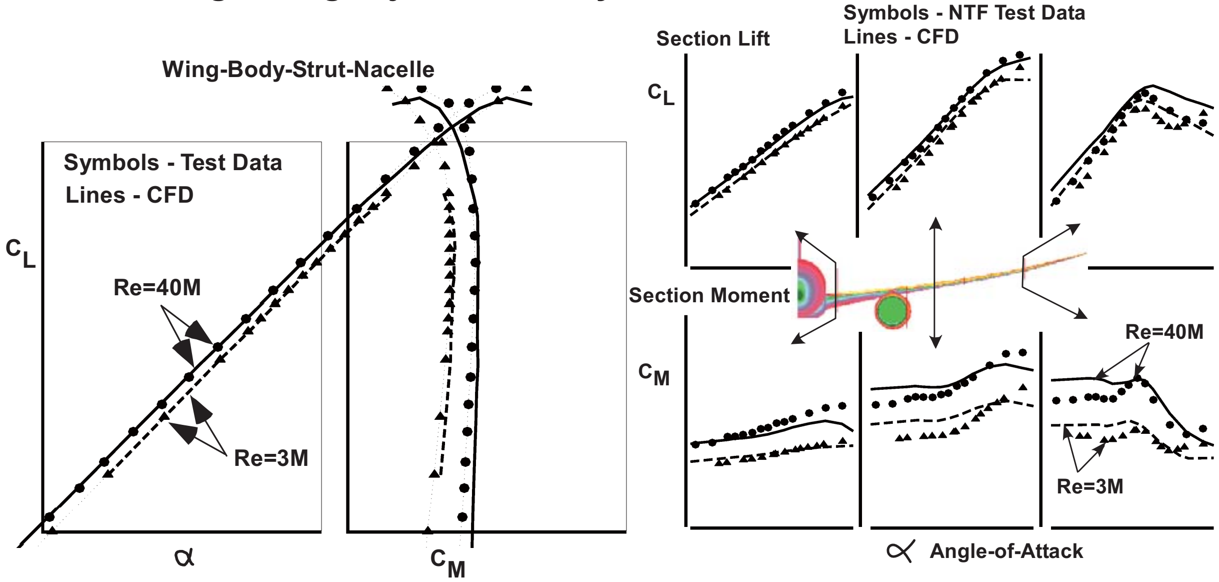
Reynolds Number Effects

- Use CFD to provide Reynolds number corrections to conventional wind tunnel data
- Consistent gridding adjusted for Reynolds number



Single tare added to CFD results

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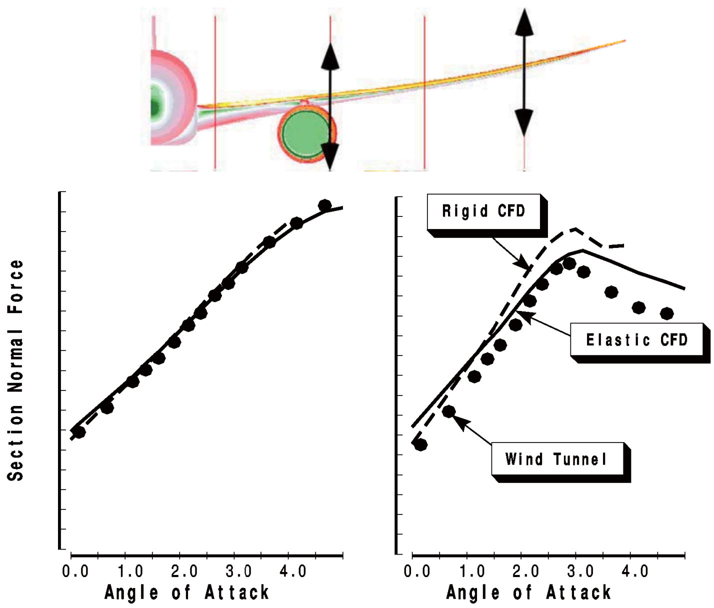
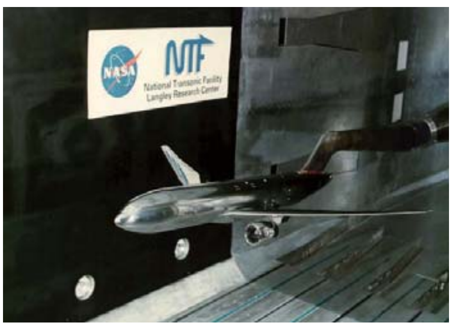
The Importance of Wing Tunnel Model Aeroelastics

- Accounting for wind tunnel aeroelastics adds confidence to CFD validation





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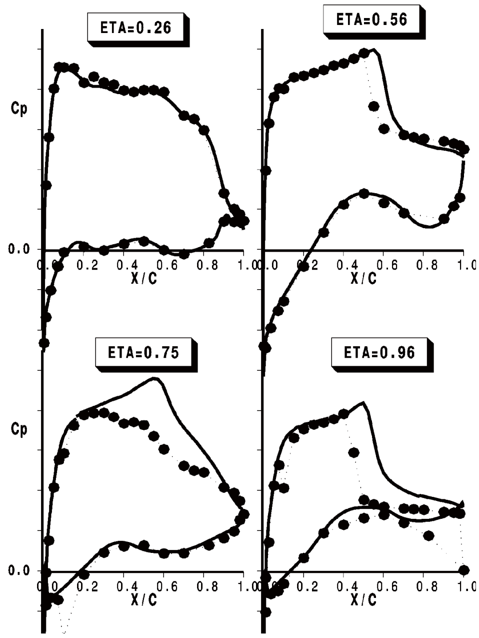
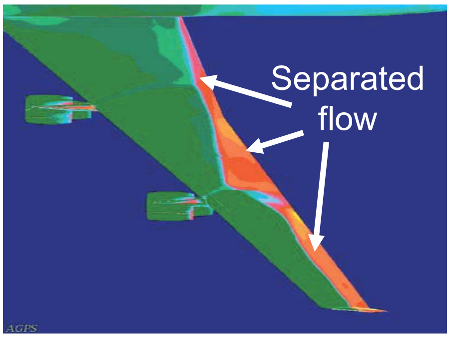
CFD at the Edges of the Envelope

- CFD Issues
  - Large regions of separated flow
  - Turbulence models
  - Need URANS or DES?
- Testing Issues
  - Close to Mach One
  - Model aeroelastics
  - Representative of "Free Air"?

