Multi-Disciplinary Optimization Technologies at Bombardier Aerospace

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  Multi-disciplinary wing optimization of business jet:

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- **Future of MDO at Bombardier**
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Bombardier Inc.

Aerospace

F09 revenues: $10.0 billion
51% of total revenues
Backlog: $23.5 billion*
Employees: 32,500*

Transportation

F09 revenues: $9.7 billion
49% of total revenues
Backlog: $24.7 billion*
Employees: 34,200*

*As at January 31, 2009

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Bombardier Aerospace

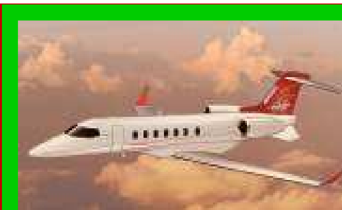
Business Aircraft Portfolio

LEARJET FAMILY

Learjet 40 XR

Learjet 45 XR

Learjet 60 XR

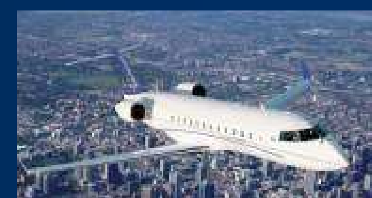


Learjet 85

CHALLENGER FAMILY

Challenger 300

Challenger 605



Challenger 850

GLOBAL FAMILY

Bombardier Global 5000

Global Express XRS

Bombardier Aerospace

Commercial Aircraft Portfolio

Turboprops

Q400 NextGen

Regional jets

CRJ700 NextGen

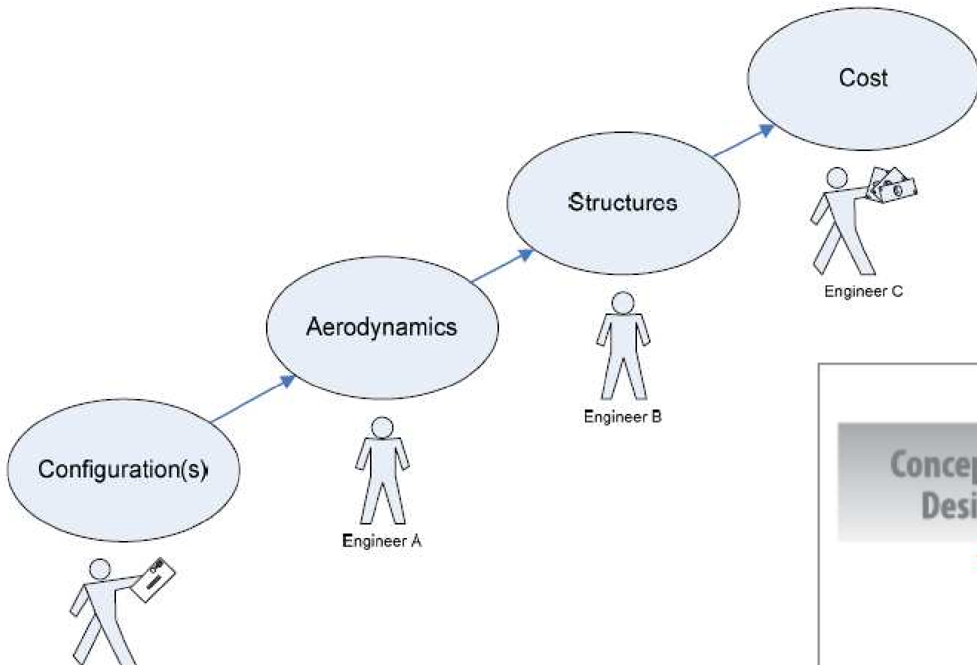
CRJ900 NextGen

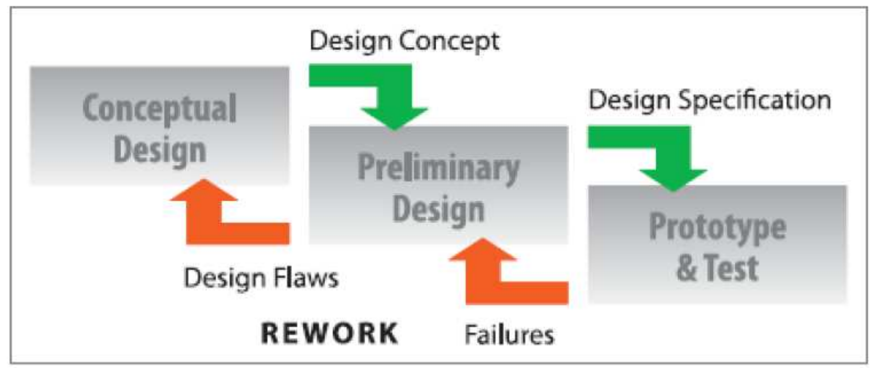
CRJ1000 NextGen

Single-aisle mainline jets

CSeries

Motivation for Multi-Disciplinary Optimization





- Traditional design process is sequential, often requiring rework loops which impact product quality & schedule

MDO technologies enable Concurrent Engineering & Set-based Design

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Motivation for MDO (cont'd)

§ **Benefits of MDO**

- Leads to more balanced designs & superior product performance
- Overcomes inherent inefficiencies in coordinating large teams of engineers working in separate disciplines
- Requires automation, which leads to improved productivity and consistency

§ **Status of MDO as a Technology**

- Field of MDO has reached maturity as a practical technology and will soon become a standard across the industry
- It is a natural evolution of engineering technology

§ **MDO Applications in Aerospace**

- Can range from maximizing return on investment (ROI) for a family of aircraft, to a "simple" trade study; e.g. trading weight vs. L/D in a wing profile design

Other Benefits of MDO

- The requirements for establishing automated MDO processes also leads to the following added benefits:

  - Improvements in the robustness and accuracy of analysis tools
  - Automation and standardization of tools and processes (automation will also facilitate a set-based design approach)
  - The use of a common work-flow integration environment, increasing productivity & traceability, and facilitating collaboration and communication between disciplines
  - The mapping of processes and tools in a re-usable environment, capturing “lessons learned”, and facilitating the training of new engineers

Approach to MDO Development at Bombardier Aerospace

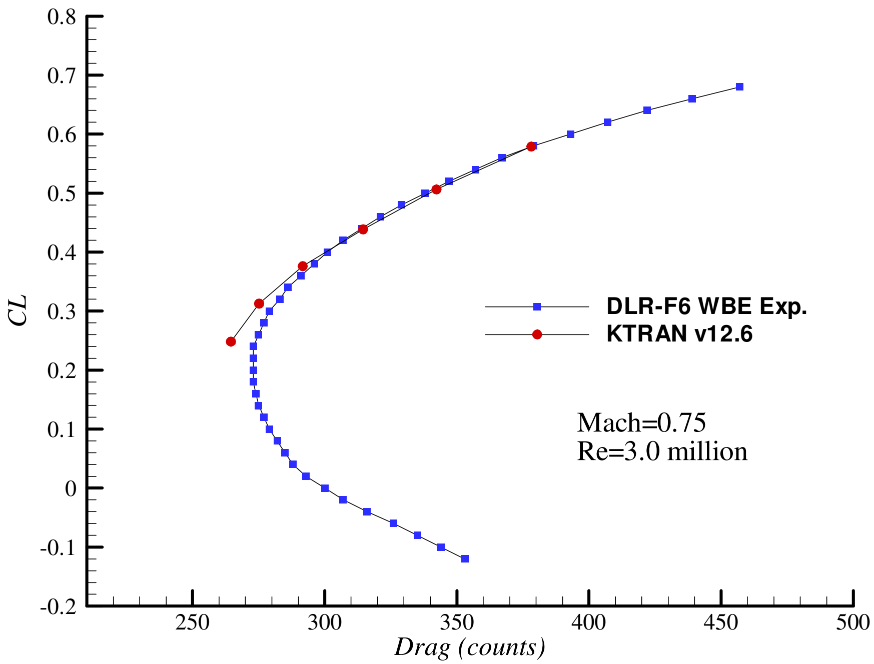
- **A multi-disciplinary methodology for aircraft design is not a single capability but rather a very large toolbox**
  - Build MDO capability incrementally by developing each component technology - ensure MDO “readiness”:
    - Issues: accuracy, robustness, & automation in each discipline
- **Successful MDO implementation must:**
  - Employ the analysis codes and engineering methodologies already in place at Bombardier
  - Engage the expertise of the engineers directly involved in the design
  - Train “multi-disciplinary” engineers

Current MDO Environment & Analysis Tools

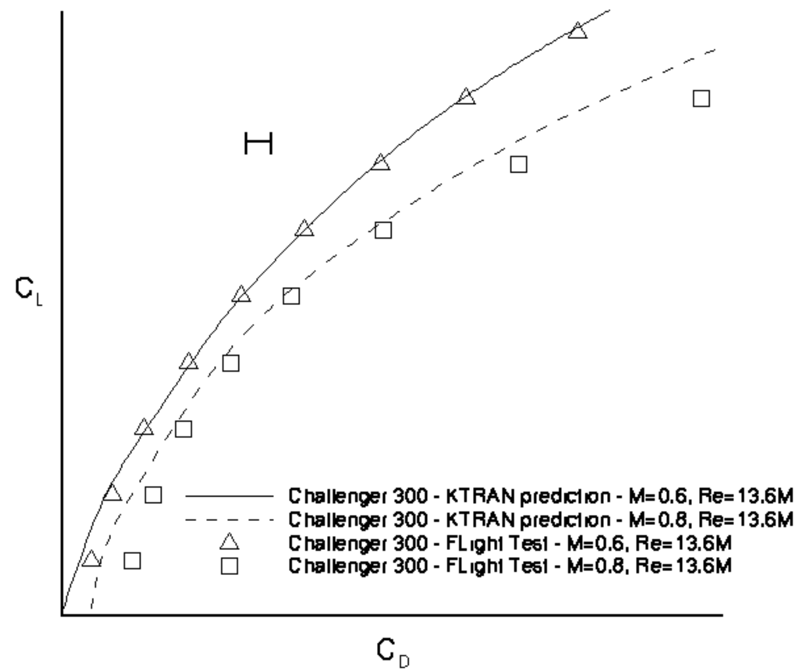
- **Optimization and Integration Framework:**
  - iSIGHT (from Engineous, now part of Dassault Systemes)
- **Optimization & inverse-design codes:**
  - ALLOP, INDES, OPTIMA2D, SYN103, SYN107
- **CFD Codes:**
  - KTRAN, FANSC, NSU3D, MSES,
  - VSAERO, NSU2D, TORNADO,
  - FENSAP, STAR-CD, CFX, CCM+
- **Wing structural analysis and design codes:**
  - TWSAP, NASTRAN

