Recent Applications of CFD to the Design of Boeing Commercial Transports

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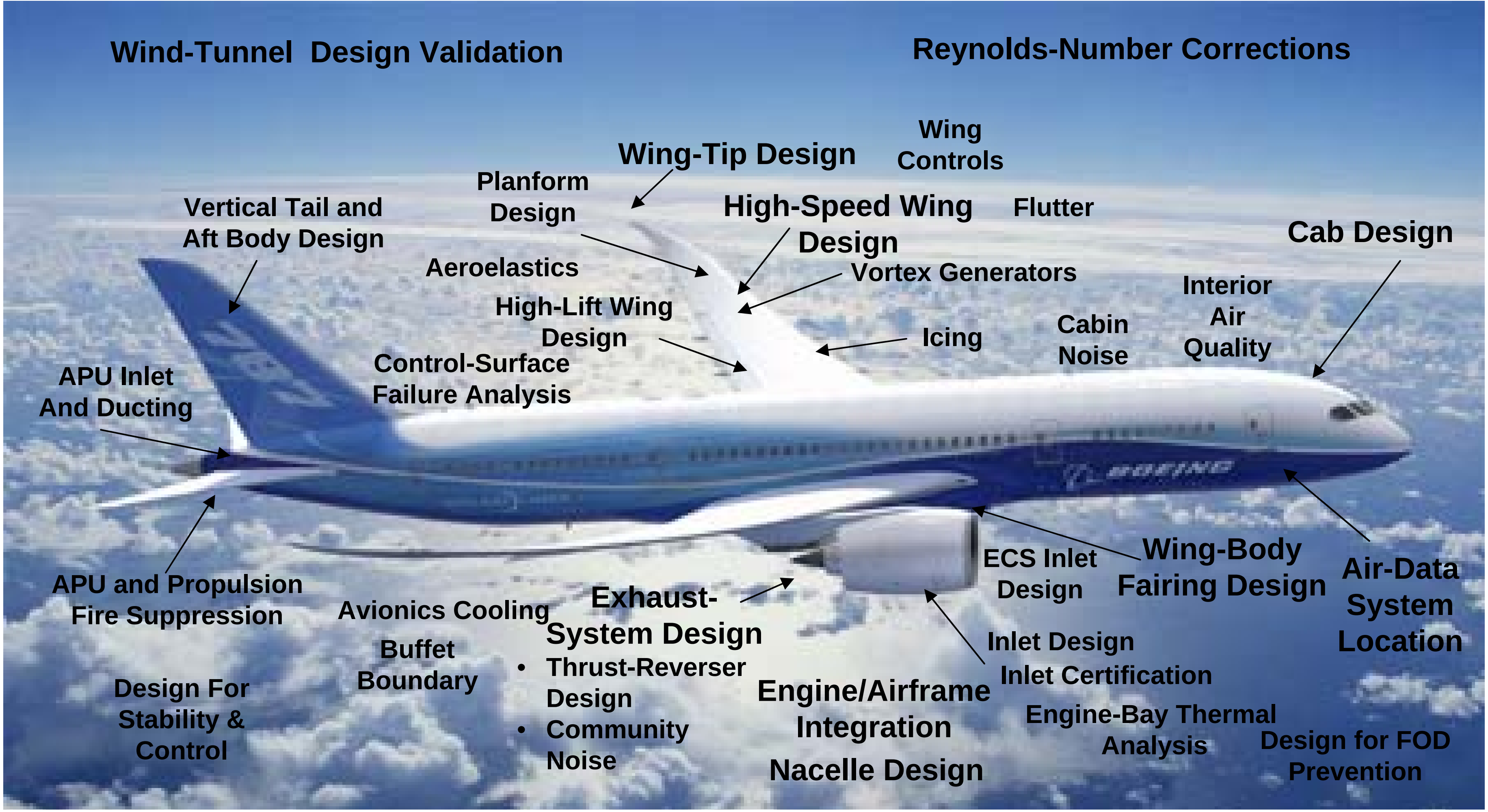
CFD Contributions to 787



Wind-Tunnel Design Validation

Reynolds-Number Corrections

Wing-Tip Design

Wing Controls

Planform Design

Vertical Tail and Aft Body Design

High-Speed Wing Design

Flutter

Cab Design

Aeroelastics

Vortex Generators

High-Lift Wing Design

Icing

Cabin Noise

Interior Air Quality

Control-Surface Failure Analysis

APU Inlet And Ducting

APU and Propulsion Fire Suppression

Avionics Cooling

Exhaust-System Design
- Thrust-Reverser Design
- Community Noise

ECS Inlet Design

Wing-Body Fairing Design

Air-Data System Location

Buffet Boundary

Inlet Design

Inlet Certification

Design For Stability & Control

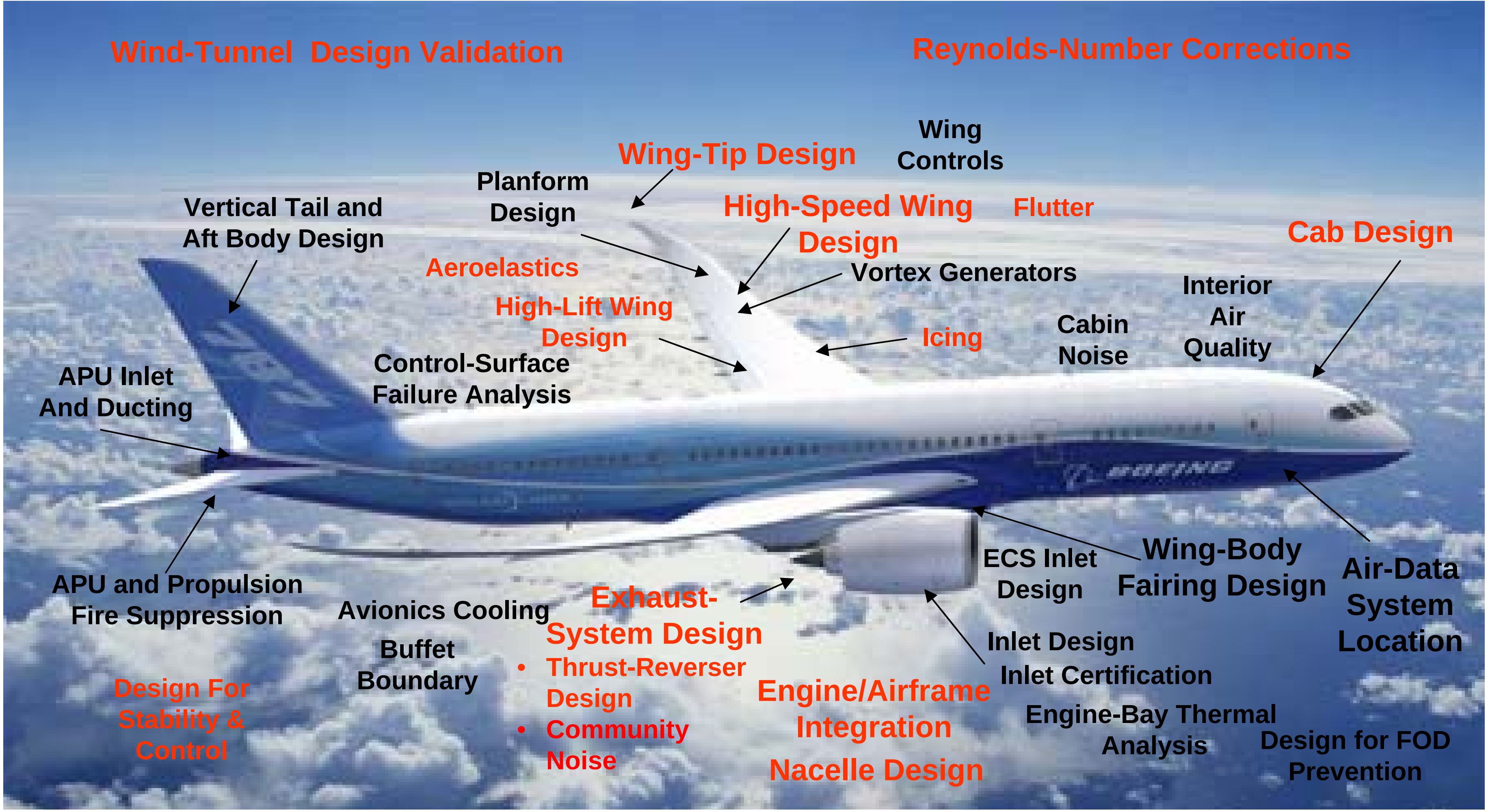
Engine/Airframe Integration

Nacelle Design

Engine-Bay Thermal Analysis

Design for FOD Prevention

CFD Contributions to 787



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Engine-Bay Thermal
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Design for FOD
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CFD for Full Flight Envelope – High Speed

Why is this Important?