Cp comparison at approximately 2.5g at Mach dive





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- Scope: Validation experiences limited to high-speed (transonic) commercial transport vehicles
- Motivation
- Validation for an Intended Purpose
  - Codes
  - Knowing the test data
  - Adventures in validation
- **Minimizing CFD Uncertainty**
- Case Study – 3rd Drag Prediction Workshop
- Concluding Remarks

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Minimizing CFD Uncertainty - Stable, Packaged Software Solutions – not just codes.

Product Development engineers must be able to focus on on engineering processes and have little time for manipulating CFD "process", i.e. codes must be very user oriented.

- Consistent, Repeatable Processes
  - Enables fast results, reduces variation.
- Integrated Stable, Packaged Software Solutions
  - Scripted Packages for "standard" configurations
  - Geometry, Grid/Paneling Generation
  - Solvers
  - Post-processing
  - Software Version Control
- Integrated Computing Resources
  - High-end Computing Resources
  - Mass Data Storage
  - Computing System Administration

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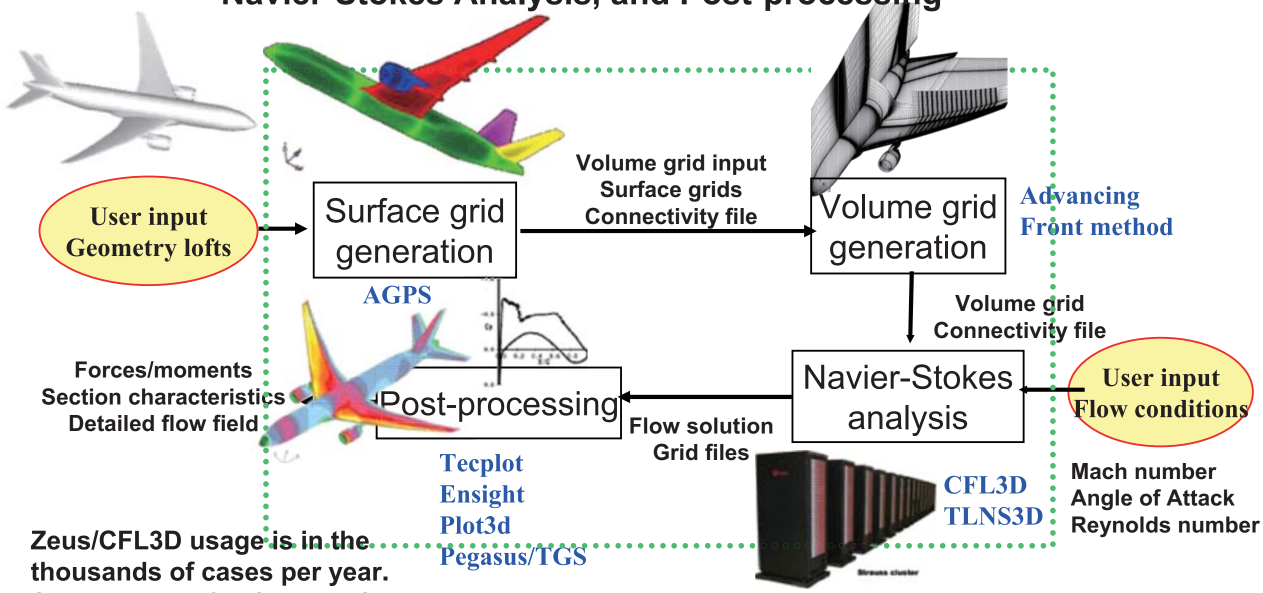
Stable, Packaged Software Solutions – Zeus/CFL3D

Driver for Surface Grid Generation, Volume Grid Generation, Navier-Stokes Analysis, and Post-processing



Zeus/CFL3D usage is in the thousands of cases per year. Similar usage for OVERFLOW.

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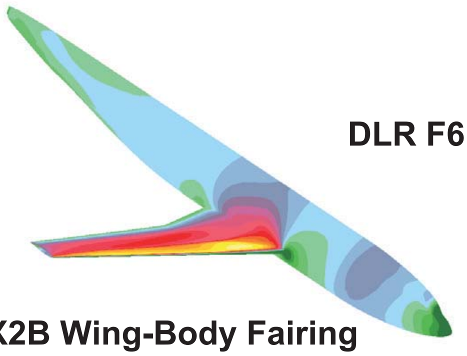
Case Study – 3rd AIAA Drag Prediction Workshop

An example of predictive CFD. All CFD solutions completed at least a year prior to wind tunnel test!

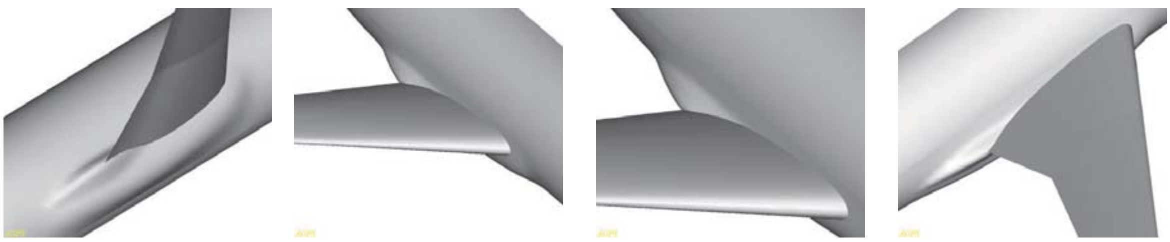


DLR F6 Wing-Body

Original Reference for base DLR-F6 geometry: AIAA 2001-2414.pdf

FX2B Reference: AIAA 2005-4730.pdf

FX2B Wing-Body Fairing



NASA completed a test of these configurations at the NTF in October 2007

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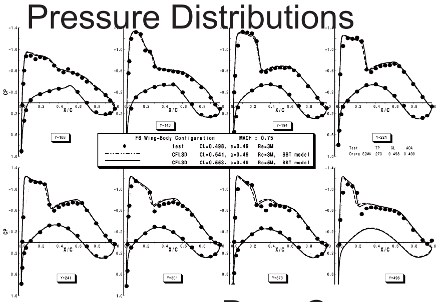
Zeus/CFL3D system – F6 with and without FX2B Fairing