Achieving Engineering Accuracy for Drag by Combining Low-Fidelity Tools & Semi-Empirical Relations

Drag predictions from KTRAN TSD code



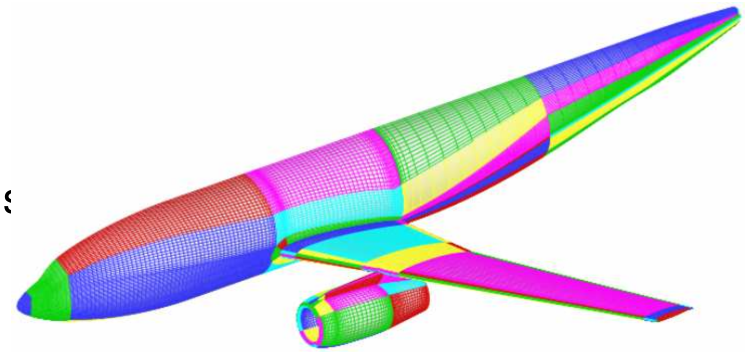
Drag prediction workshop



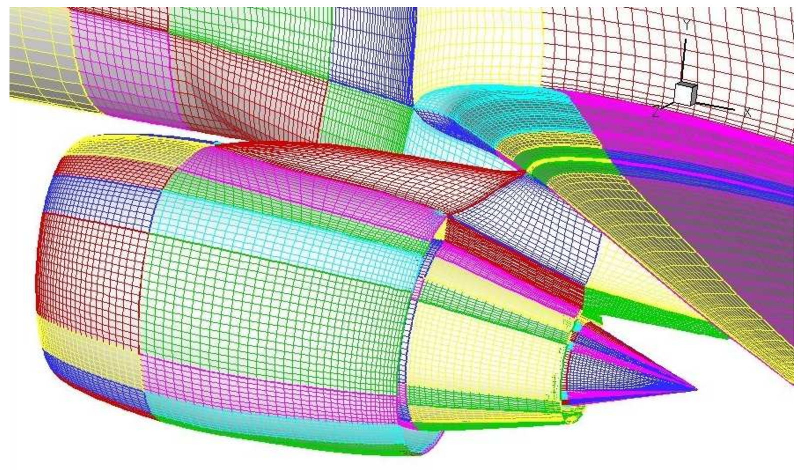
Flight test results on CL-300

FANSC – Full Aircraft Navier-Stokes Code
Overview

- **Flow models :**
  - 3D Euler / Boundary-layer
  - Reynolds-averaged Navier-Stokes
    Spalart-Allmaras, Menter k-ω turbulence model
  - Integrated far-field drag analysis module



- **Discretization :**
  - Multiblock structured grids
  - Finite Volume Method, Cell-centered
  - JST and matrix artificial dissipation schemes



- **Solver :**
  - Runge-Kutta time-stepping
  - Multigrid, Implicit Residual Smoothing
  - Low Mach-number preconditioning
  - Dual Time Stepping unsteady solver
  - Parallel (MPI library)

Developed in-house at Bombardier Aerospace over past 10 years

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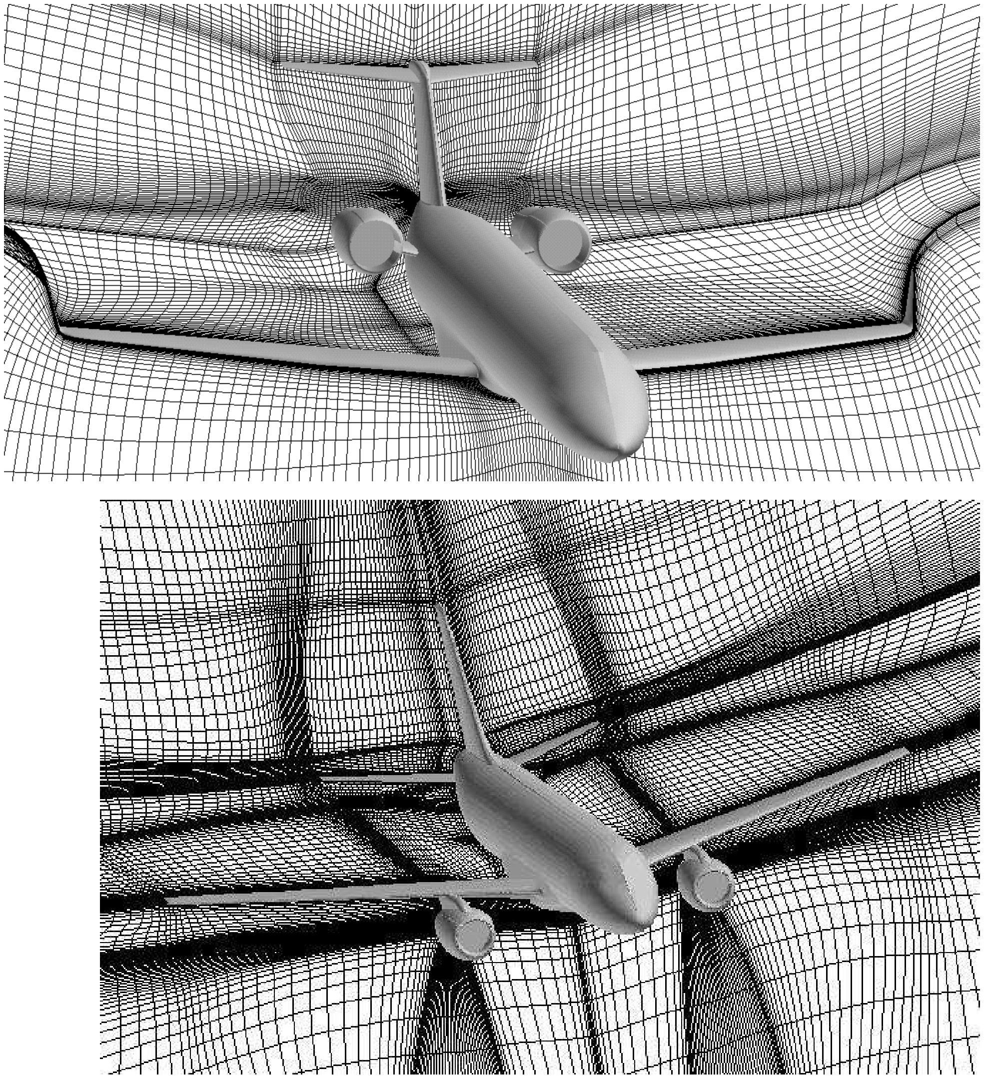
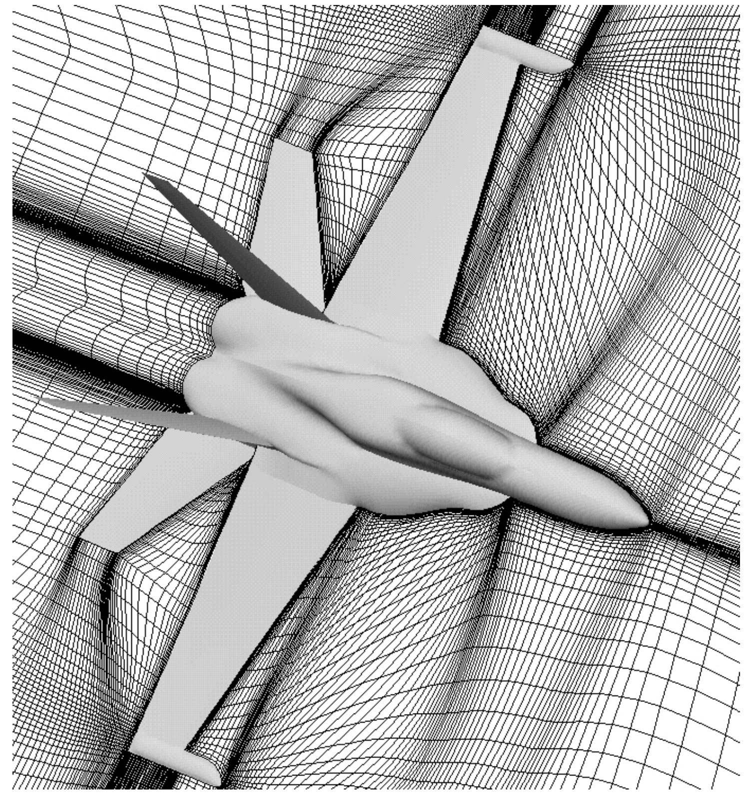
Structured Grid Generation at Bombardier Aerospace
Catia-Based MBGRID