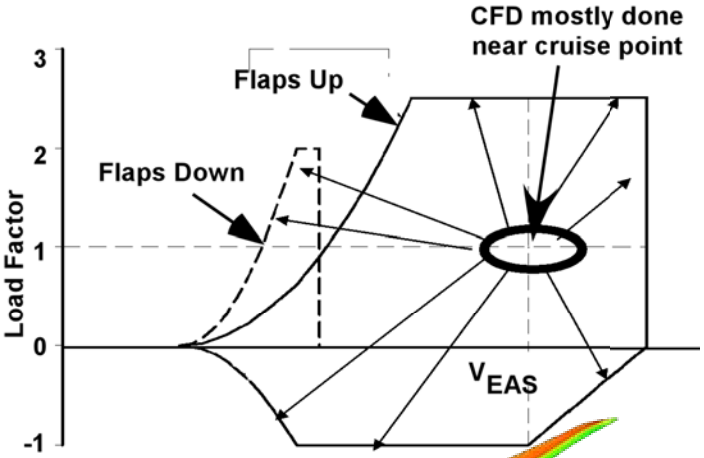
- Reducing Design Cycle Time while increasing data fidelity in the early development phases of a new airplane program is critical to competitiveness
- Creating flight predicted S&C and Loads aero data is very time consuming and requires much wind tunnel testing.

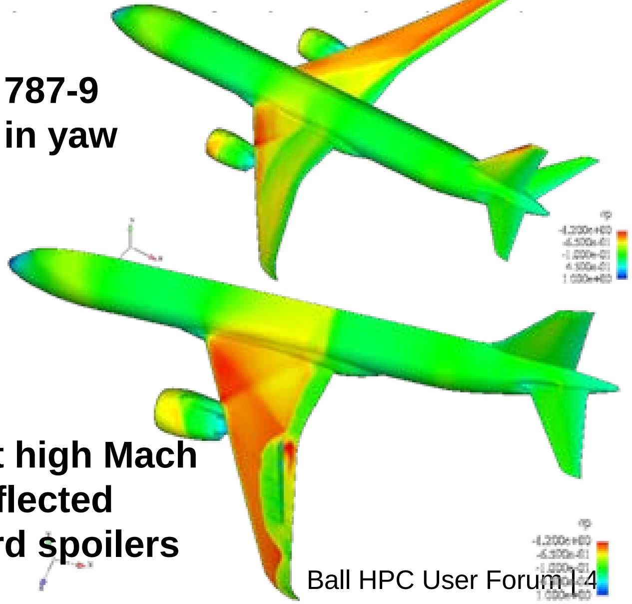
What are the Technical Challenges?

- Accurate CFD prediction of Loads and S&C characteristics at flight conditions with significant flow separation.
- Timely, robust, and repeatable modeling of configurations with control deflections including spoilers, vortex generators, etc.

What are we doing?

- Developing Navier-Stokes CFD processes for accuracy, reliability, and robustness for use by product development engineers for engineering applications.
- Validating/Expanding CFD use in Loads and S&C disciplines
- Integrating wind tunnel and CFD use to reduce cycle time, cost.





787-9 in yaw

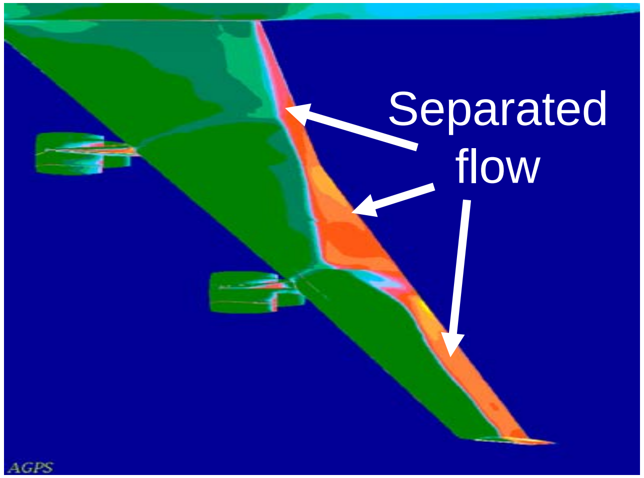
787-8 at high Mach with deflected outboard spoilers

CFD at the Edges of the Flight Envelope

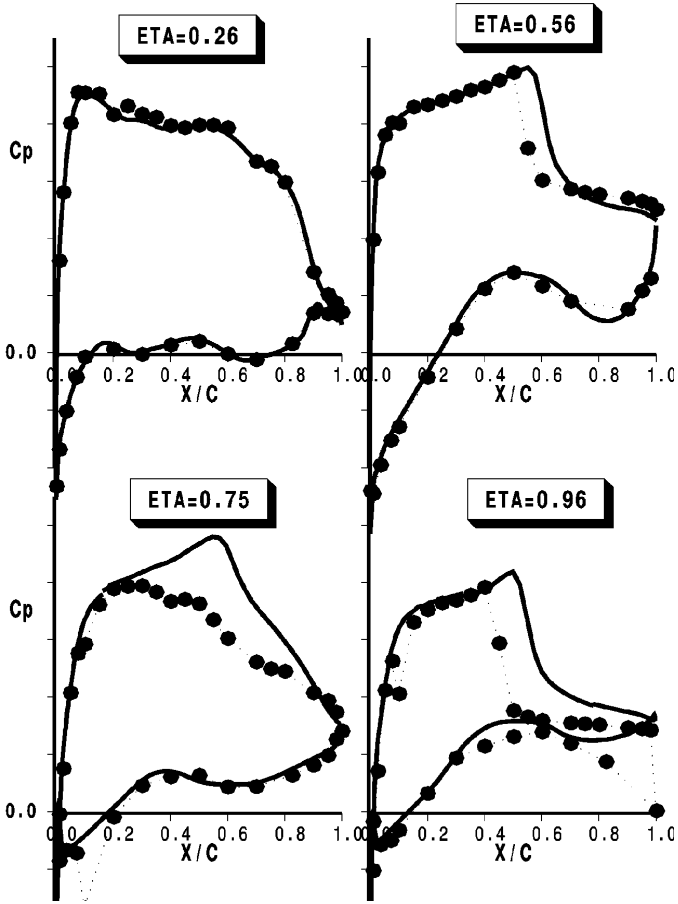
What are the Challenges?

- 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”?

These CFL3D RANS four-engine transport results are typical of CFD issues at the edge of the envelope



Cp comparison at approximately 2.5g at Mach dive



High-Lift CFD

Why is this Important?

- Optimization of high-lift configurations
- Study of simplified/revolutionary high-lift concepts
- Study of large number of geometries, device positions
- Understanding of high-lift flow physics
- Ability to predict maximum lift
- Study of flow-control concepts
- Reduction of wind-tunnel tests
- Eliminate wind-tunnel effects from test data
- Extend test data to full scale Reynolds numbers

What are the Technical Challenges?

- Understanding highly complex flow phenomena
- Consistent process for prediction of CLmax
- CFD Challenges
  - Lack of robustness
  - Grid resolution requirements are unknown
  - Turbulence modeling effects are unknown
  - Unsteady flow analyses are required but unavailable

2D High-Lift CFD

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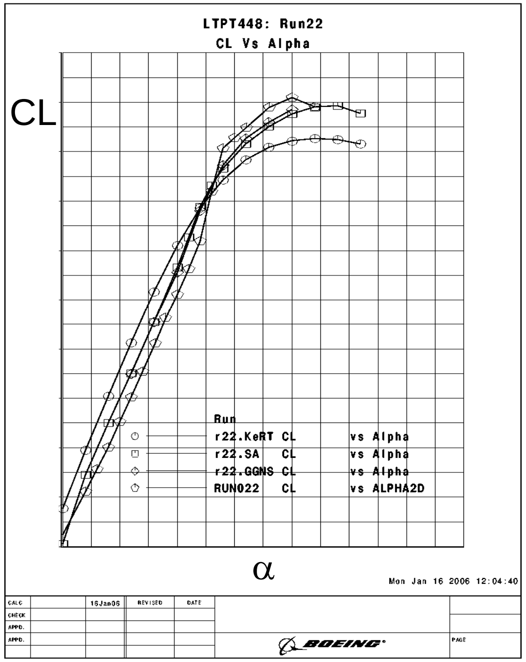
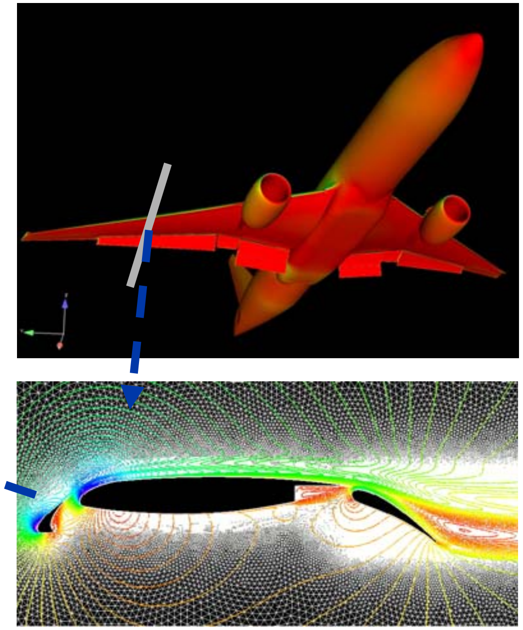
What Are We Doing?