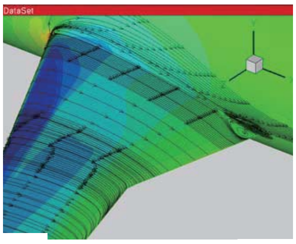
Four Grids - 2.6 to 31 Million Cells

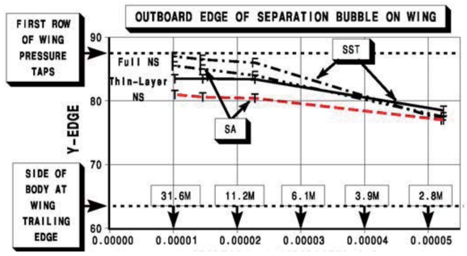
Four combinations - SA or SST Turbulence Models
- Thin-Layer or Full Navier-Stokes Terms

Pressure Distributions

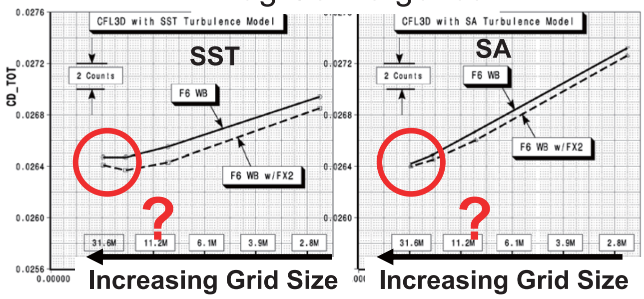


Separation Bubble Extent

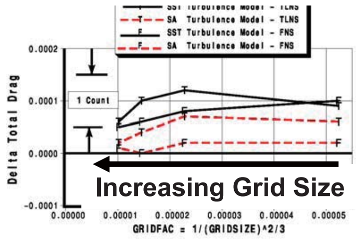




Drag Convergence



Drag Increment Convergence



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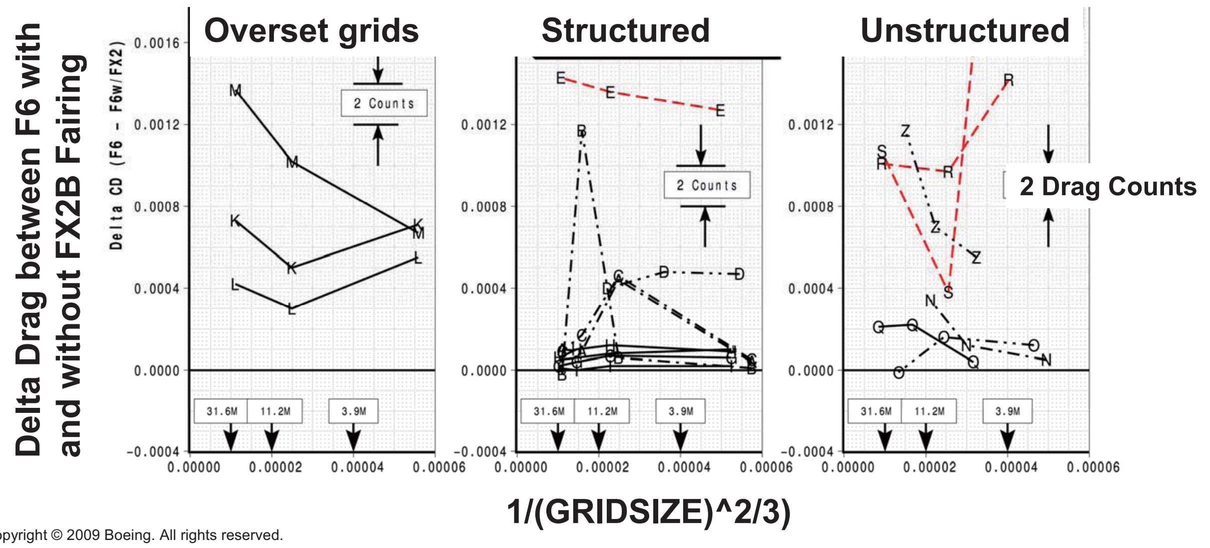
Drag Increment Predictions by DPW3 Participants

F6 Wing-Body w/wo FX2, MACH = 0.75
Re = 5 Million, Fixed CL=0.50

Delta CD (WB - WB w/FX2)

These are results from codes that are considered validated!