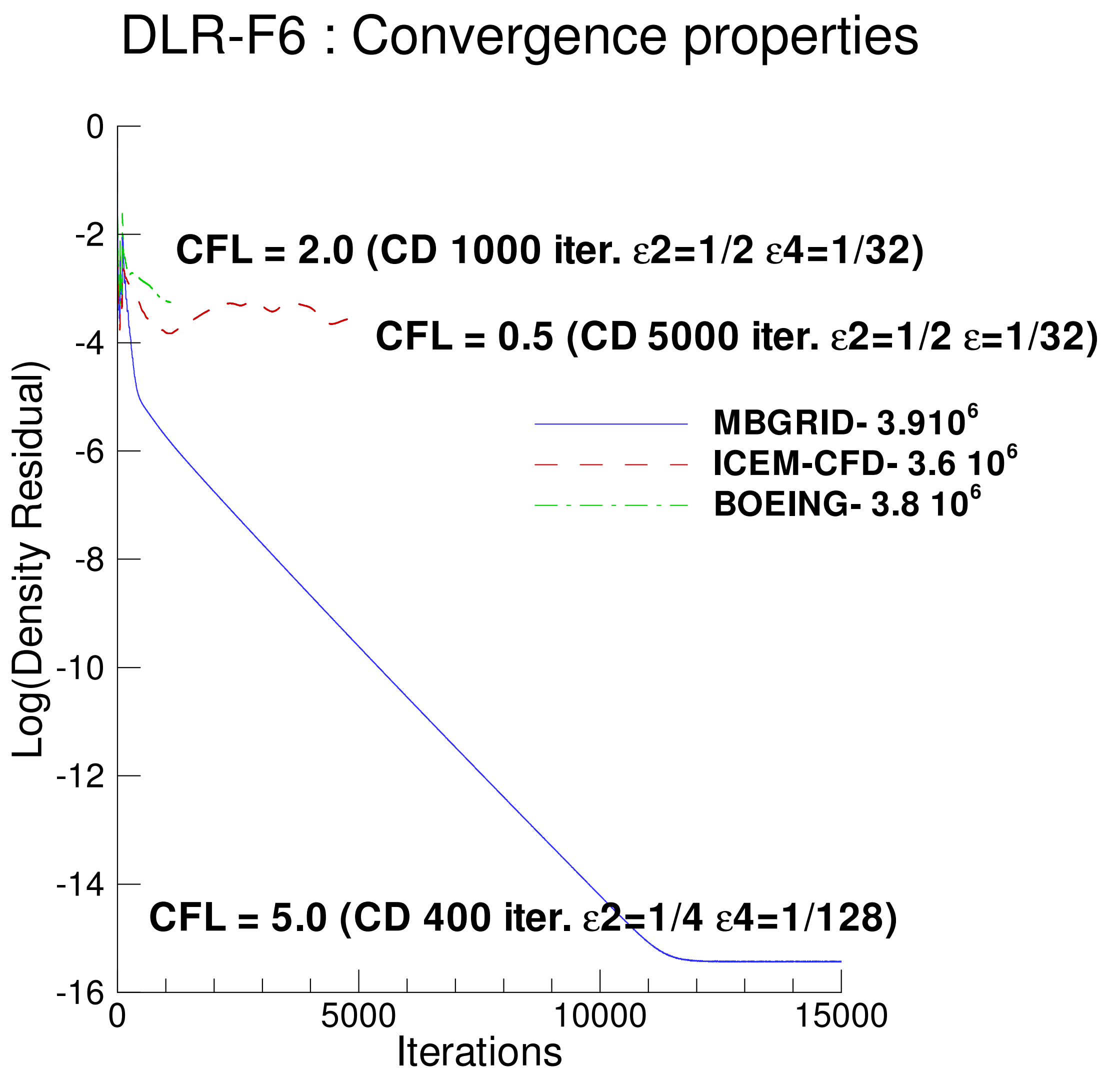


Commercial A/C



Military A/C

Navier-Stokes Analysis with FANSC / MBGRID



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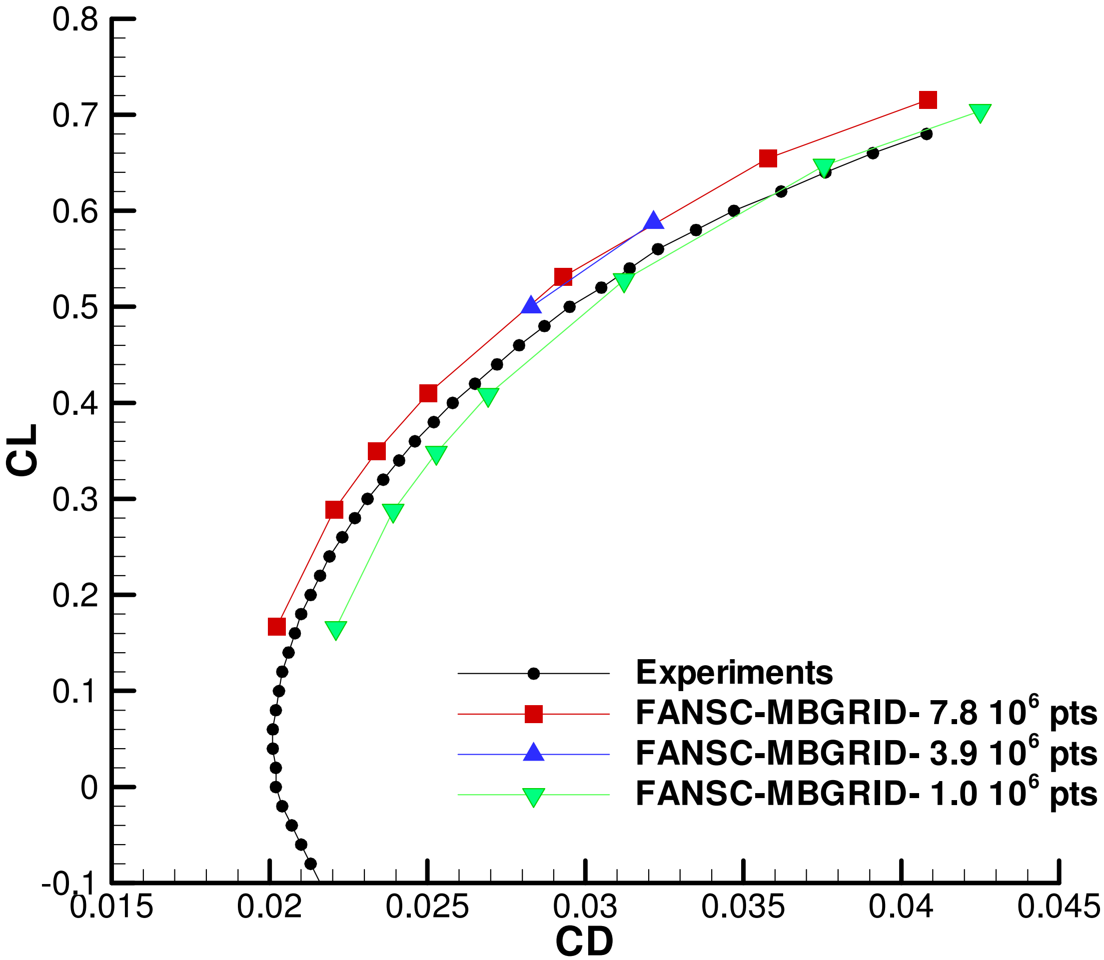
Navier-Stokes Analysis with FANSC

Drag Prediction workshop: DLR-F6



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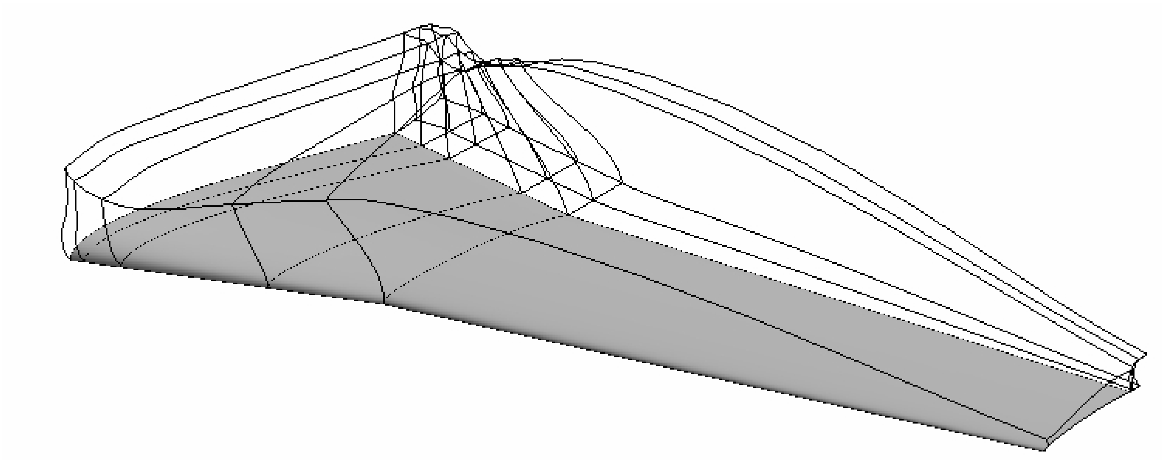
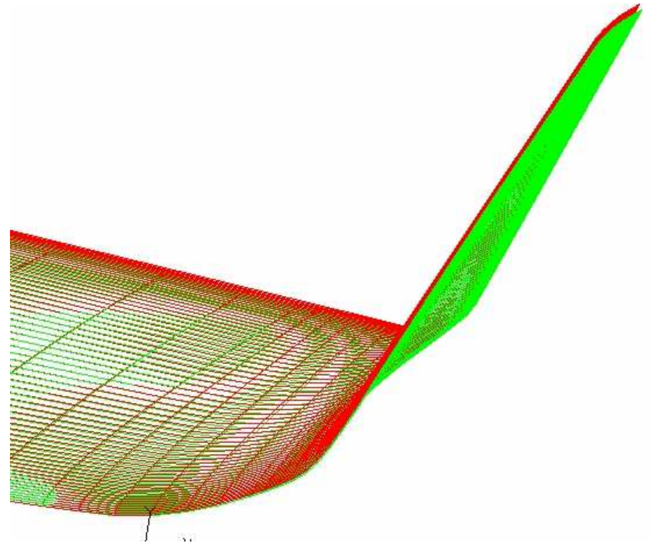
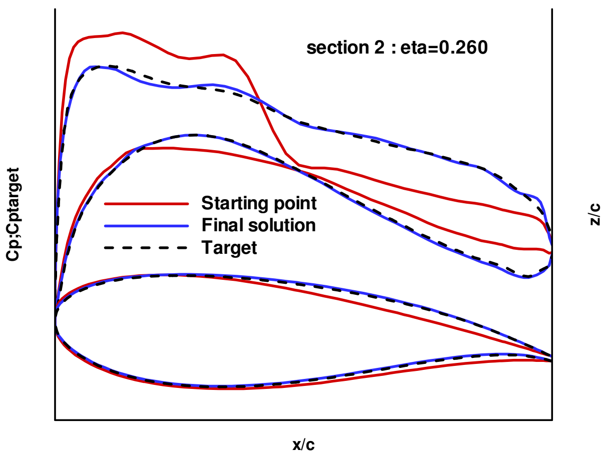
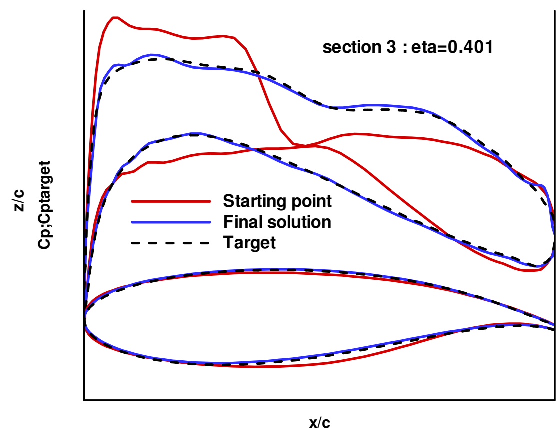
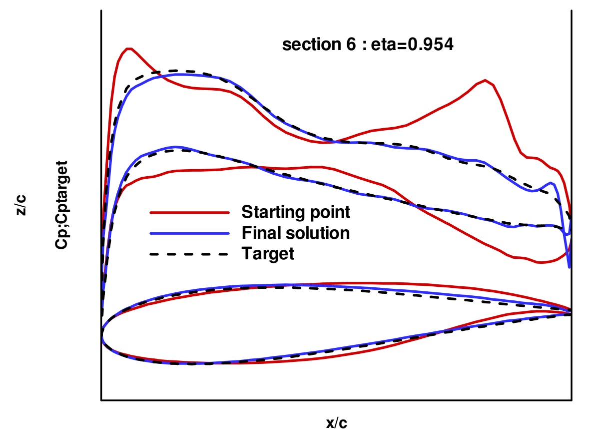
Structured Euler / Navier-Stokes Analysis & Design:
FANSC-INDES-MESHMOVER Inverse Design