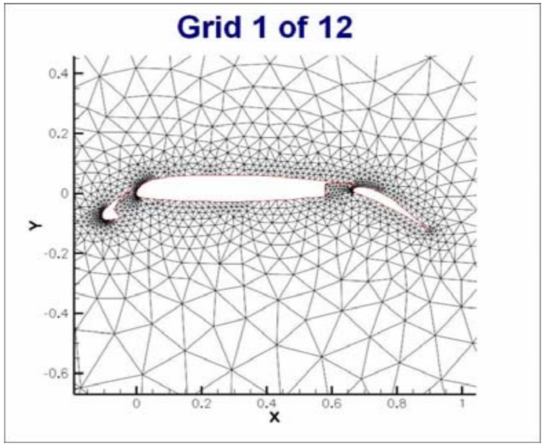
- Developed Automated Navier-Stokes Two Dimensional Setup Process, ANTS
- Rapid Navier-Stokes analysis of multiple 2-D high-lift wing sections
- Produce accurate and consistent prediction of performance and flow-physics data

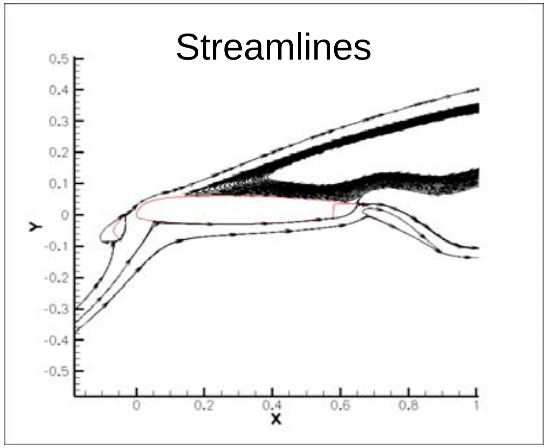


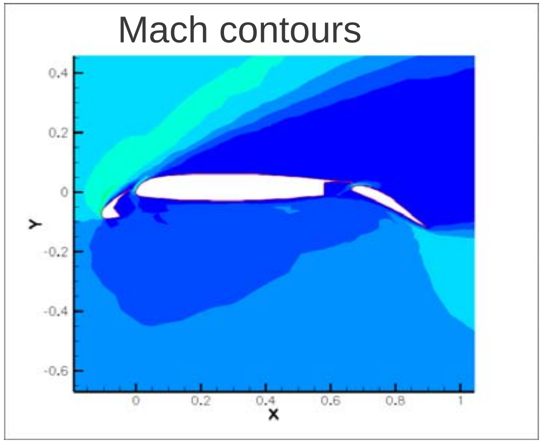


2D High-Lift CFD

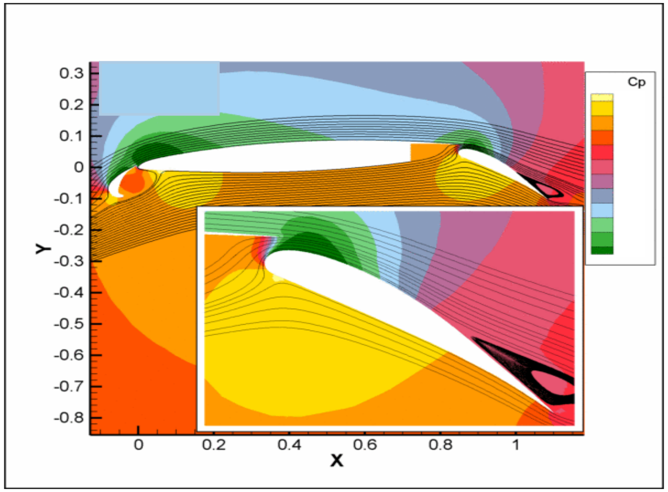
- GGNS 2D: Adaptive high-lift grid







- 2D flap optimization to reduce flow separation



3D High-Lift

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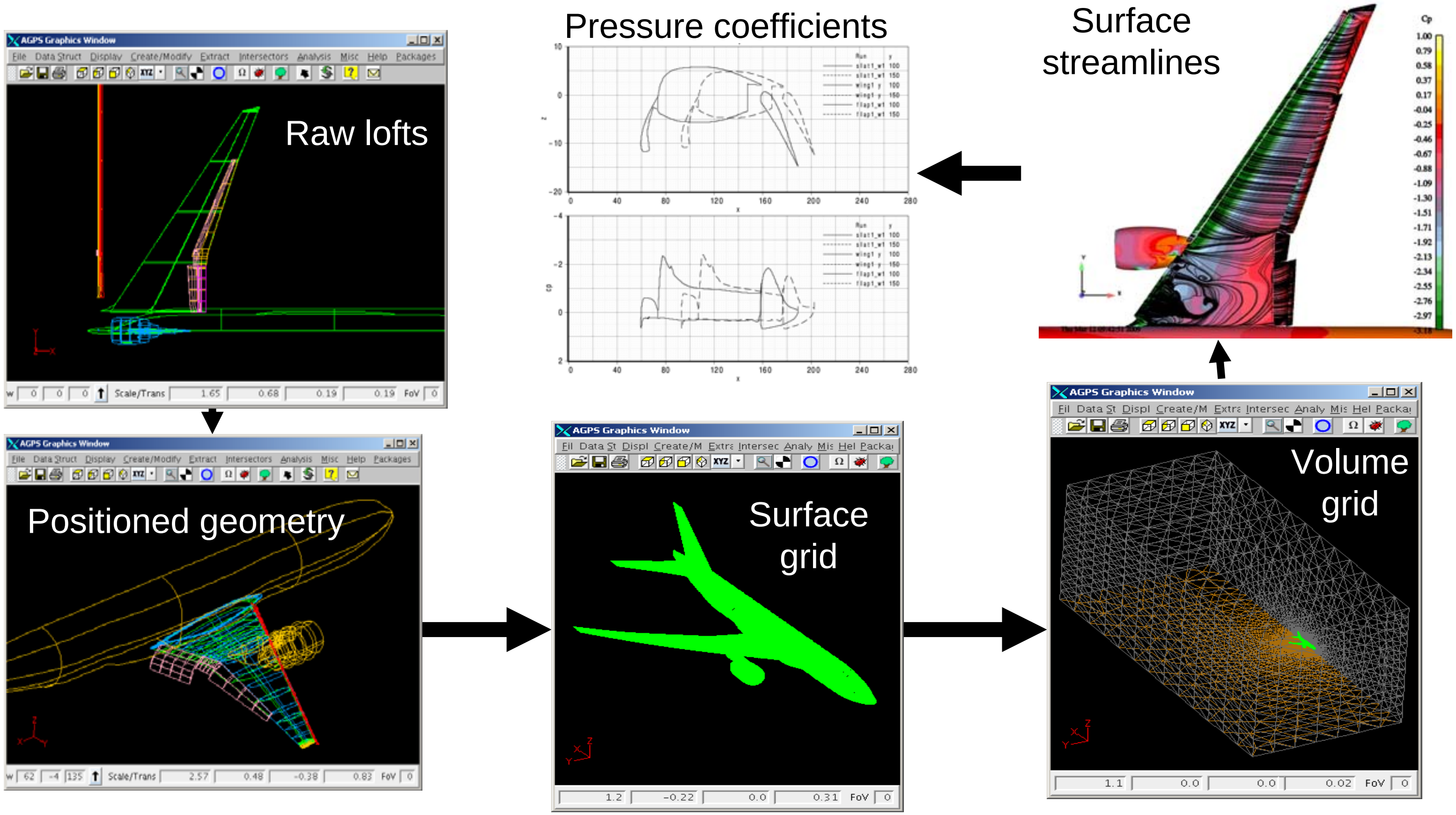
What Are We Doing?