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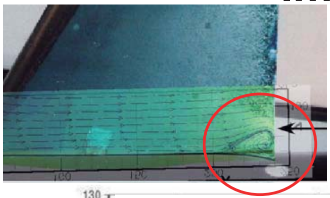
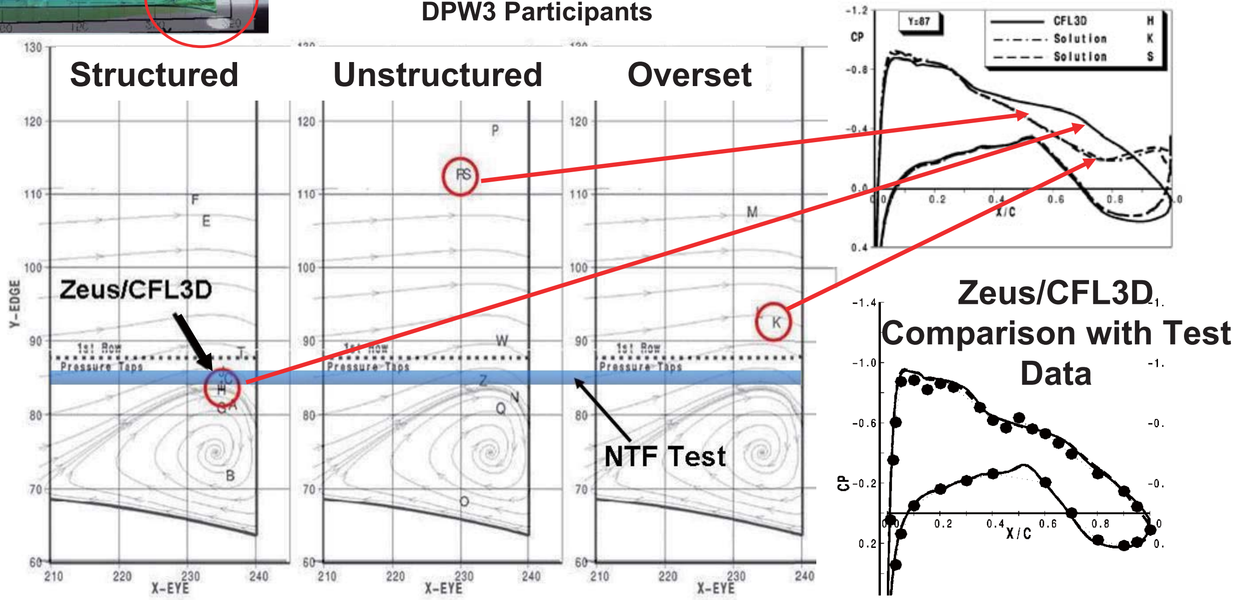
Impact of Separation Bubble Size on Wing Pressure Distribution



Extent of Separation Bubble from Various DPW3 Participants

Solutions at CL=0.50, Re=5M



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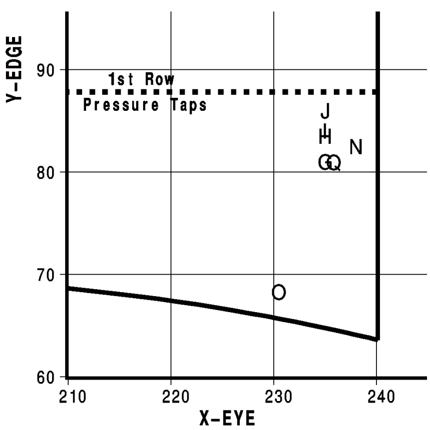
Drag Increment Predictions After Filtering Out

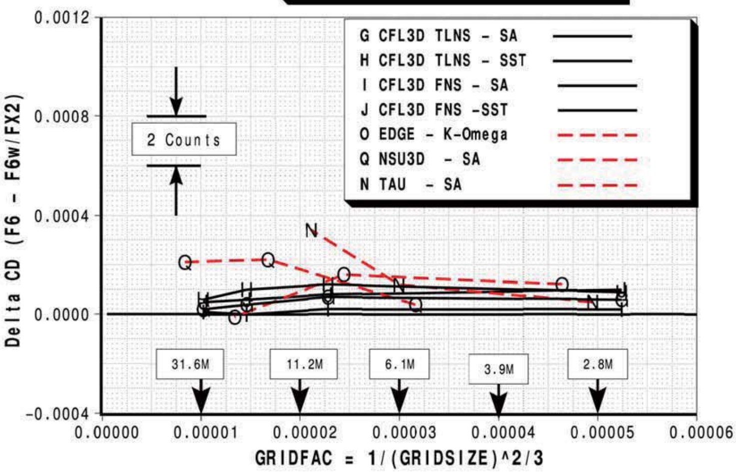
Predictions of Large Separation Bubble
Pressure Distribution Anomalies

F6 Wing-Body w/wo FX2, MACH = 0.75
Re = 5 Million, Fixed CL=0.50

Edge of Separation Bubble



Delta CD (WB - WB w/FX2)



First presented in June 2006

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Drag Increment Predictions After Filtering Out

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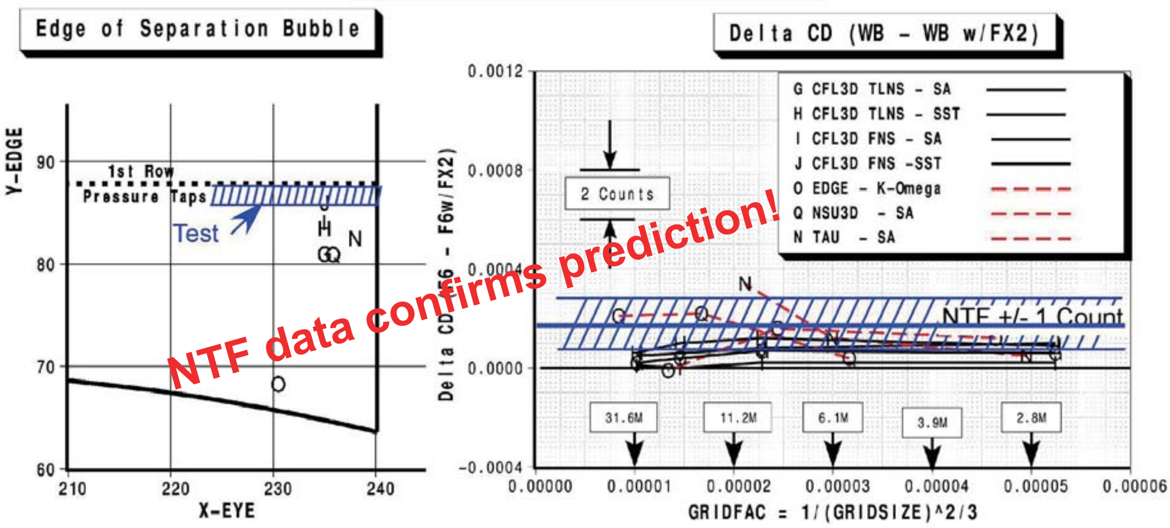

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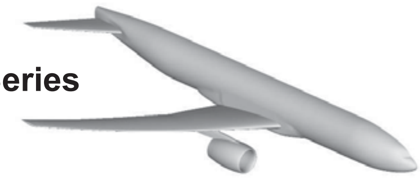
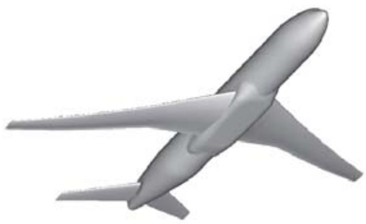
Stumbling Block to Building Confidence

Key to developing the confidence to use CFD in a predictive manner is the on-going, never-ending, validation process. Difficult to do in isolation and without access to a large experimental data base!