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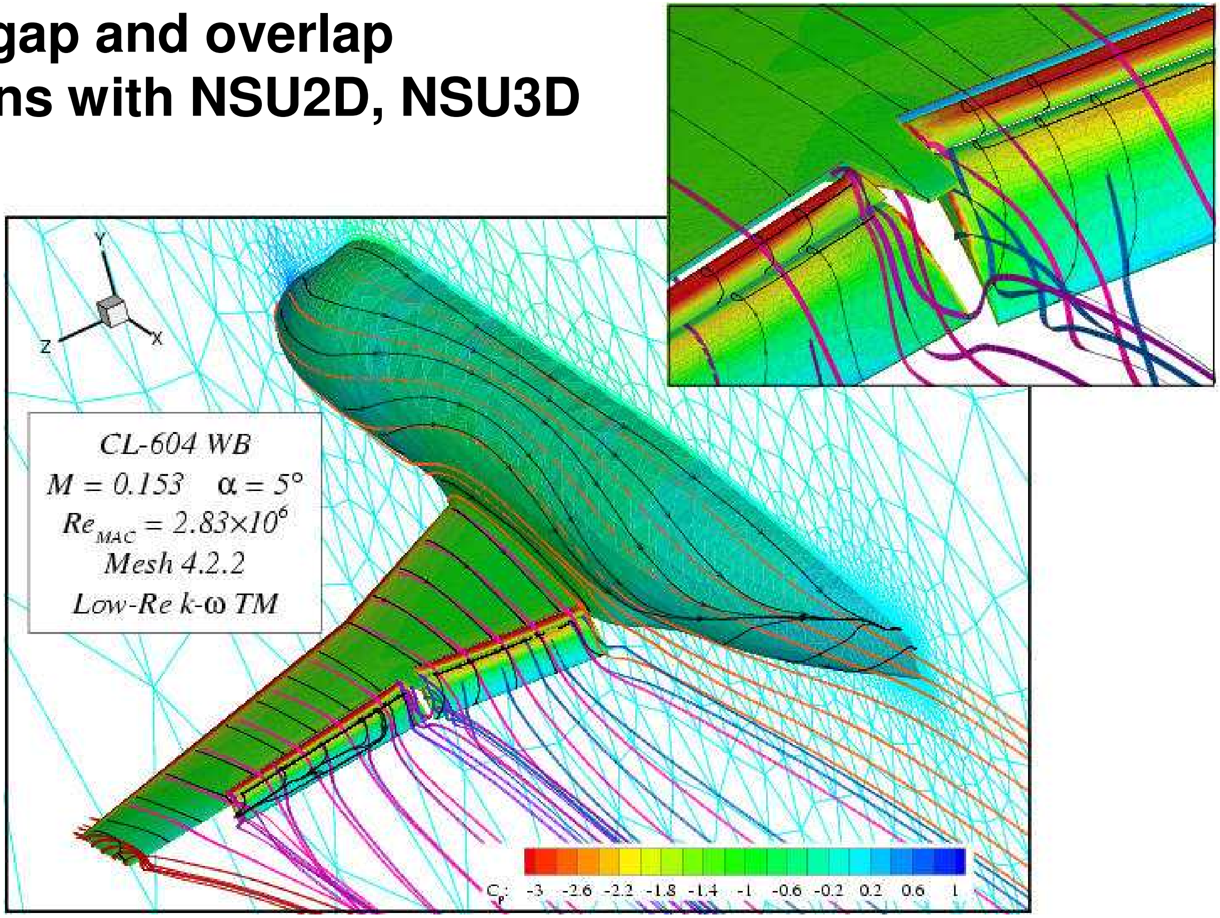
NSU3D, NSU2D Navier-Stokes Code
Linked to Optimization through ICEM-Tetra interface

Slat & flap gap and overlap optimizations with NSU2D, NSU3D



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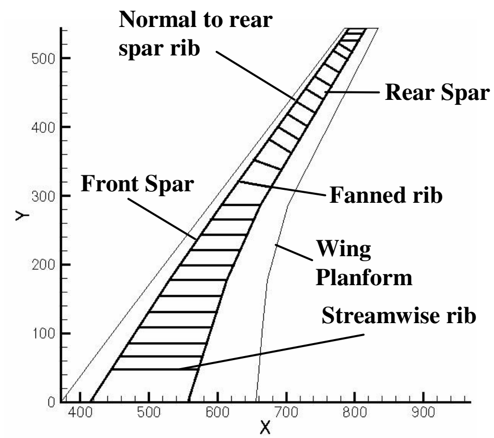
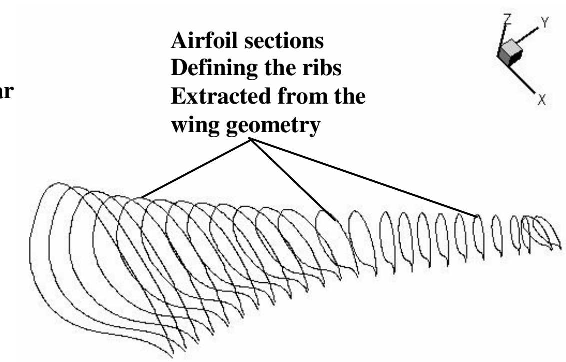
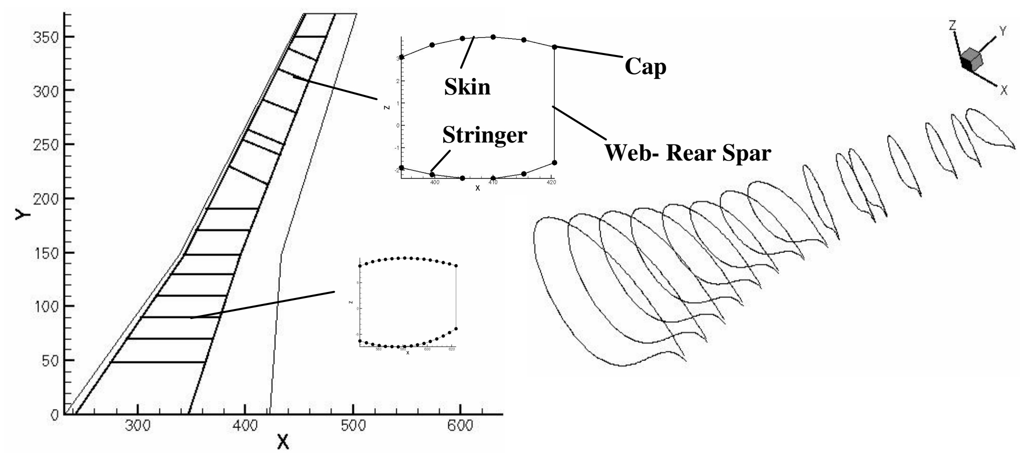
TWSAP – Automated Structural Wing Box Design

- Rib and Spar layout Module

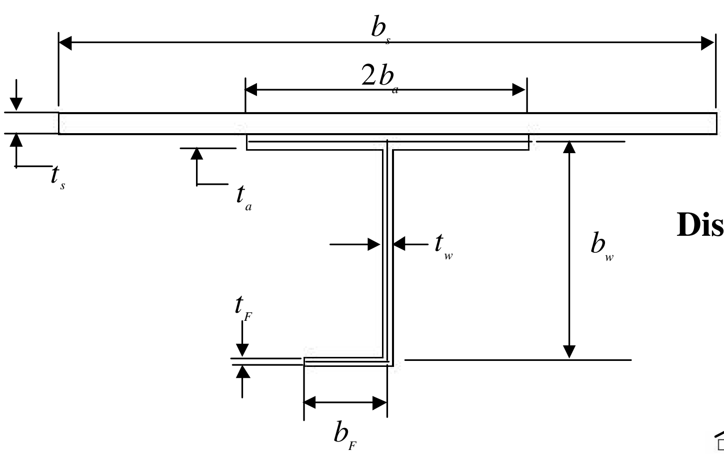


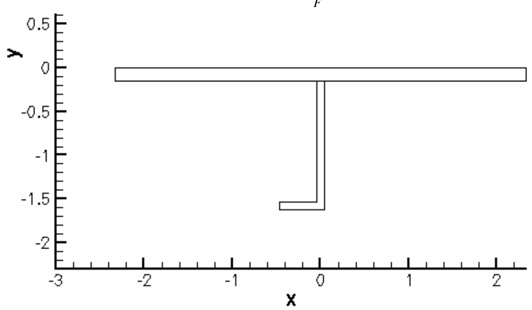


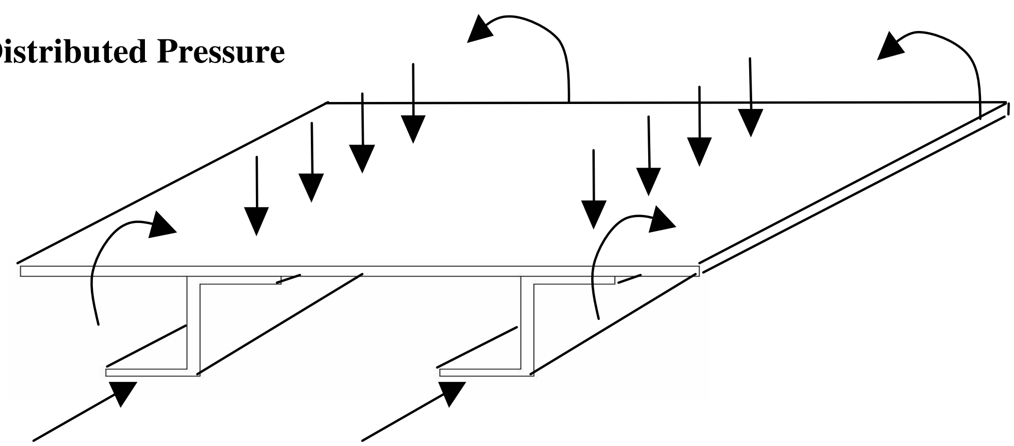


Wing Box Component Design …continued

- **Conceptual Skin-Stringer Design Module**
  - A methodology was developed for the conceptual design of stringer stiffened compression panels
  - The design method includes local (based on plate theory) and general failure modes common to aerospace compression structures. It also takes into account the panel beam-column analysis