- Developed automated Navier-Stokes 3D system analysis process flow with one day turn around

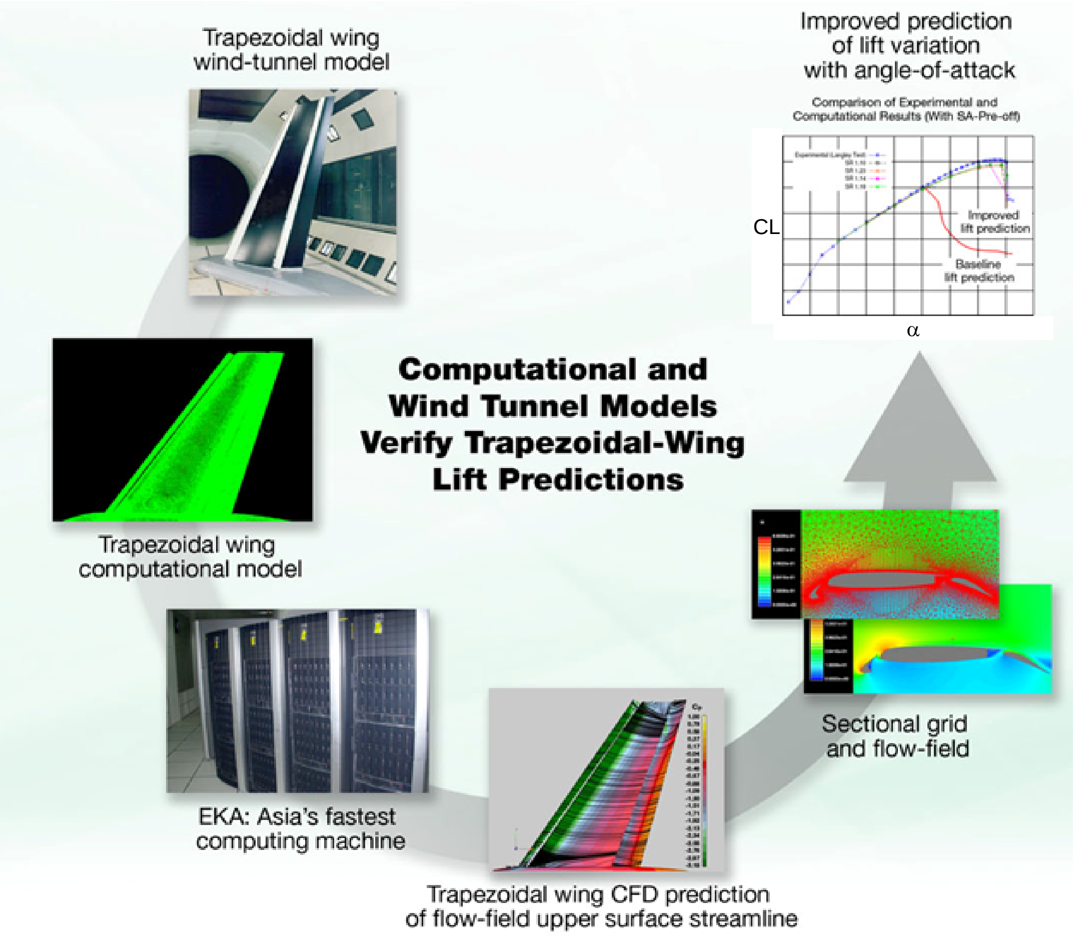


Maximum lift prediction

What are we doing?

- Cooperative project with Computational Research Laboratories, Pune, India
- Extensive code development and validation studies using SLUGG (System for Low-speed Unstructured Grid Generation) : geometry preparation and grid generation and CFD++: Unstructured-grid flow solver

Maximum lift predicted to within 2%



CFD in Flutter Predictions

Why is this Important?

- Reduce potential flutter risks in new airplane programs
- Enabler to look into non-linear aeroelastic effects earlier in the design cycle
- Minimize impact of design modifications necessary to eliminate potential flutter risks
- Avoid costly design “fixes” to mature airplane design
- Enabler to generate databases for reducing wind-tunnel testing time, cycle time and cost

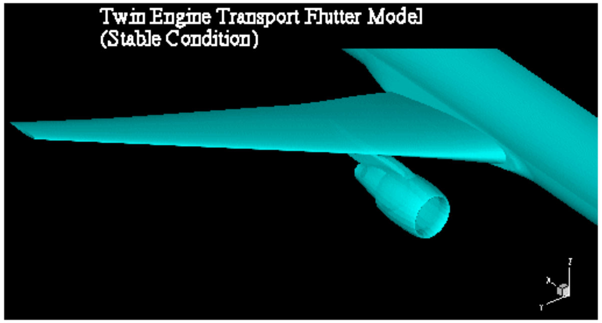
What are the Technical Challenges?

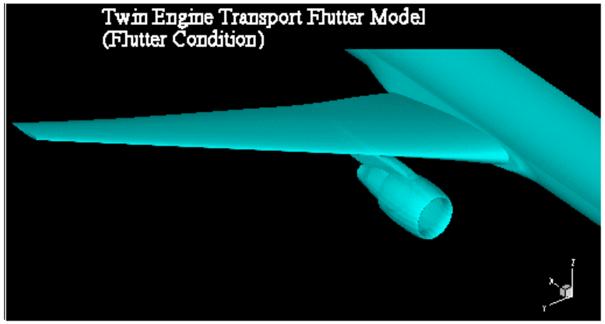
- Highly complex unsteady flow Phenomena: coupling of unsteady flow with unsteady structural dynamics
- Existing high speed flutter experimental data are very limited
- High speed flutter tests are costly with long design time and limitations due to wind tunnel, model integrity, subjective engineering calls during tests, etc.
- Computational simulations challenges include: long unsteady cycle time, limited validated methods, mesh deformation robustness for complex geometry, as well as typical steady computational challenges.

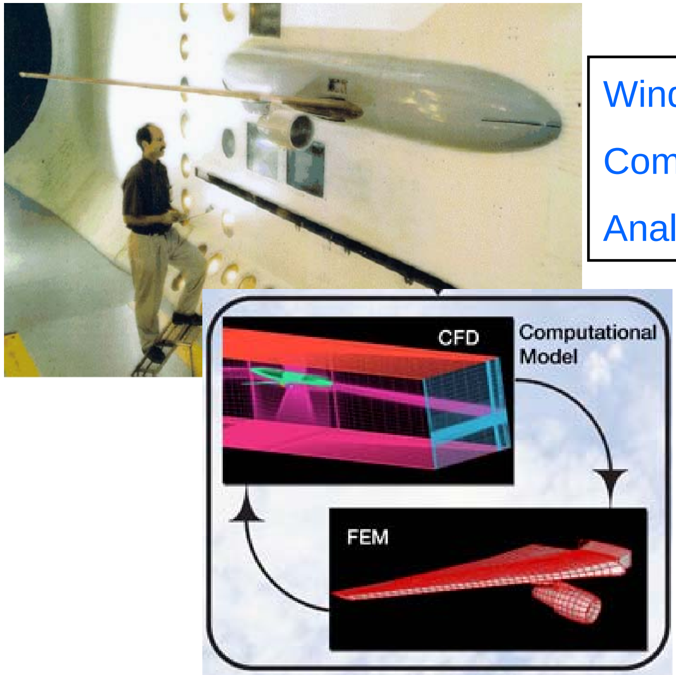
CFD in Flutter Predictions

What Are We Doing

- Create, correlate, and validate both steady and unsteady aeroelastic processes.
- Assure the processes (TRANAIR-based and CFL3D-based) are robust and repeatable.
- Validate process components for each component to assure accurate results:
- Initially validate unsteady code for ‘simple’ wing and isolated nacelle oscillations
- Apply methodology to compute wind-tunnel static aeroelastic deformations and high speed flutter