- Open workshops very valuable for information exchange
  - CAWAPI F-16XL project
  - AIAA Drag Prediction Workshop Series



- NASA Common Research Model
  - Public domain geometry and test data
  - Testing planned to start in 2009



- 4th AIAA Drag Prediction Workshop
  - June 20-21, 2009 – San Antonio, Tx

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Concluding Remarks

- Validation for an intended purpose is absolutely necessary for confident “predictive” use
  - Requires intimate knowledge of both CFD and experimental data
  - Agglomeration of comparisons at multiple conditions, configurations, code-to-code, code-to-test
- Not just a code but the entire CFD process
  - Geometry, grid generation, solver, post-processing
  - Users
- Need consistent, repeatable CFD processes
  - Packaged processes for “standard” configurations
  - Minimize user “knobs”
  - Standardized grid generation

It is difficult if not impossible to put a precise numerical definition on what is CFD validation and when CFD is “good enough” but I know it when I see it. And to know it requires seeing a lot of it to develop that confidence that it is “good enough.”

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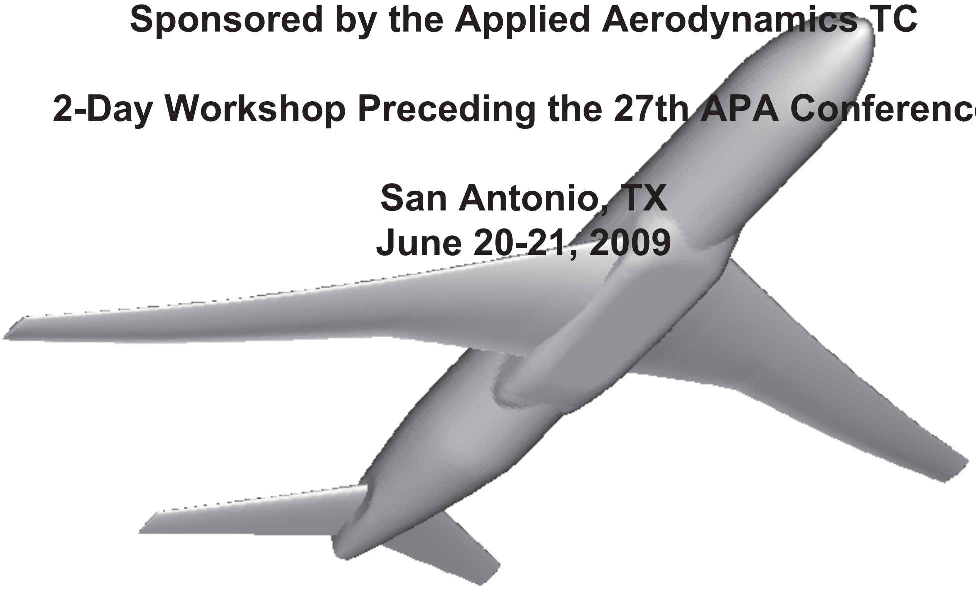
4th AIAA CFD Drag Prediction Workshop

Sponsored by the Applied Aerodynamics TC

2-Day Workshop Preceding the 27th APA Conference

San Antonio, TX
June 20-21, 2009



http://aaac.larc.nasa.gov/tsab/cfdlarc/aiaa-dpw/

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Case 1 – Grid Convergence and Downwash Studies:

1. **Grid Convergence study** at Mach=0.85, C_L=0.500 (±0.001)
   - Tail Incidence angle, i_H = 0°
   - Coarse, Medium, Fine, Extra-Fine Grids
   - Chord Reynolds Number 5x10^6 based on c 275.80 in
2. **Downwash Study** at M=.85
   - Drag Polars for alpha= 0.0°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°, 4.0° (?)
   - Tail Incidence angles i_H = -2°, 0°, +2°, and Tail off
   - Medium grid
   - Chord Reynolds Number 5x10^6 based on c_{REF}= 275.80 in
   - Drag delta tail off vs. on (trimmed, derived from the three polars at i_H = -2°, 0°, +2°)

Case 2 (Optional) – Mach Sweep:

1. **Drag Polars** at:
   - Mach=0.70, 0.75, 0.80, 0.83, 0.85, 0.86, 0.
   - C_L=.400, .450, .500 (±0.001)
   - Untrimmed, Tail Incidence angle, i_H = 0°
   - Medium grid
   - Chord Reynolds Number 5x10^6 based on c 275.80 in

Case 3 (Optional) – Reynolds Number Study:

Reynolds Number study at Mach=0.85, C_L=0.500 (±0.001)
- Tail Incidence angle i_H = 0°
- Medium grid
- Rn=5x10^6, 20x10^6 based on c_{REF}= 275.80 in

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- Backup

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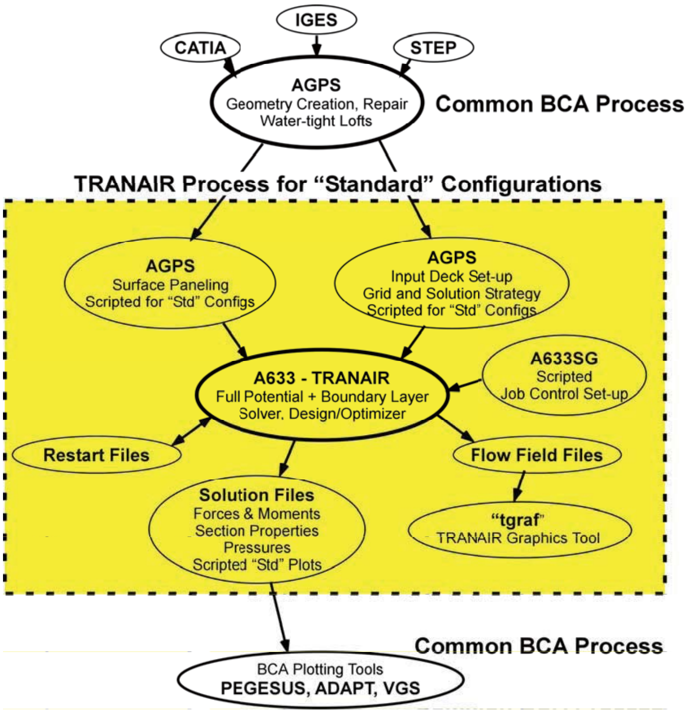
Stable, Packaged Software Solutions – TRANAIR