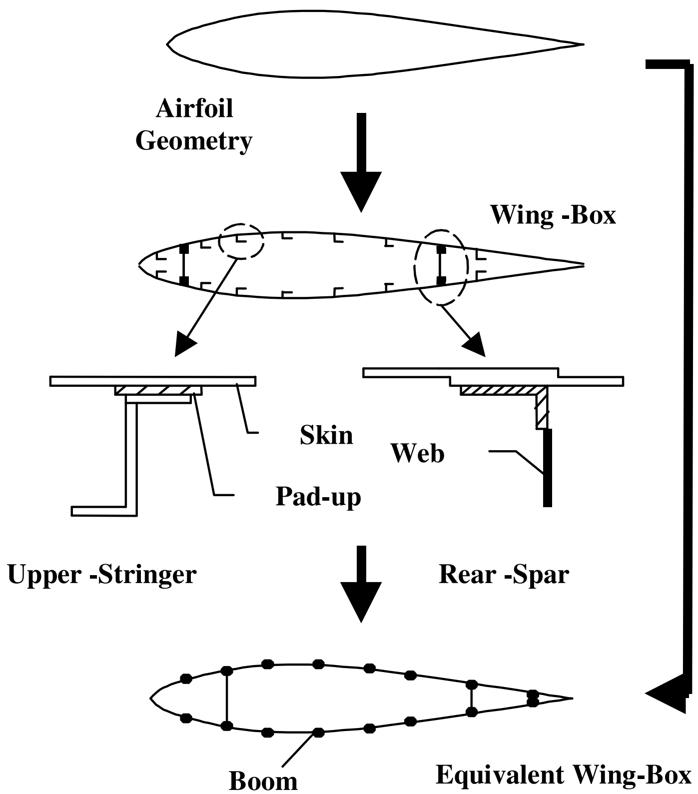


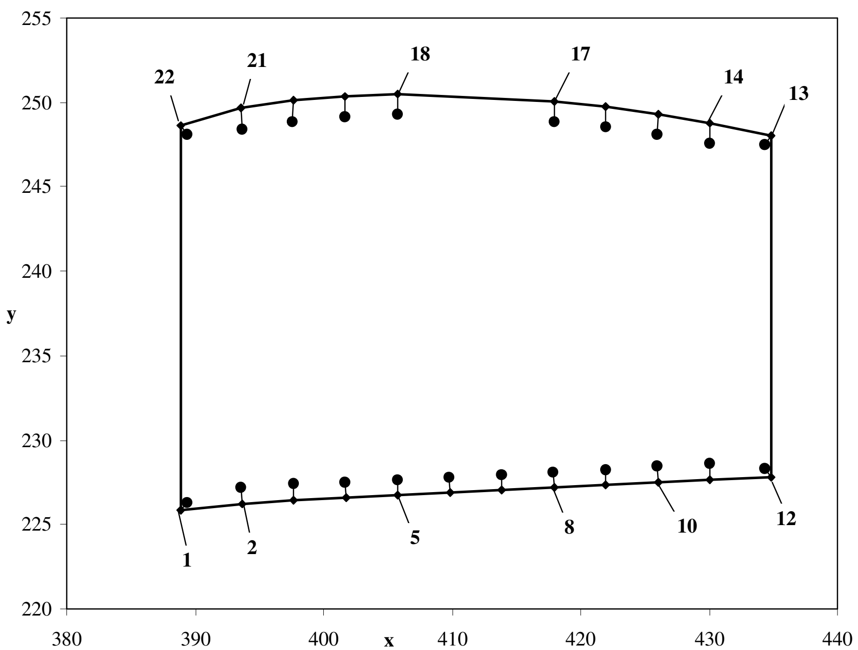




Thin-Walled Structural Analysis

- The TWSAP program uses thin-walled, single cell sections to represent the wing-box. Each wing box section is modeled with a set of skin-stringer panels, front and rear spars and upper and lower spar caps





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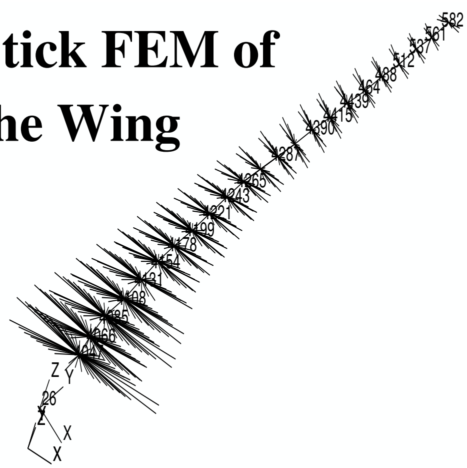
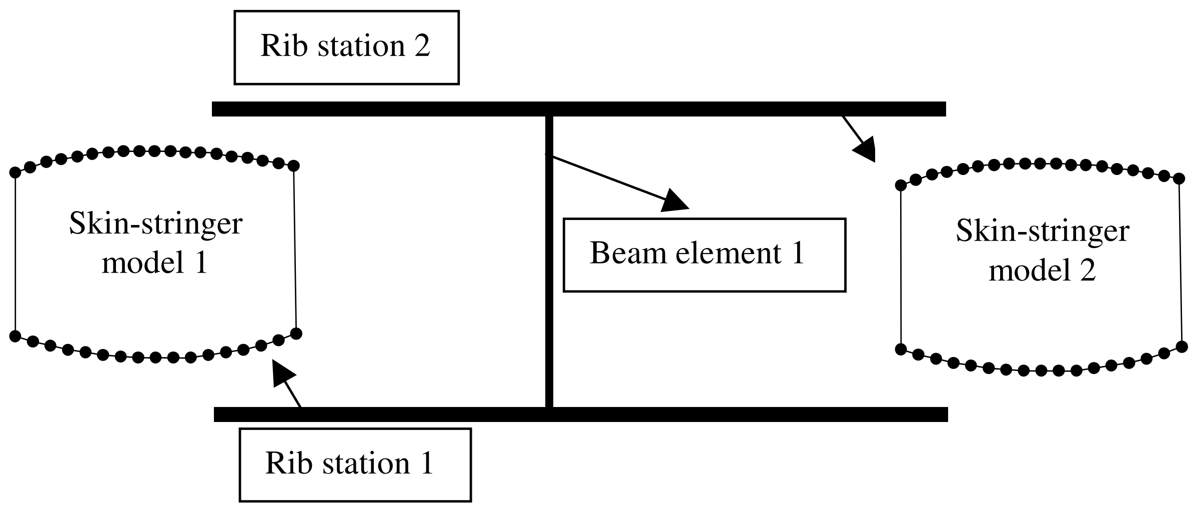
Wing Stick Model

- Predicting accurate values of the **bending and twisting** of the wing in flight depends on the fidelity of the stiffness properties of the finite element model of the wing as well as the aerodynamic loads
- The stick model of a wing structure is a series of tapered or uniform beam or bar elements
- The TWSAP program automatically generates the **stick finite element model** of the conceptually designed wing

Stick FEM of the Wing





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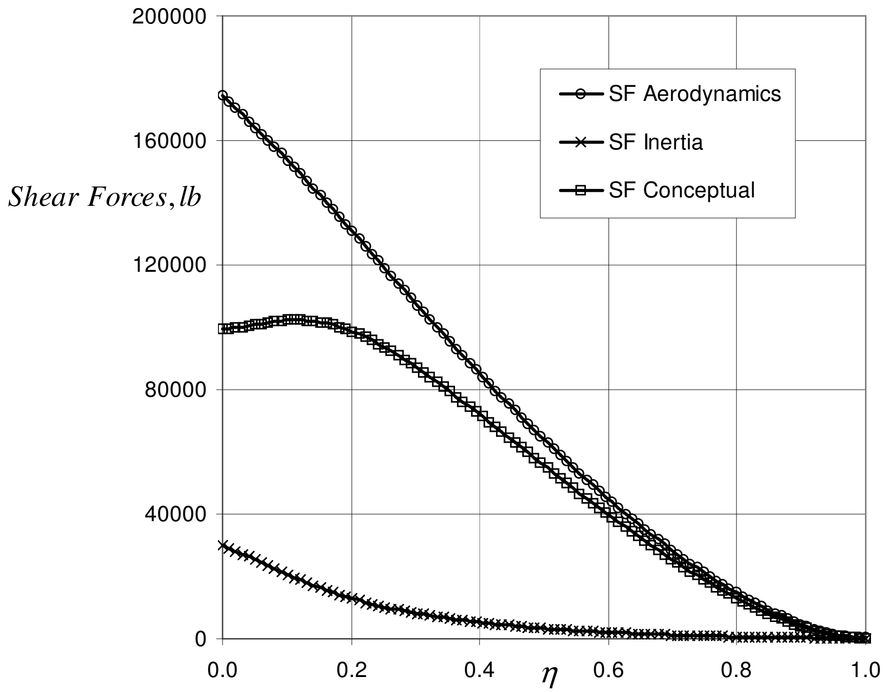
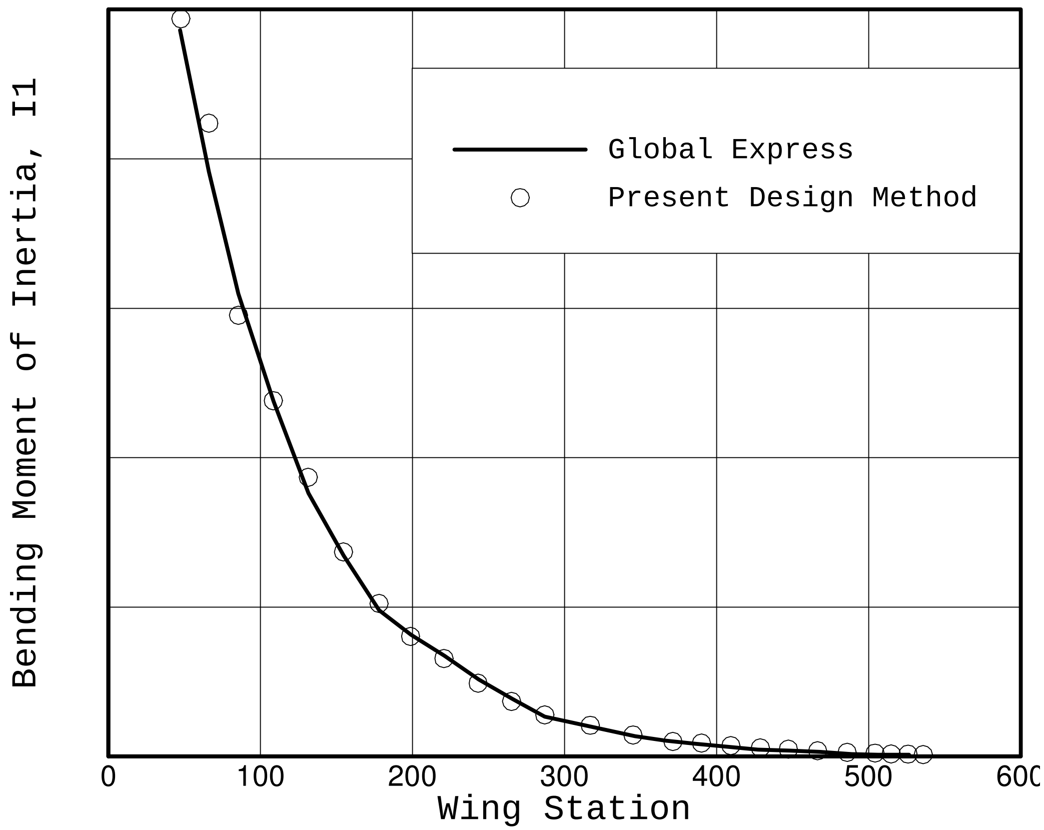
Conceptual Design Loads Module