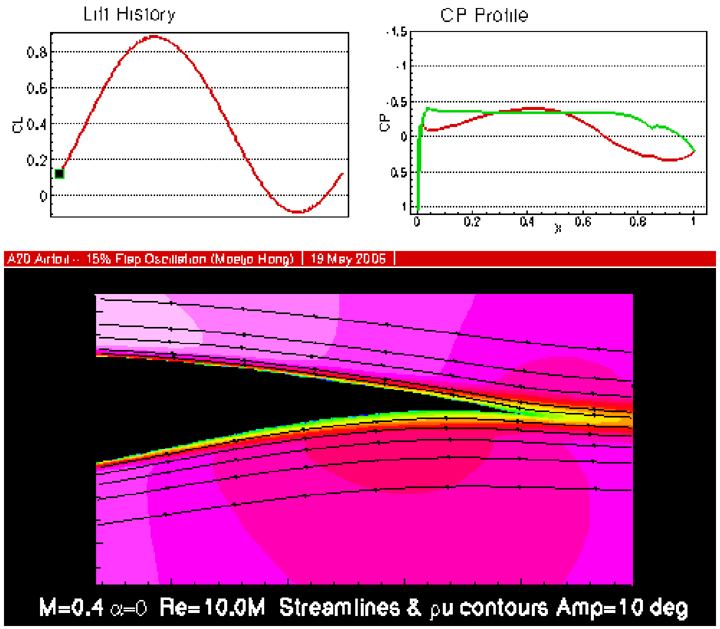


Wind Tunnel Model
↓
Computational Model
↓
Analysis of Flutter Conditions

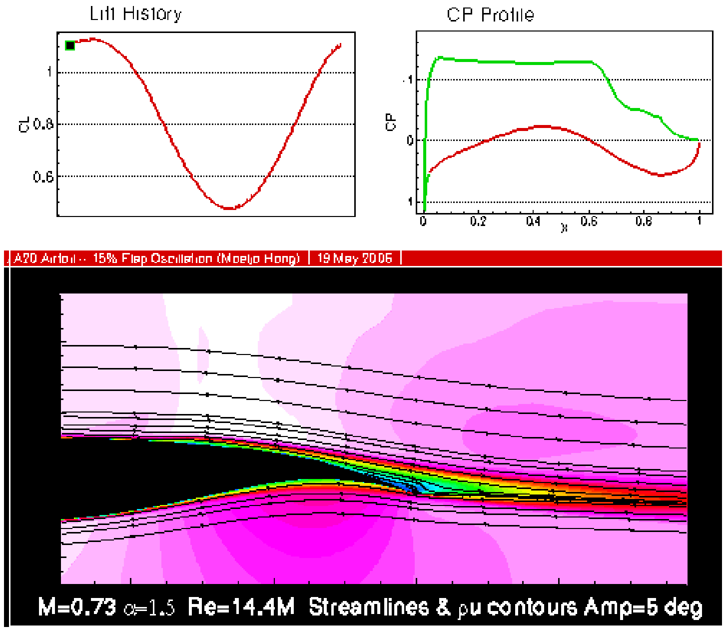
CFD in Flutter Predictions

Unsteady Control Surface Modeling with CFL3D

Low Subsonic Speed



Transonic Speed



Aeroelastic Loads Predictions

Why is this Important

- FAA Part 25: Airworthiness Standards: Transport Category Airplanes
  - Required to be validated by flight loads measurement.
  - Unless the methods are shown to be reliable.
- Support PD, Initial, Preliminary, Design and Certification Loads Analyses

What are the Technical Challenges

- Because of validation and reliability requirements, wind tunnel is the main source of aero data for Loads.
- Aero Database is distributed, not just total airplane (6 DOF) based.
- Loads Design Envelope extreme:
  - High Speed (Mach 0.40 to 0.98)
  - Low Speed (5-6 flaps down geometries)
  - Stall speed to Dive speed
  - -1.0 to 2.5 G's
  - Pitch, Roll and Yaw Maneuvers (controls aero important)
- Higher fidelity aero databases required due to Load Alleviation implementation.
- Non-linear local aerodynamic effects increasingly in significance for design.

Aeroelastic Loads Predictions

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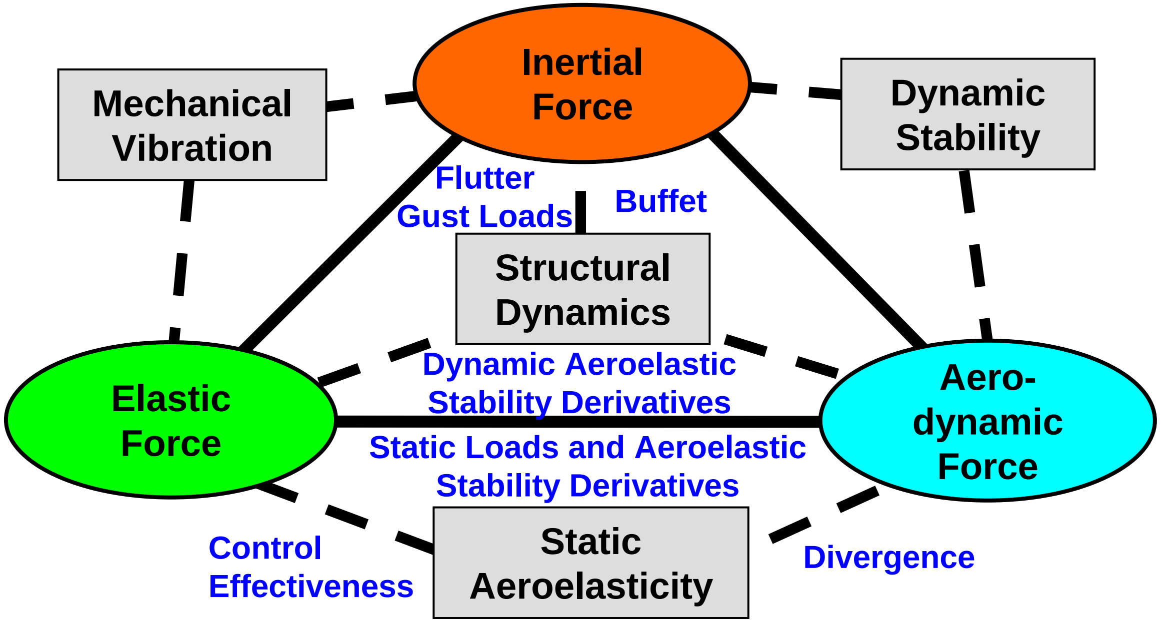
Aeroelastic Triangle



Aeroelastic Loads Predictions

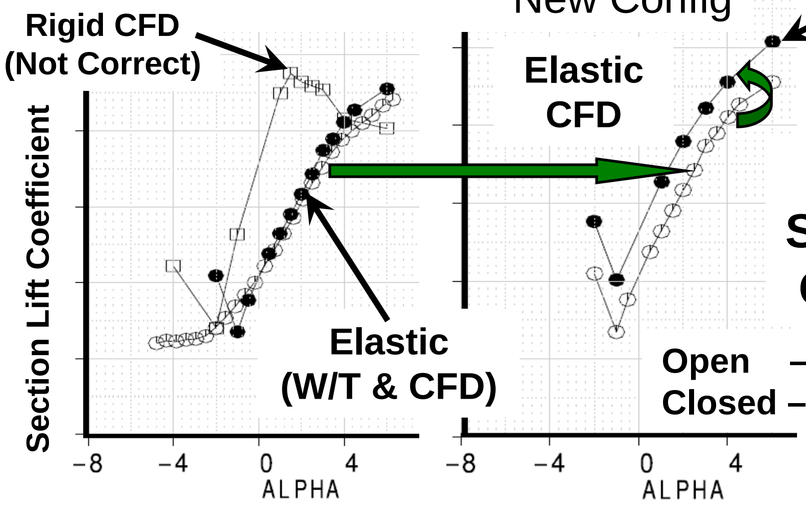
What Are We Doing

- Configuration or Derivative updates to wind tunnel based aero database for wing tip changes and body length stretches.
- Navier-Stokes (RANS & LES) run as pseudo wind tunnel to derive incremental aerodynamic changes from baseline configuration.
- CFD run coupled with computational structural model (FEM) of wind tunnel model.

"New" Config incorporated wing tip camber and twist changes.