Scripted and Packaged for a "Standard" Class of Configurations

- Integral part of the engineering process
- Reduces solution flowtime
- Improves consistency and repeatability of results
- Uses common BCA processes
- Improves productivity

TRANAIR usage is in the 10's of thousands of cases per year



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Wind Tunnel Data Corrections

Clear tunnel flow conditions are subject to small variations in pressure and flow direction. The introduction of the wind tunnel model further disturbs these quantities away from "free-air".

- Mach Number – Function of total and static pressure
  - Centerline pressure vs. static measurement
  - Static pressure change due to model presence – "Mach Blockage"
- Angle-of-Attack – A derived quantity – physical angle + corrections for:
  - Flow angularity – "Up-flow"
  - Lift interference – "δ_o" – Model to tunnel size, tunnel wall ventilation, Mach
- Drag – Measured force corrected for angle-of-attack, + corrections for:
  - Clear tunnel buoyancy
  - Solid blockage buoyancy
  - Internal cavity pressures
  - Normalized skin friction
- Tare and Interference – can effect all quantities, specific to model, tunnel, Mach number

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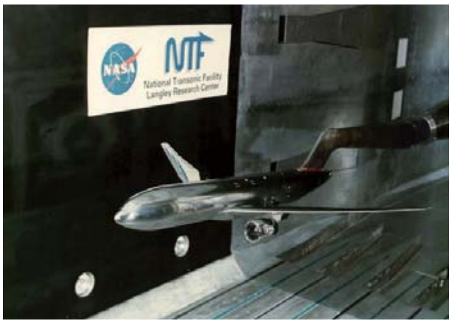
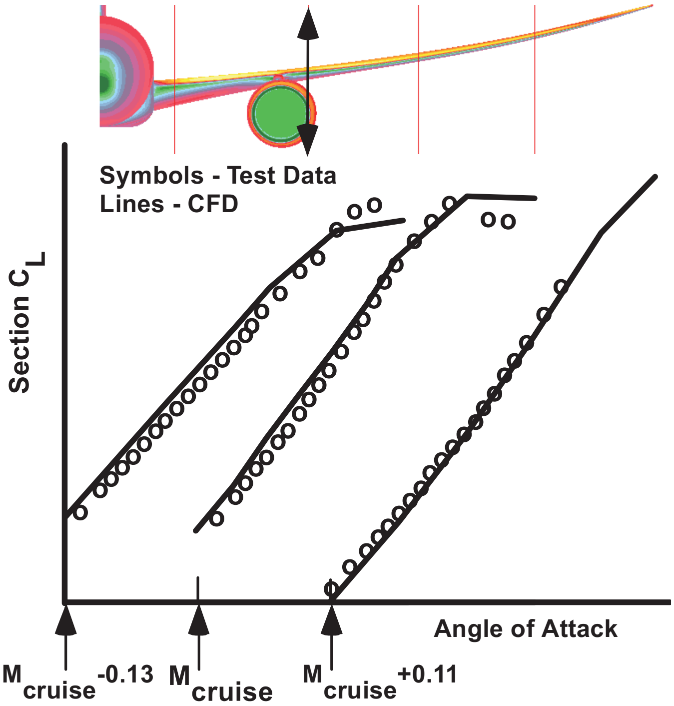
Mach Number Effects on Section Lift

- Use CFD to determine initial loads prior to a wind tunnel entry
- Consistent process yield consistent solutions
- Consistency yields confidence





Single α tare added to CFD results

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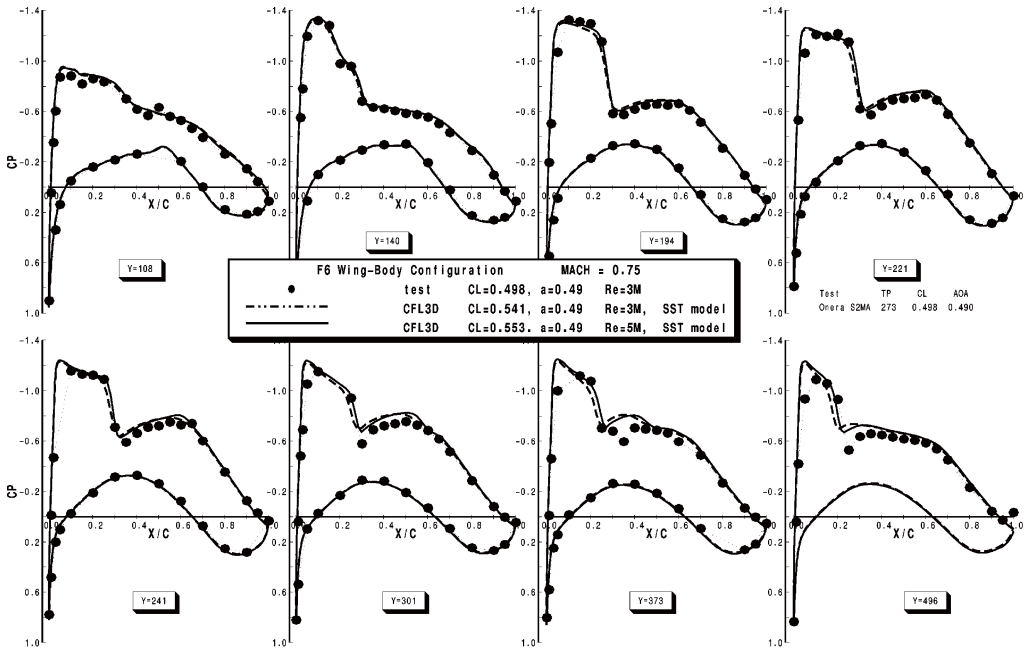
F6 Wing-Body - Wing Cp's – Comparison with Original ONERA test at Re=3M – Solution at Re=5M also shown