- The process of generating the conceptual spanwise design loads, which are used in the sizing process of wing-box skin-stringer panels and spar-cap assemblies, was developed and transformed into a design module
- The design loads that are needed in the present conceptual design processes are the load intensities, the shear forces and the bending moments



Conceptual Wing Box Design Test

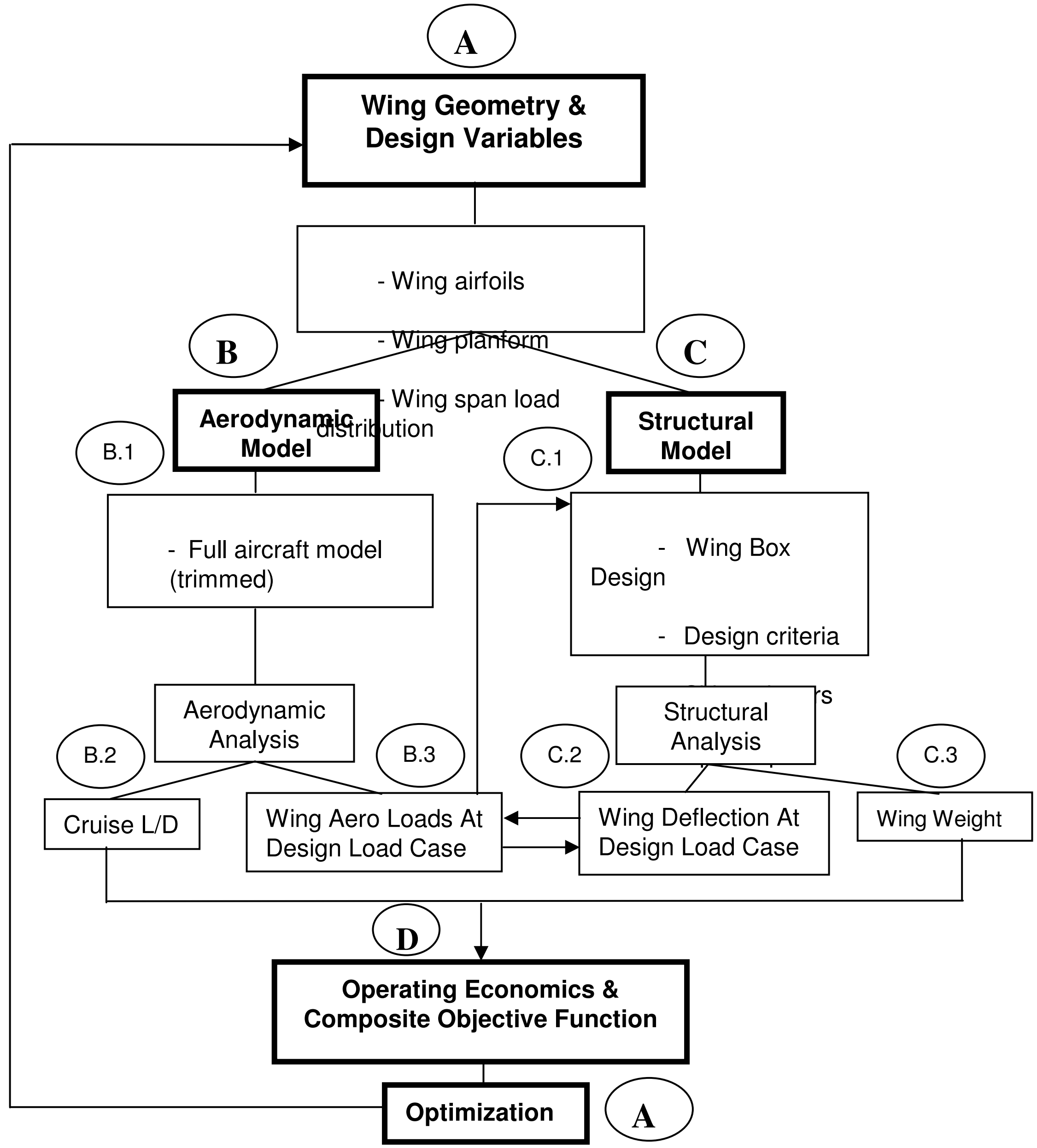
- The TWSAP program was validated by computing the stiffness of a conceptual wing structure designed by TWSAP to simulate the **Bombardier Global Express** aircraft wing



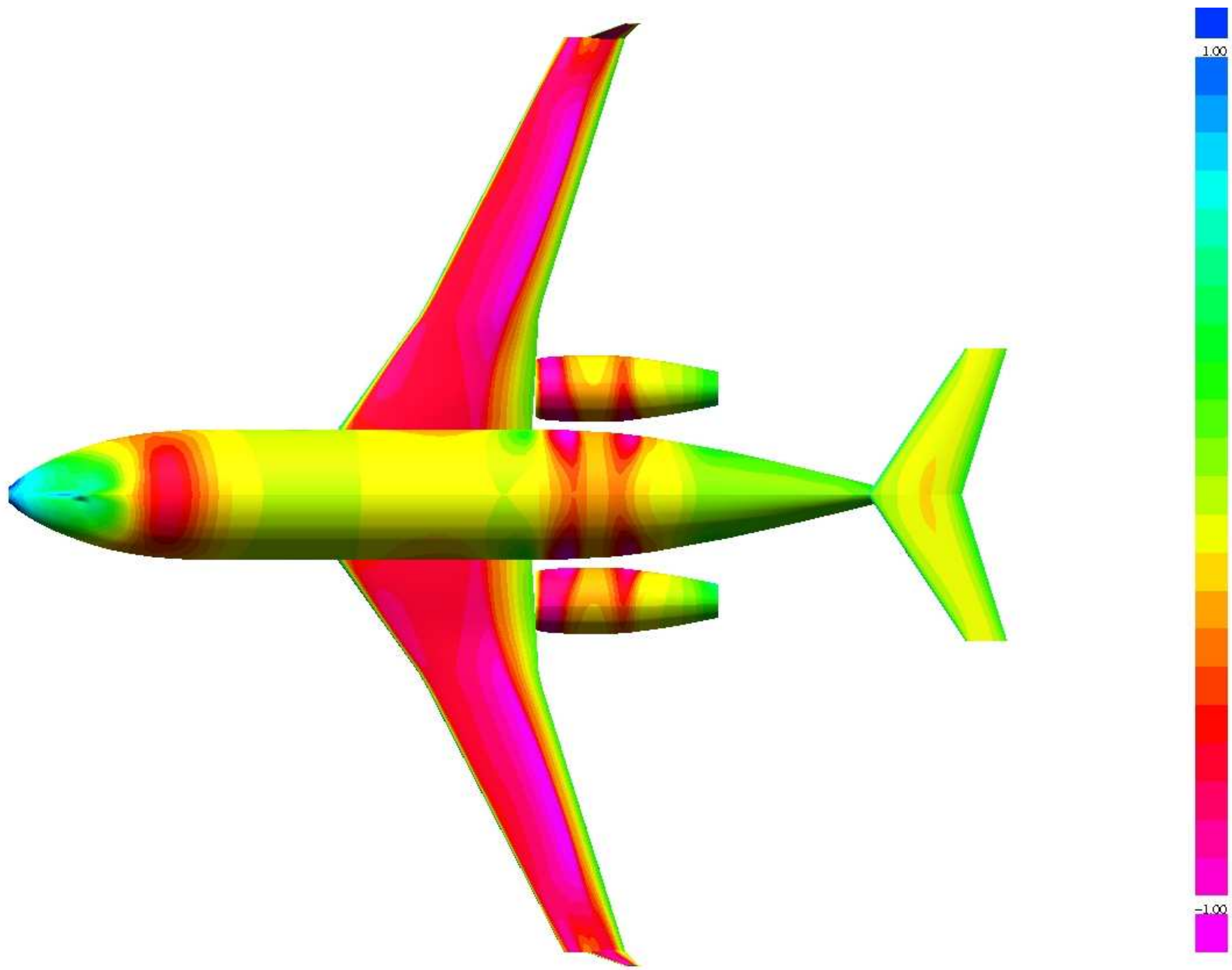
MDO Application – Proof-of-Concept

- **Full A/C Variable Wing Planform MDO using:**
  - Minimize total weight of fuel and structure as a function of the shape (sections and planform) of the wing
  - Used KTRAN for aero & TWSAP for structure
  - L/D gains converted to fuel weight reduction
    for constant range, constant MTOW, constant wing area
  - Single Load Case: 2.5 g maneuver design point
  - Total number of design variables: 99
    - 7 wing sections x 13 variables (91)
    - AR, Λ, TR (3)
    - Spanload (4)
    - Skin thickness (1)