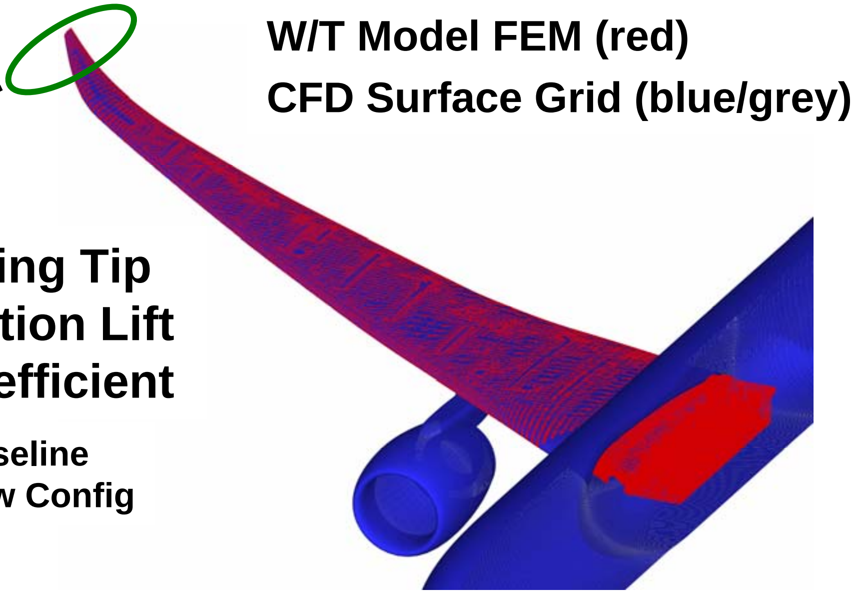
Baseline
W/T & CFD

CFD
Baseline &
New Config



W/T Model FEM (red)

CFD Surface Grid (blue/grey)



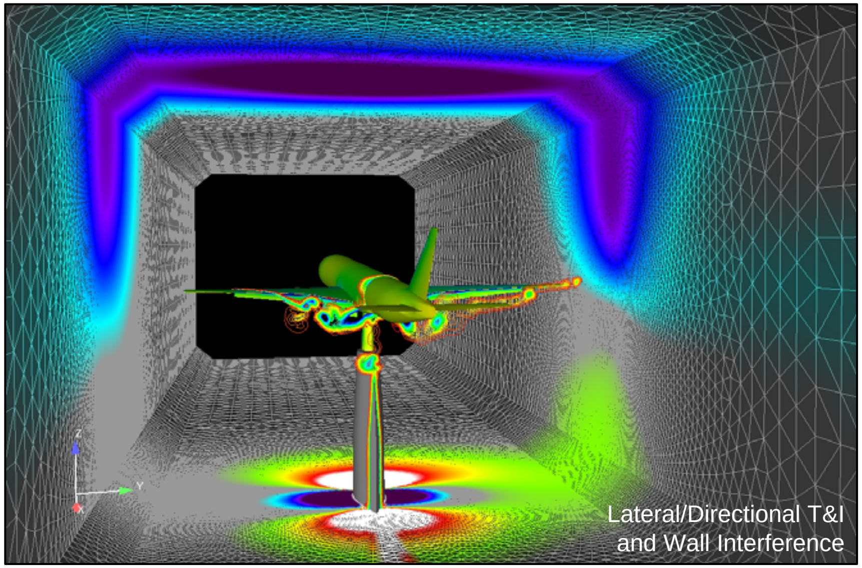
Stability & Control Application of CFD

Why is this Important?

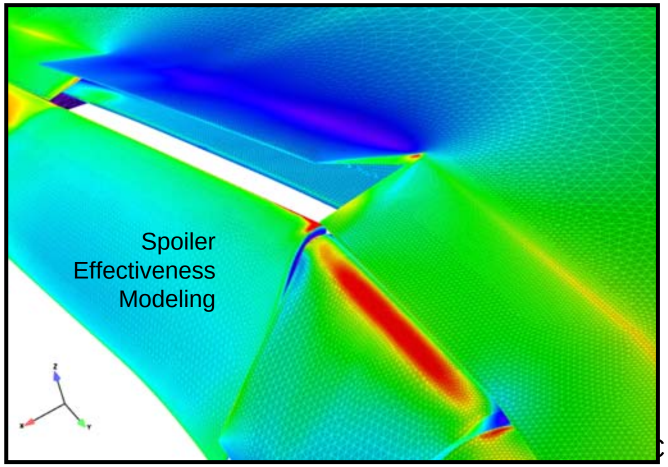
- Aircraft weight/performance impacts
- Actuator sizing & system requirements
- Improved simulation fidelity
- Reduced WT testing

What are the Technical Challenges?

- Highly complex geometries
- Increased reliance on augmentation
- Multi-functional controls
- Higher fidelity aero predictions required
- Unsteady flow regimes
- Large matrix of data required
- Asymmetry conditions effects on test data and CFD analyses



Lateral/Directional T&I and Wall Interference



Spoiler Effectiveness Modeling

Stability & Control Application of CFD

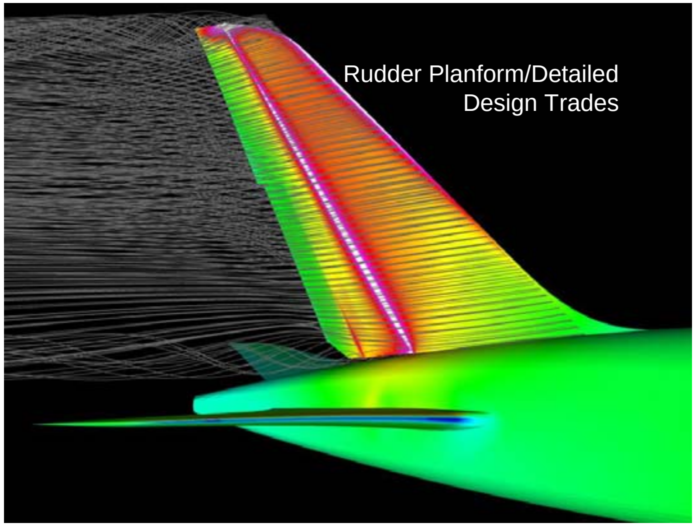
What Are We Doing

- Control surface design
  - Sizing trades
  - Control loads (hinge moments)
  - Design details
- Configuration trade studies

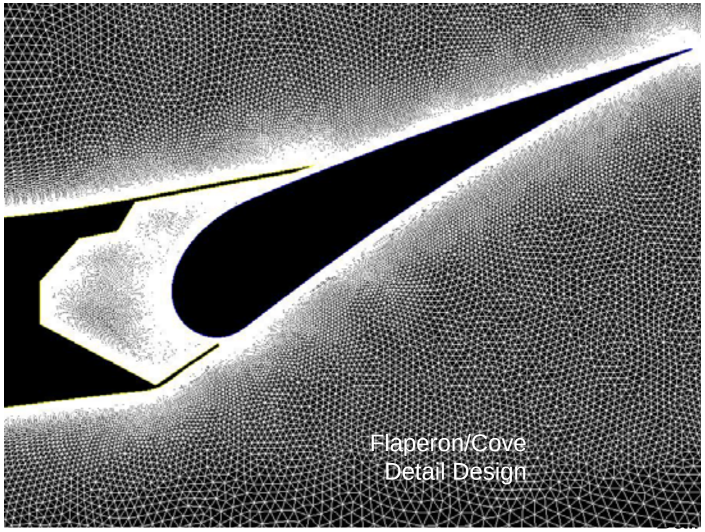
- Wind tunnel-to-flight corrections
  - Tare & Interference
  - Wall effects
  - Reynolds Number effects

- Aerodynamic database development
  - Aeroelastic corrections
  - Dynamic derivatives
  - Supplement WT

- Full Spectrum of Codes
  - A502
  - Tranair
  - CFL3D
  - CFD++ (3D & 2D)

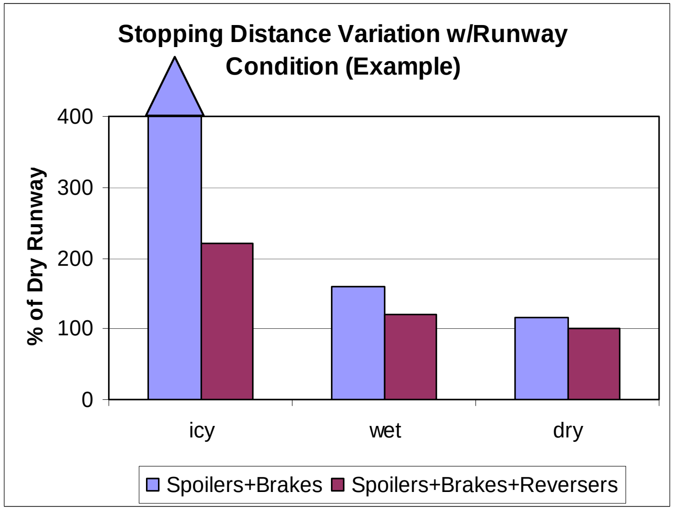


Rudder Planform/Detailed Design Trades



Flaperon/Cove Detail Design

Propulsion Aerodynamics – Thrust Reverser

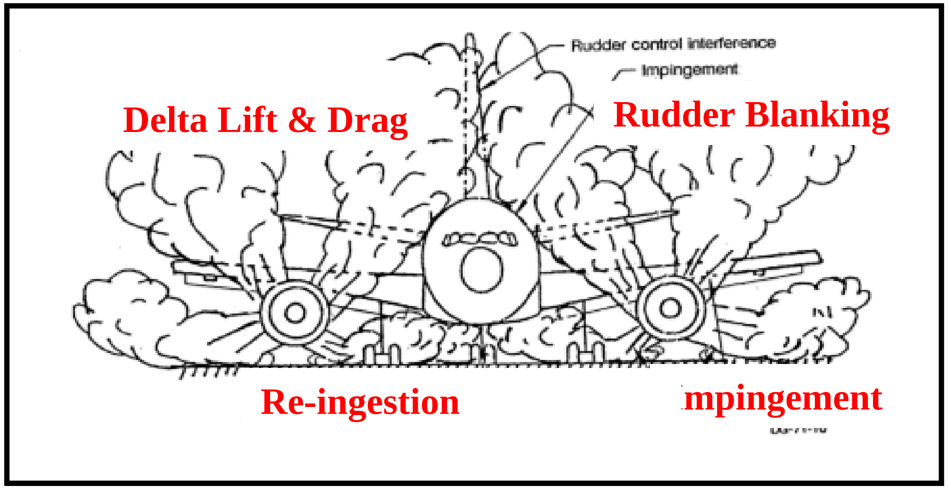


Why is this Important?

