Impact of Computational Aerodynamics on Aircraft Design
Outline

• Aircraft Design Process
• Aerodynamic Design Process
• Wind Tunnels & Computational Aero.
• Impact on Aircraft Design Process
  – Revealing details of fluid flow phenomena
  – Design optimization
  – Reducing design flow time
  – Great opportunity for innovative design
• Specific Examples
  – Airfoil design
  – Wing design optimization
  – Engine airframe integration
• Future applications
Aircraft Design Process

The Overall Design Process

Conceptual Design
- Define mission
- Preliminary sizing
- Weight, Performance

Preliminary Design
- Aerodynamics
- Design/analysis
- Structure Design/Analysis
- Control Design/analysis
- ........

Final Design
Current Aerodynamic Design Process in Preliminary Design
The inner aerodynamic design loop

• **In each iteration of the design**
  – Generating a mesh for the new configuration
  – Performing the CFD analysis.
  – Computer graphics software is then used to visualize the results
  – The performance is evaluated

- Generating a mesh
- Performing the CFD analysis
- Visualizing/Evaluation

- Linear potential
- Full potential
- Euler equations
- N-S equations
The inner aerodynamic design loop

- Key points of the flight envelope for transport airplane
  - Nominal cruise point
  - Cruise at high lift and low lift to allow for the weight variation between the initial and final cruise as the fuel is burned off
  - A long range cruise point at lower Mach number
    - Important to make sure there is no significant drag creep
  - The climb condition
    - Requiring a good lift to drag ratio at low Mach number and high lift coefficient with a clean wing
The inner aerodynamic design loop

• Typical aerodynamic design problems
  – Airfoil design optimization
  – Wing design optimization
  – Analysis/design of wing-body combinations
  – Analysis/design of wing-body-nacelle
  – ……
Wind Tunnels & Comput. Aero.

- **Wind tunnels**
  - Can carry out the hundreds of thousands of the data points necessary in an aircraft development program
  - For after-the-fact design validation
  - Not well suited to provide detail information

- **Comput. Aero.**
  - Can provide detail information everywhere in the flowfield
  - Can be used in an “inverse design” or “optimization
  - Its accuracy is limited by the assumptions of math model, solution algorithm
The role of CFD in Aircraft Design

• Major applications reveal details of fluid flow phenomena that wind tunnels cannot produce
  – Providing detail understanding of the flow
    • Surface pressure distributions
    • Shock wave locations and strength
    • Streamline paths
    • Boundary layer behavior
  – This information is used
    • to assess the equality and characteristics of a particular flow
    • to learn about cause and effect relationships
    • to point the way toward a better design
The role of CFD in Aircraft Design

• Making design optimization possible
  – Airfoil design optimization
  – Wing design optimization
  – Configuration design optimization

![Diagram showing the role of CFD in aircraft design]

- CFD Codes
- Airfoil design
- Wing design
- Configuration design
- Flow analysis
- Performance evaluation
- Optimizer
The role of CFD in Aircraft Design

• Reducing design flow time and cost
  – Computational aerodynamics provides an ability to rapidly and cheaply carry out a small number of simulations leading to understanding necessary for design.
The role of CFD in Aircraft Design

- Great opportunity exists for innovative design
  - When faced with a configuration concept for which no experimental data base exists, computational methods usually can produce a design that will perform well enough in its first wind tunnel entry to allow meaningful evaluation and a clear path toward incremental improvement.
  - Without computational design, first wind tunnel results frequently turn out to be unacceptably bad and with no clear path toward improvement.
Some Application Examples

- Engine airframe integration
  - Boeing 737
  - Boeing 777
  - Global Express

- Airfoil design

- Wing design
Wing/Nacelle Design of Boeing 737 –200

• Background
  – Boeing 737 series might not have remained in production beyond the mid-1980s, if not for the installation of a modern, large diameter, high bypass ratio turbofan engine.
    • Competitive pressures from MD-82
    • New federal regulations demanded significant noise reduction
    • The installation of a modern turbofan engine could meet the need, if it could be accomplished without incurring an excessive increase in interference drag, weight, or cost.
Boeing 737-100
CFM56 - 3 TURBOFAN
• The Conventional wisdom
  – To avoid the interference drag would have required lengthening the landing gear to provide proper ground clearance.
  – Increasing the landing gear length would result in extra weight and excessive costs to modify the aircraft structure.
• Challenge

  – Finding the solution, which allowed a much larger diameter engine to fit under the wing without increasing the main landing gear length.