Aero-Structural Optimization Process



Full A/C Model of Initial Business Jet Configuration
@ M=0.8, CL=0.5



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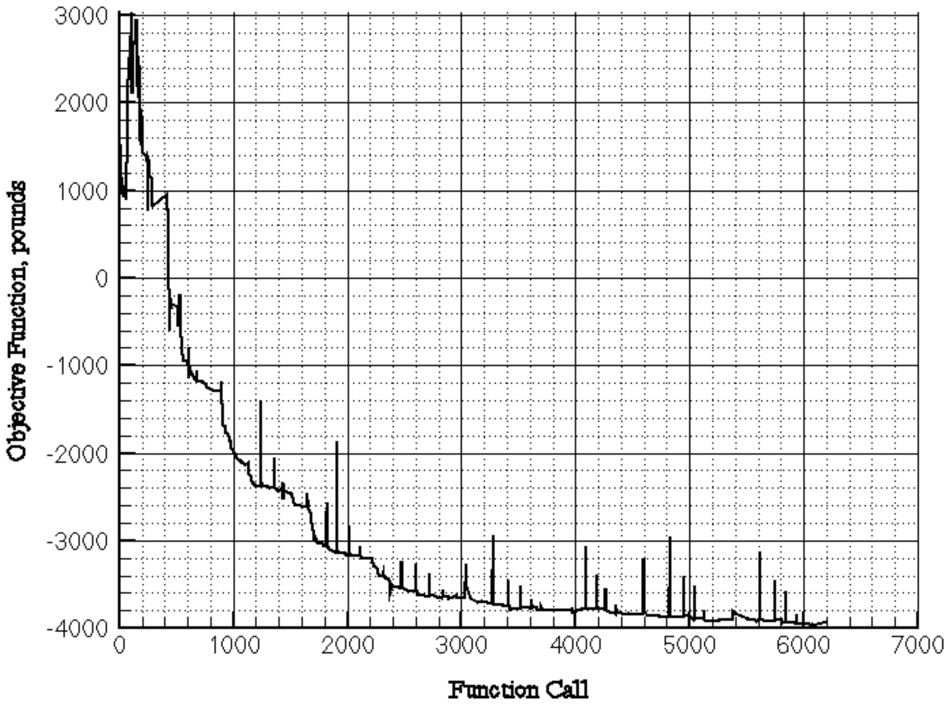
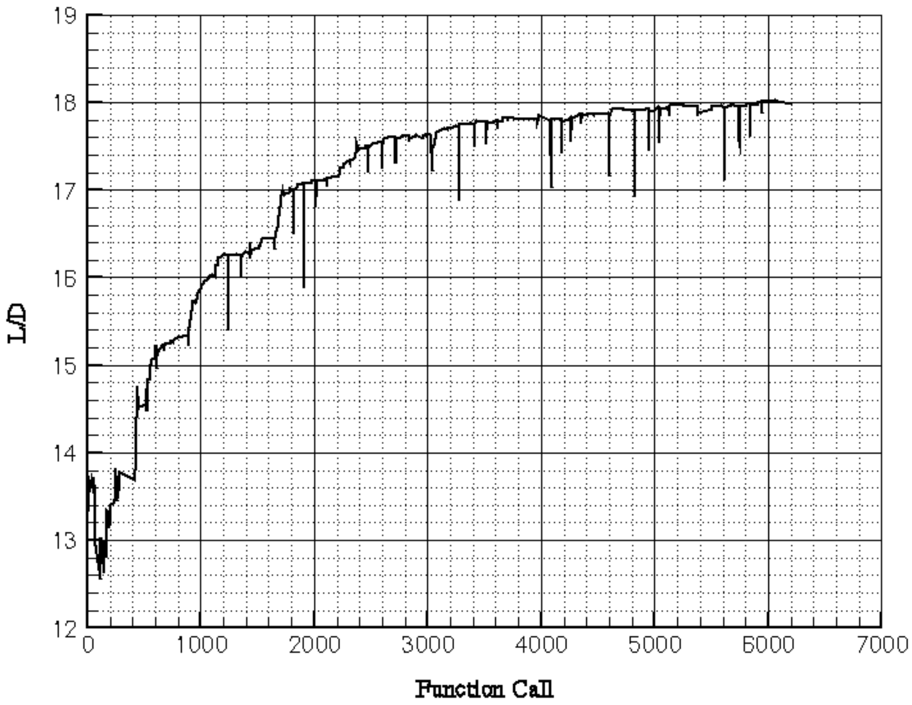
Application

Aero-Structural Optimization results

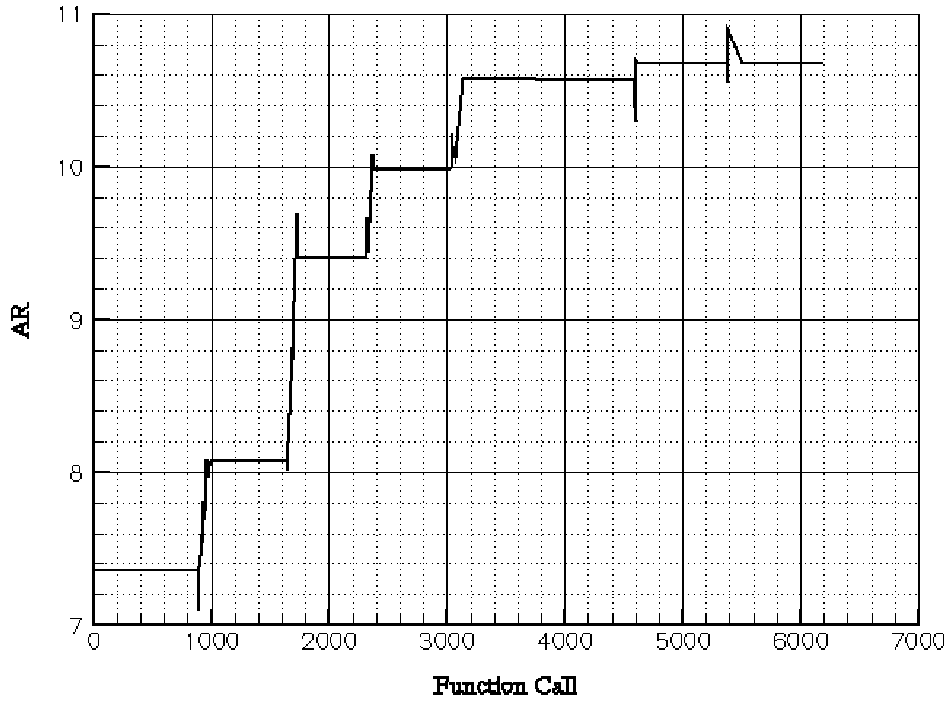




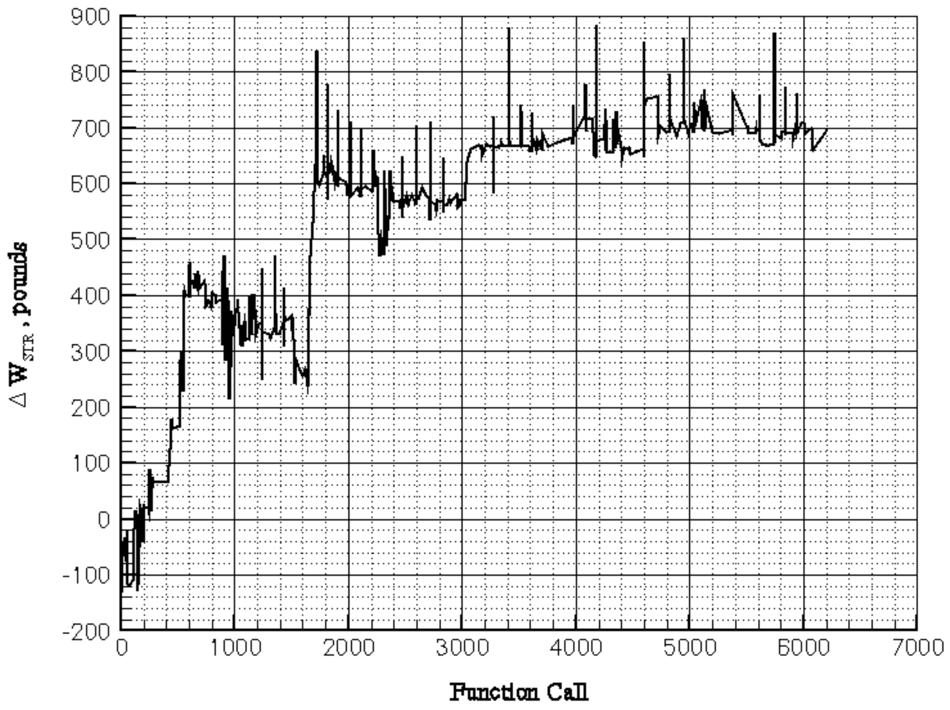
Weight of fuel + structure, lbs.

Lift-to-Drag Ratio

Aero-Structural Optimization results



Evolution of Wing Aspect Ratio

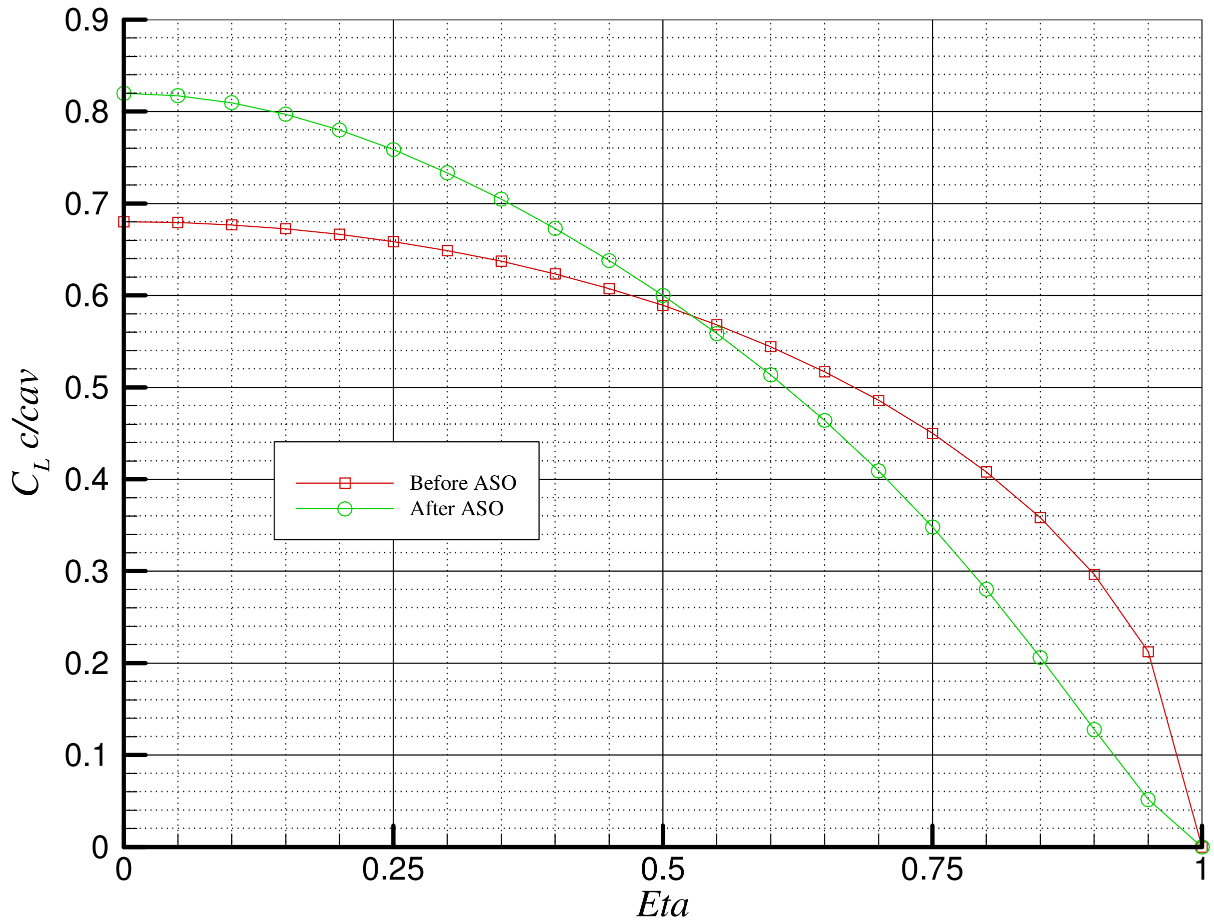


Wing structural weight, lbs.