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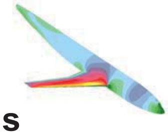
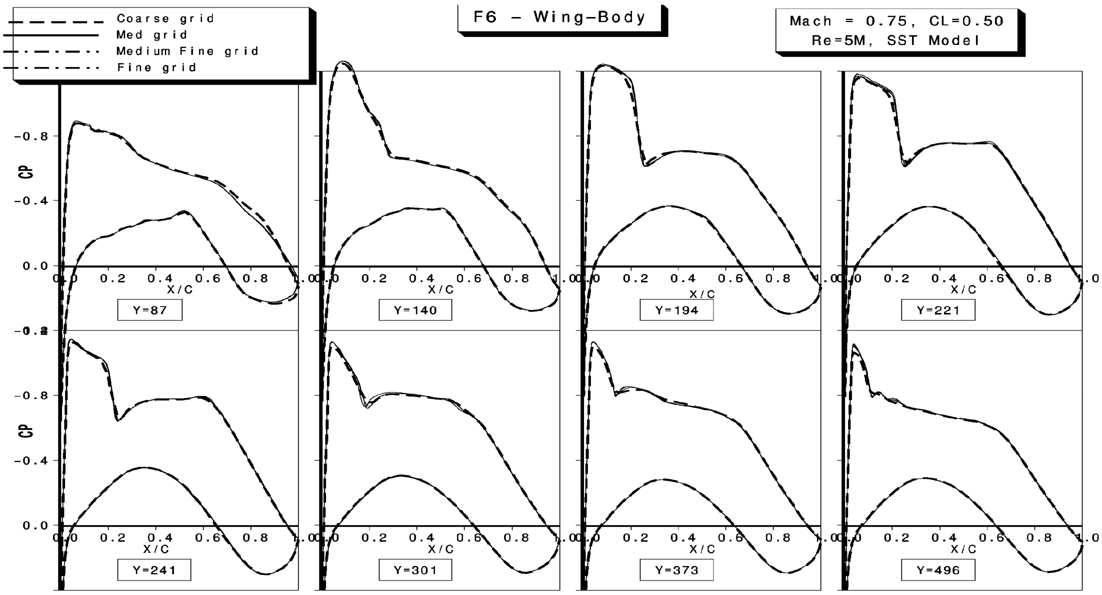
F6 Wing-Body - Wing Cp's – Grid Convergence

Four Grids - 2.6 to 31 Million Cells for each configuration
Four combinations - SA or SST Turbulence Models
- Thin-Layer or Full Navier-Stokes Terms





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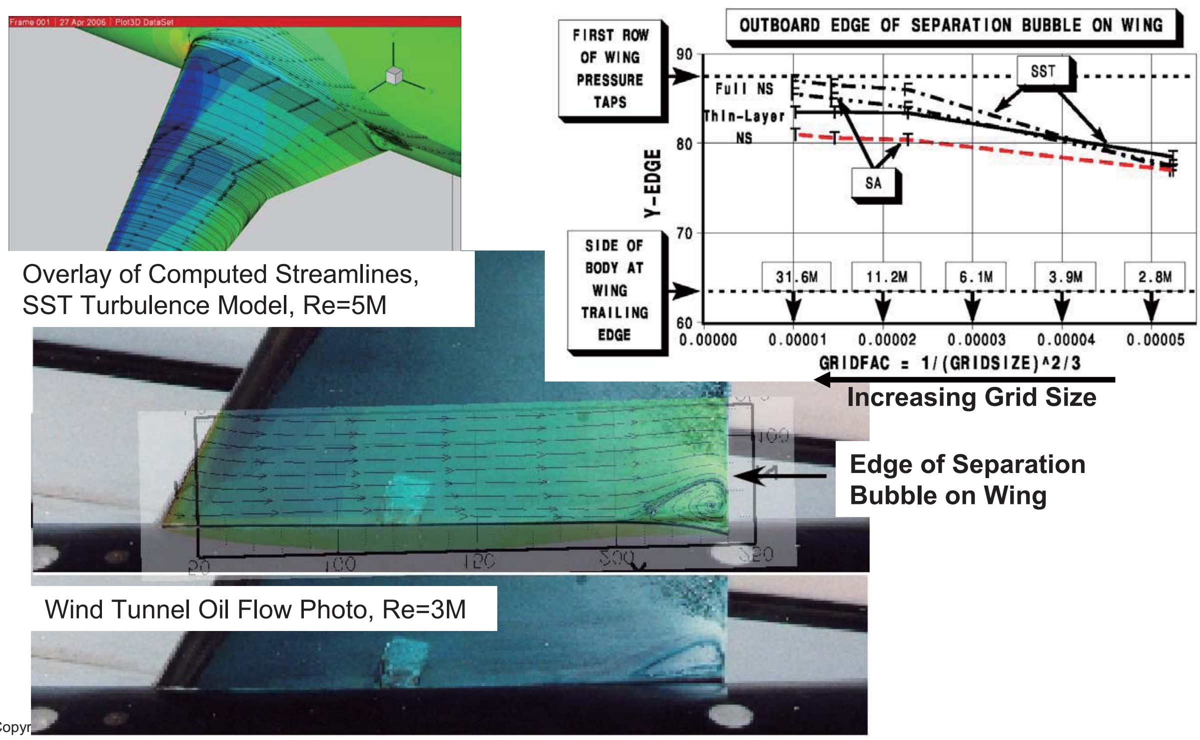
F6 WB Separation Bubble on Wing – Turbulence Modeling