*Figure 7. Impact of Close Nacelle Coupling on the 737-300 Design*
- The need, the opportunity, and technology were available to provide a solution to this challenge.
• Understanding the problem using CA
  – The numerical simulation revealed that the source of the interference drag is induce drag or vortex drag caused by a change in wing span loading due to the presence of the nacelle and strut.
  – The wind tunnel had been unable to do it.
• **Resolving the problem**
  
  – Redesigning the nacelle and strut to prevent adverse impact to spanwise load distribution of the wing.
  
  – Properly contoured nacelle and strut design could and was done much more effectively with computational methods than with the wind tunnel because computational method automatically produce finely detail pressure on all wing, strut, and nacelle surface.
• **Impact of CFD**
  
  – The knowledge provided by CFD made possible the very successful major derivative to original 737.
    
   • **737-300/400/500/600/700/800**
  
  – This story showed that the impact of CFD contribution to most successful commercial jet airplane series in history.
**737-300**
As a replacement for 737-200s, the forward-looking 737-300 offered more seats, better performance and fuel economy, and much lower noise.

**737-400**
The 737-400 offers the revenue opportunities of additional cargo capacity and more seats, as well as the operating savings of crew and engine commonality and lower seat-mile costs.
737-500

Although it has the largest model designator of its generation, the 737-500 is actually smaller than either the 737-300 or the 737-400.

737-600

The smallest member of the Next-Generation 737 airplane family, is equivalent in size to the 737-500, and provides seating for 110 to 132 passengers.
737-700

Equivalent in size to the 737-300, the 737-700 has a new larger wing, a larger tail, and new engines that ensure 737 market leadership well into the 21st-century.
The role of CFD in the design of the Boeing 777

- Cruise wing and propulsion/airframe integration
  - More detail later

Cab design
  - No further changes were necessary as result of wing tunnel testing.

Aft body and wing/body fairing shape design
  - CFD provided insight and guided the design process through the calculation of pressure distribution and streamlines.

- The design of the flap support fairings
  - CFD augmented wind tunnel testing
The role of CFD in wing design optimization

- **Code**: TRANAIR
  - 3D full potential finite element code with directly coupled boundary layer.
  - Having both analysis and design optimization capability

- **Design variables**
  - Wing geometry

- **Objectives**
  - Pressure distribution matching
  - Mach gradient minimization
  - Drag minimization

- **Constraints**
  - Lift, moments, minimum thickness, curvature, smoothness, etc
The role of CFD in the design of the Boeing 777
Wing design optimization

Figure 9
The role of CFD in the design of Global Express Wing design optimization

- Codes
  - FLO22OP
    - 3D full potential code with directly coupled boundary layer was used for optimization.
  - KTRAN and MBTEC
    - was used to check that nacelle interference on the wing transonic performance was acceptable.
  - FLO67V
    - an Euler/3D boundary layer codes was used to check viscous effects in off-design conditions.

- Design variables
  - Wing geometry

- Objectives
  - To minimize drag
  - To deduce structure weight, maximize fuel volume, Clmax conditions

Mission

Ultra Long Range
High-speed Business Jet
91,000 lb MTOW
6,500 NM @ Mach 0.80
6,300 NM @ Mach 0.85
5,000 NM @ Mach 0.88
The role of CFD in the design of Global Express
Wing design optimization

- **Results**

  - Before optimization, the isobars show a strong shock wave at the outboard wing brake, sweeping toward the leading edge near tip.