- Thrust Reverser (T/R) provides additional deceleration after landing.
- The T/R is essential to meet landing and take off field length requirements, particularly under icy runway conditions.

What are the Technical Challenges?

- Provide required reverse thrust while considering limits imposed by
  - Impingement on A/C surfaces
  - Re-ingestion by A/C engine
  - Rudder blanking
  - Nacelle integration



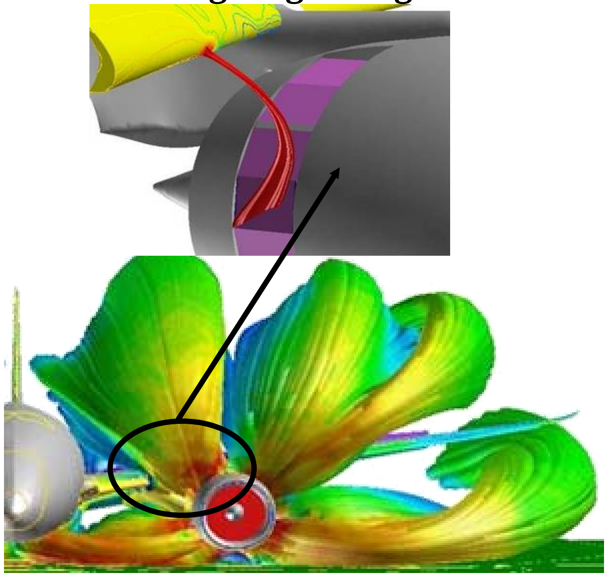
Propulsion Aerodynamics – Thrust Reverser

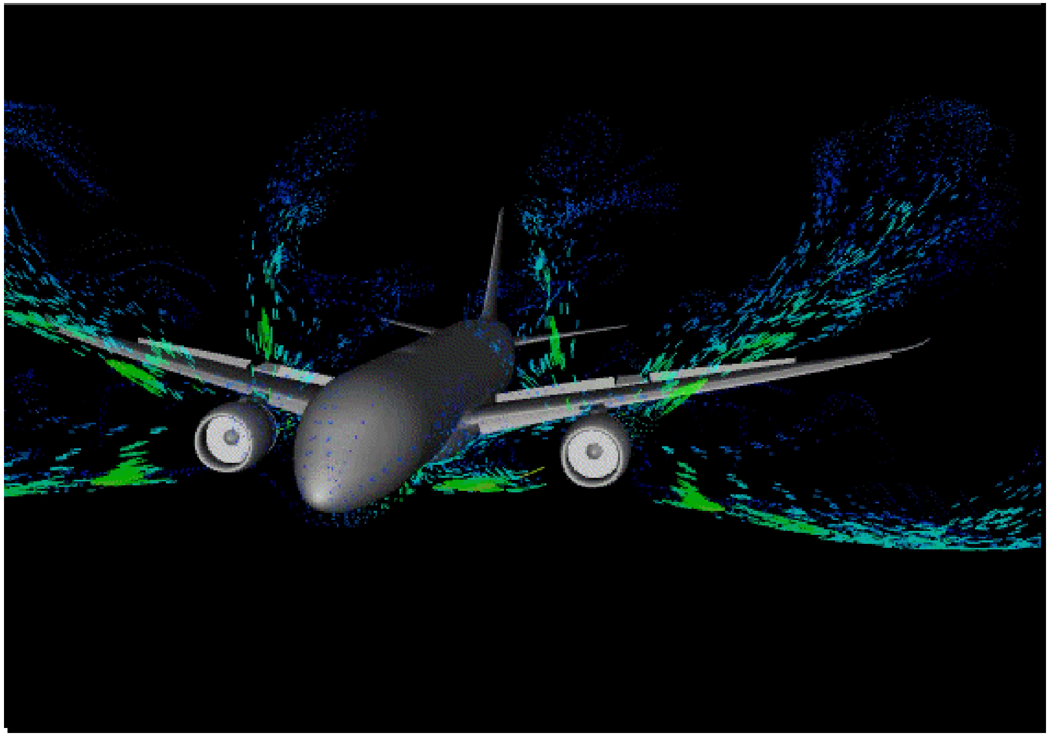
What Are We Doing?

- CFD process developed within Boeing utilized ANSYS/ICEM and CFD++ solver in support of T/R external efflux pattern development and related analysis of re-ingestion, impingement, and controllability concerns.

Reverser/Airframe Compatibility – Installed Analysis

Leading-Edge Integration





Nacelle Thermal Analysis

Why is this Important

- Minimizes schedule risk
- Reduce flight test (cost and schedule savings)
- Optimize fuel burn (most efficient use of cooling air)
- Provide basis for combustor case burnthrough certification

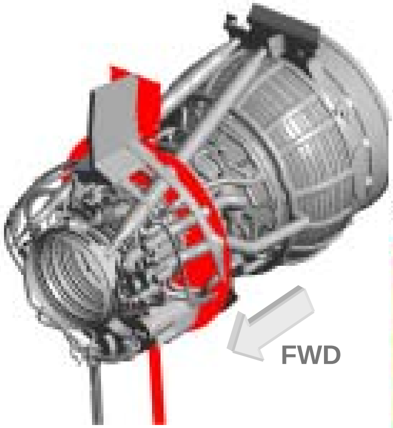
What are the Technical Challenges

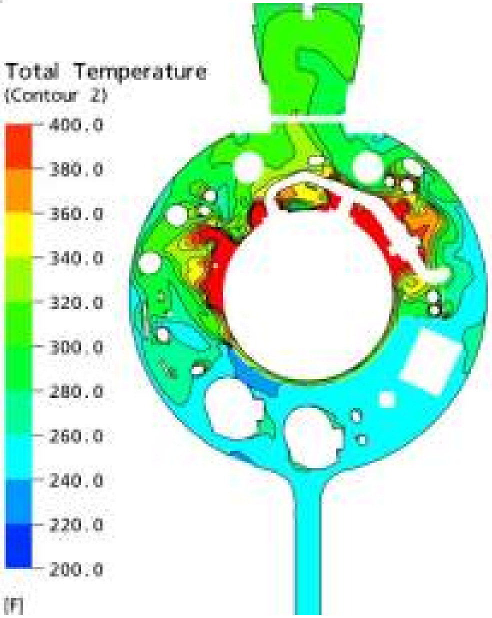
- Very complex geometry
- Complex boundary conditions
- Varying flow regimes (low speed to highly under-expanded jets)