Overlay of Computed Streamlines, SST Turbulence Model, Re=5M

Wind Tunnel Oil Flow Photo, Re=3M

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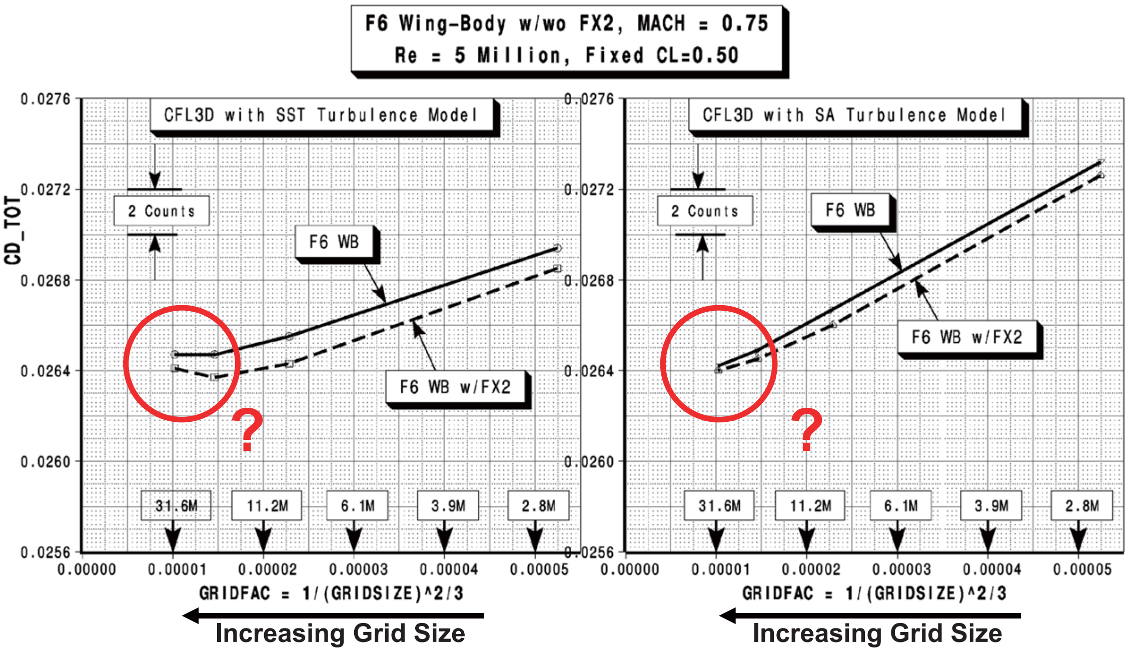
Drag Convergence with Thin-Layer CFL3D, M=0.75, CL=0.50



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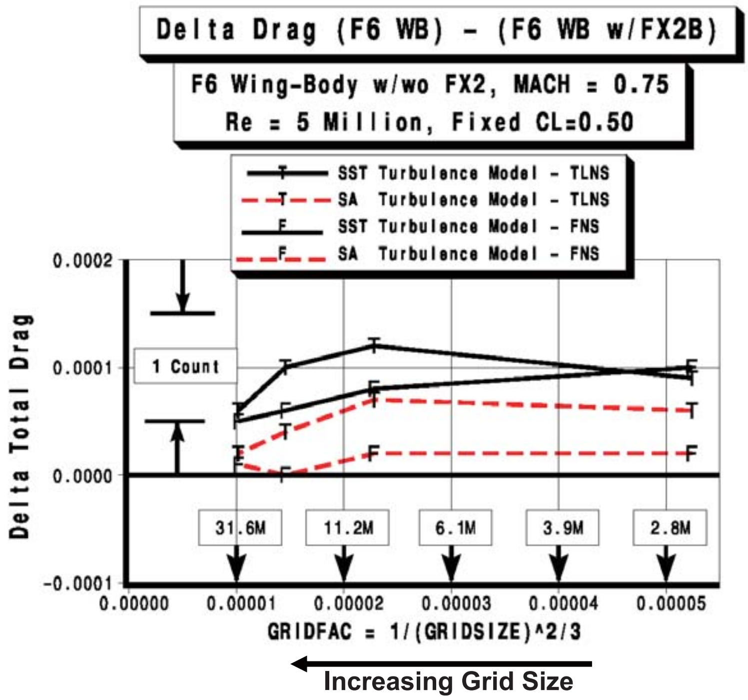
Drag Increments between Configurations



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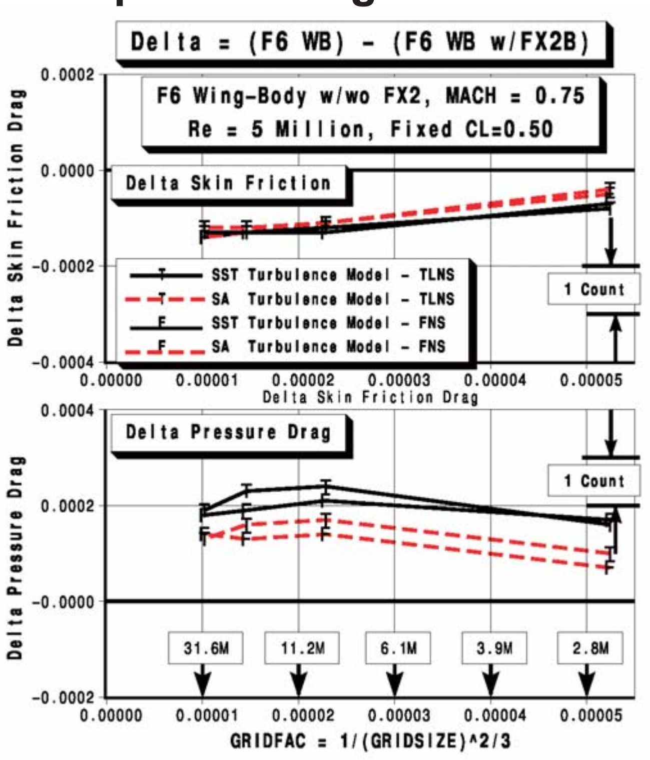
Component Drag Increments



Drag increment variation is due to pressure drag changes we believe are related to the separation bubble prediction