  - After optimization, the straight isobars mean a better flow behavior with a weak shock, consistent with a computed lower drag that was verified in the wind tunnel testing.
The role of CFD in the design of Global Express Power plant integration

- **Objectives**
  - To eliminate undesirable shocks on the surface of the pylon and the nacelle during cruise above Mach 0.8

- **Code**
  - KTTRAN: a transonic small disturbance code
  - MBTEC: a multi-block Euler code

- **Result**
  - By reshaping the fuselage, the shocks, denoted by the red colored areas, were eliminated
  - Tests results confirmed the conclusions.
The role of CFD in the design of ERJ-135

• Background
  – The market analysis indicated that there was need for jet aircraft capable of transporting between 30 to 40 passengers.
  – EMBRAER decided to develop the ERJ-135
    • 37-seat commuter jet
  – The ERJ-135 is based on the larger ERJ-145
  – One of the key differences in the new ERJ-135 regional jet from EMBRAER is its shortened fuselage relative to the somewhat larger ERJ-145.
The role of CFD in the design of ERJ-135

• Downwash Effects Issues
  – The wing downwash, the downward motion of the mass of air accelerated by the wing, causes the flow to reach higher speeds at the engine pylon and horizontal tail lower side.
  – The positioning of the engines closer to wing could produce a shock wave on the pylon and turn the flow more critical on the horizontal tail.
  – A shock wave would eventually cause flow to separate, generating noise, vibration, and more drag.
The role of CFD in the design of ERJ-135

- **Downwash Effects Issues**
  - The pylon also should not generate lift, which would produce induced drag.
    - This task also included the alignment of the pylon to the streamlines in its vicinities.
  - The worst case scenario would have made it necessary to redesign the pylon, which would have increased the cost of the aircraft and delayed the program.
  - Another related issue was that the downwash from the wing would alter the magnitude and direction of the velocity vector in the engine inlet, increasing the flow distortion in this region.
The role of CFD in the design of ERJ-135

• How to deal with the issues?
  – Wing tunnel testing
    • Some transonic wind tunnel testing are required to ensure the absence of shock waves forming over the lower side of the engine pylon that might have affected the performance of the aircraft and reduced buffeting margins.
  – CFD
    • EMBRAER engineers want to save a considerable amount of money and time by using CFD simulation to prove that flow characteristics of the ERJ-135 are very similar to the already-certified ERJ-145.
    • After validating the RAMPANT CFD software package, they decided to use CFD to solve this problem.
The role of CFD in the design of ERJ-135

CFD simulations

Comparison of pressure distribution over the pylon mid-section between the ERJ-135 and ERJ-145. Plot shows similarity between the two planes in testing.
The role of CFD in the design of ERJ-135

- Simulation Results
  - The analysis results showed that the flow at the pylon's front portion of the ERJ-145 was slightly supersonic at cruise conditions but no shock wave was observed there.
  - Regarding the ERJ-135 flow over the pylon, it is speedier than the ERJ-145 at the same condition with no shock wave forming there.
  - The analysis showed that no pylon redesign was needed.
The role of CFD in the design of ERJ-135

• Simulation Results
  – The flow pattern at the horizontal tail was also the same for both aircraft.
  – The simulation showed that the downwash angle in the flowfield outside of the nacelle was around two degrees more for the ERJ-135 compared to the ERJ-145 aircraft.
    • However, in the engine inlet no significant differences in the flow pattern were found.
The role of CFD in the design of ERJ-135

- **Flight tests**
  - Regarding the flight characteristics of the new aircraft, pilots flying the prototypes often report they could not tell the difference between the ERJ-145 and ERJ-135.
  - Flight test data indicates the ERJ-135 stall-warning computer will have the same stall speed settings as the ERJ-145 and will be the same part number as installed in the other aircraft.
The role of CFD in the design of ERJ-135

• Conclusions
  – This application provides a clear example of how recent advances in CFD software makes this technology practical for a wide range of external/internal aerodynamics applications.
  – The computer simulations saved $150,000 during the development of the new commuter jet by reducing the need for some wind tunnel testing, and flight tests.
Future Applications

• Drag predictions
  – Improve accuracy to predict drag within +/-0.00001

• Stability and control
  – Currently stability and control data in the wind tunnel are usually acquired after the aerodynamic design.

• Multidisciplinary Design Optimization (MDO)
  – Finding an better design
  – Reducing design/development cycle time
  – Reducing design costs
Project 3

• Article (at least 1200 words)
  – The Role of Computational Aerodynamic in Aircraft Design

• References
  – Check reading list at the web site