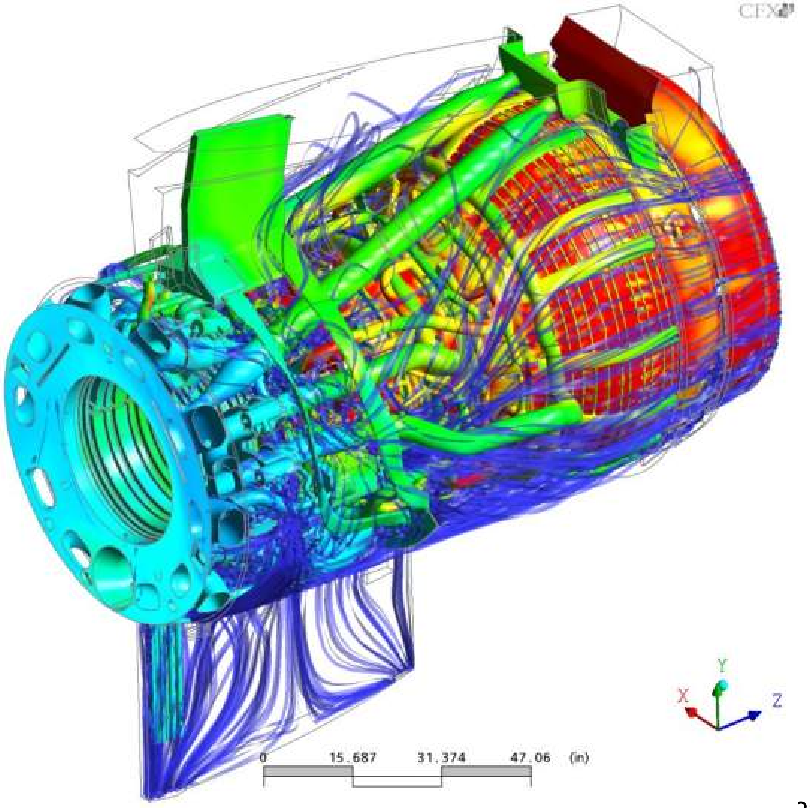
Nacelle Thermal Analysis

What Are We Doing

- Engine Bay CFD Analysis (Primarily done by Engine companies)
- Coupled fluid/thermal analysis of nacelle structure
    - Combustor case burnthrough
    - Auxiliary exhaust thermal mixing



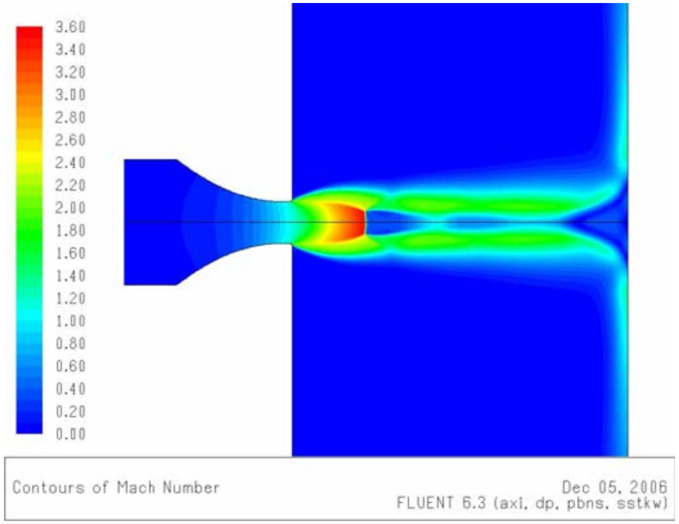


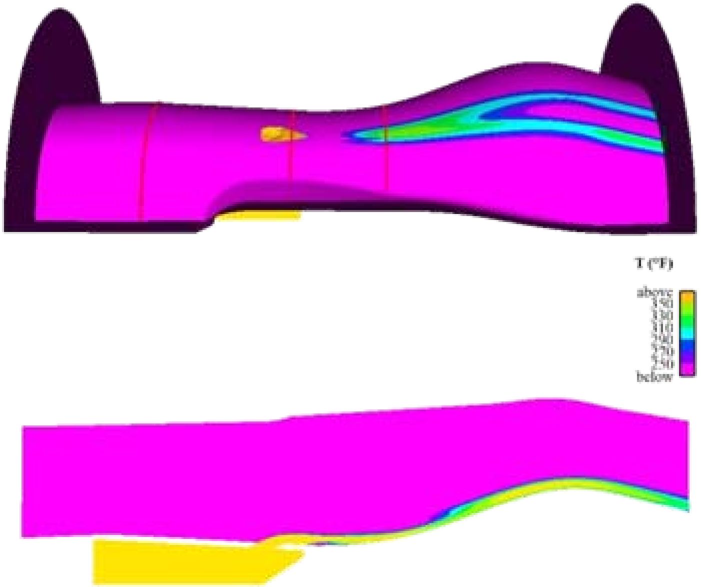


Nacelle Thermal Analysis

Combustor case burn-through analysis was employed to define the thermal environment used for part 25 certification

Auxiliary exhaust temperature mixing analysis was instrumental in the thermal design of the nacelle





Computational Ice Shape Generation

Why is this Important?

- Airframe ice shapes corresponding to critical flight conditions were needed for 787 low speed wind tunnel testing to measure the impact on aircraft handling characteristics and maximum lift.
- LEWICE3D, a code developed by NASA, greatly reduced the need to interpolate/extrapolate ice shapes to generate wind tunnel model parts.
- Using LEWICE3D drastically reduced the time needed to generate ice shapes.

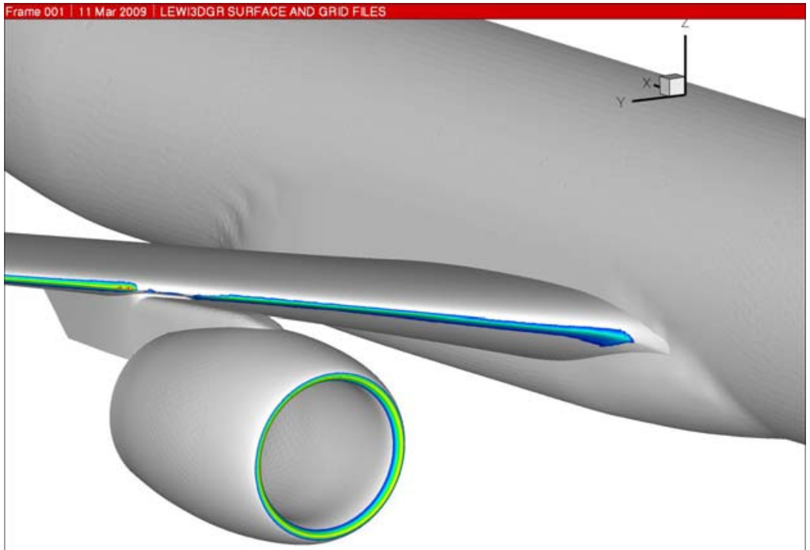
What are the Technical Challenges?

- LEWICE3D calculates water droplet trajectories through a converged CFD flow-field to generate a 3D droplet collection efficiency distribution on the airframe. This is a large computation, which had to be parallelized in order to be feasible.
- Finding enough experimental swept wing ice shape data to further refine the ice shape generation model and methodology is problematic.

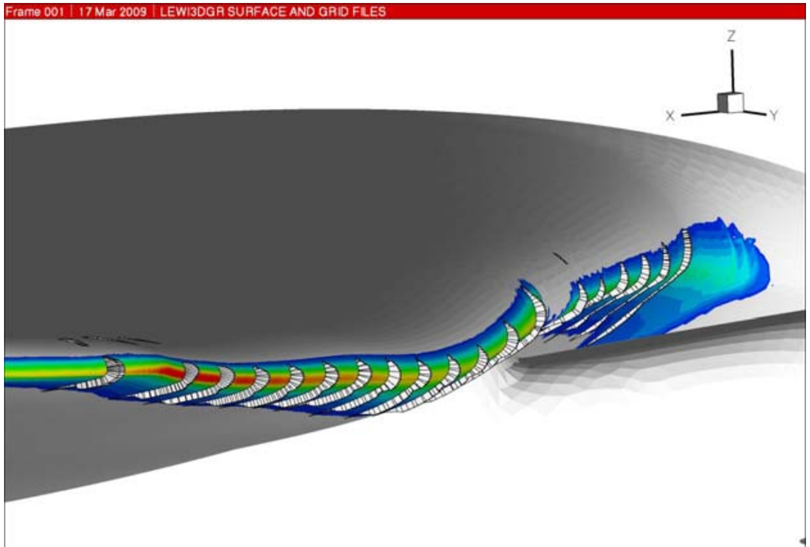
Computational Ice Shape Generation

What Are We Doing?

- Flight conditions considered critical for airframe icing were selected.
- Navier-Stokes solvers CFD++ or OVERFLOW were run with these conditions to generate a flow-field for input into LEWICE3D.
- LEWICE3D generated a collection efficiency and ice shape cuts.
- Ice shape cuts were used to produce lofts for stereo lithography production into wind tunnel model parts.



Water Droplet Collection Efficiency



Ice Shape Cuts on Wing Leading Edge

Closing Thoughts

- CFD exists to enable new solutions to problems, reduce airplane development cost, and reduce time to market
- CFD can allow you to safely explore areas of the flight regime without putting a pilot at risk
- CFD can allow you to analyze conditions for which physical simulation is either very expensive or not possible, such as hypersonic propulsion systems and full flight Reynolds number testing
- Accuracy, robustness and timeliness are the keys to acceptance and use in an industrial environment
- Impediments: applications that do not scale well (to 1000's of processors) – this is science, resources to run 1000s of flight conditions on 100's of processors – this is engineering & business

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