Application

...continued

Aero-Structural Optimization results



Wing Spanwise lift distribution including Winglet

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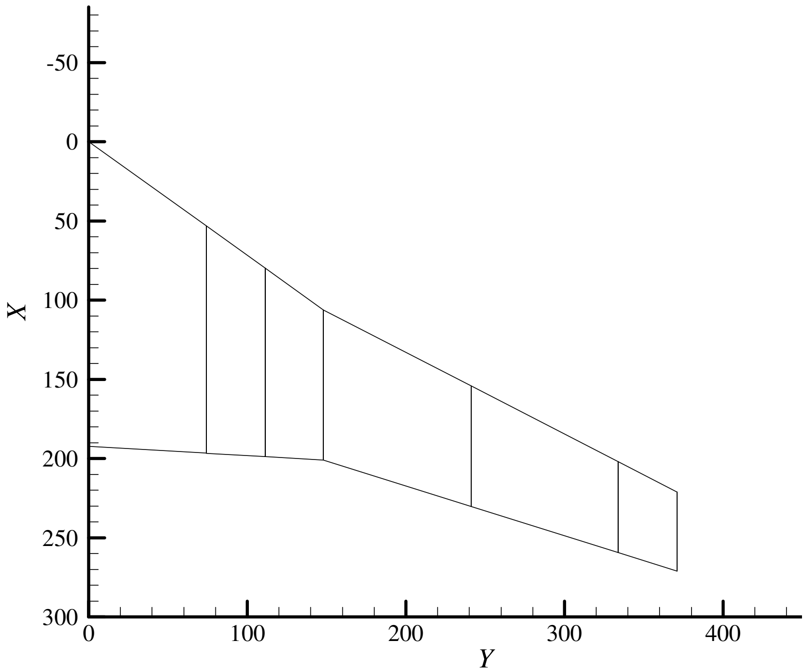
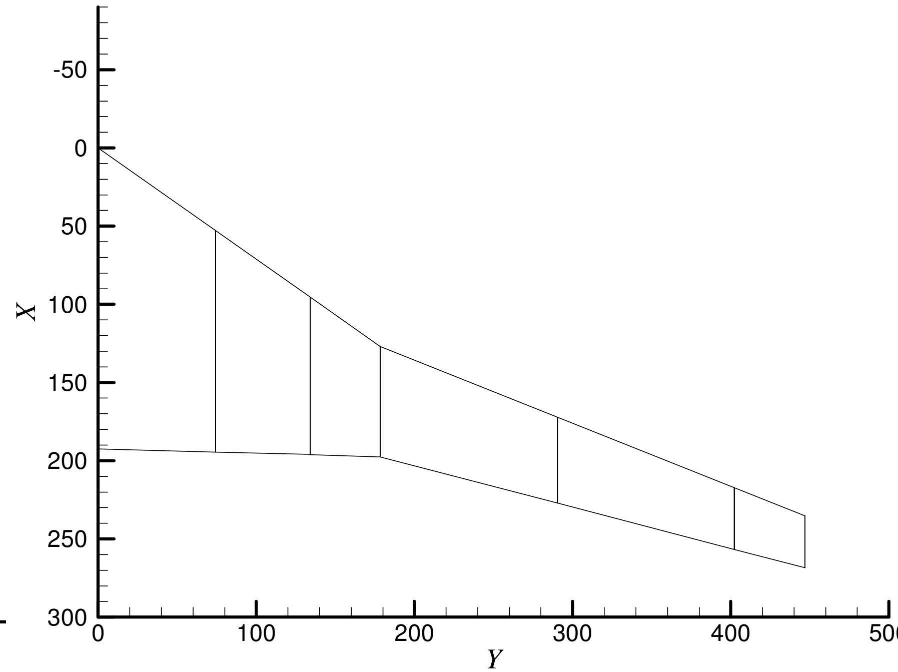
Application

…continued

Variable Wing Planform Optimization

for complete business jet configuration @ M=0.8, CL=0.5





Before MDO

AR=7.4

After MDO**

AR=10.6

****Wing sweep reduced by 10^o inboard, 7^o outboard,**

Wing ave. t/c reduced by ~2%.

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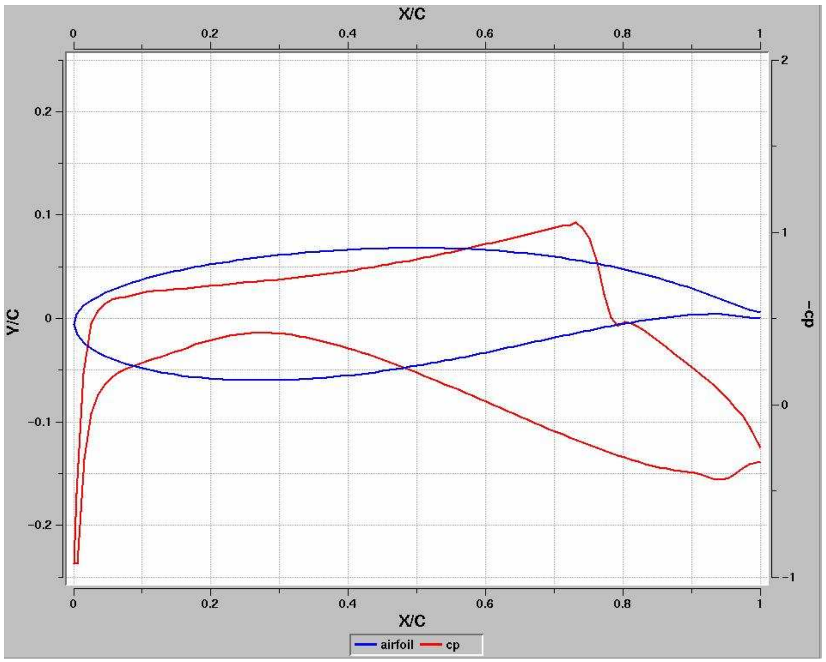
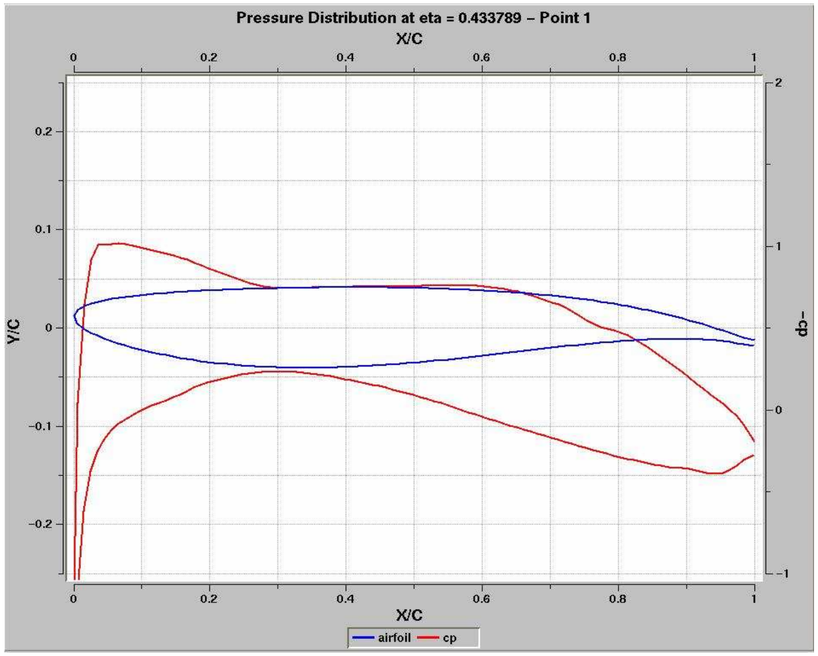
Applications

...continued

Aero-Structural Optimization results



Before MDO

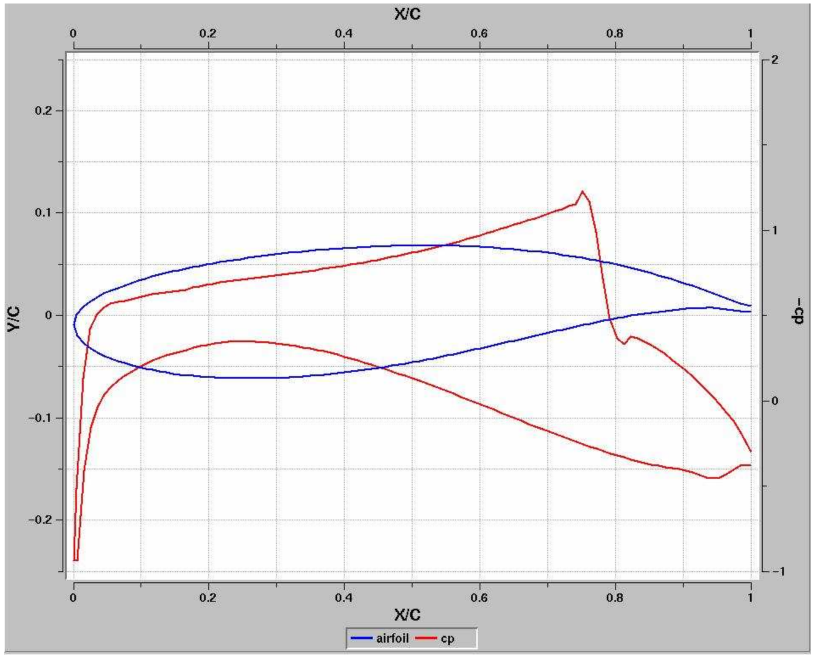


After MDO

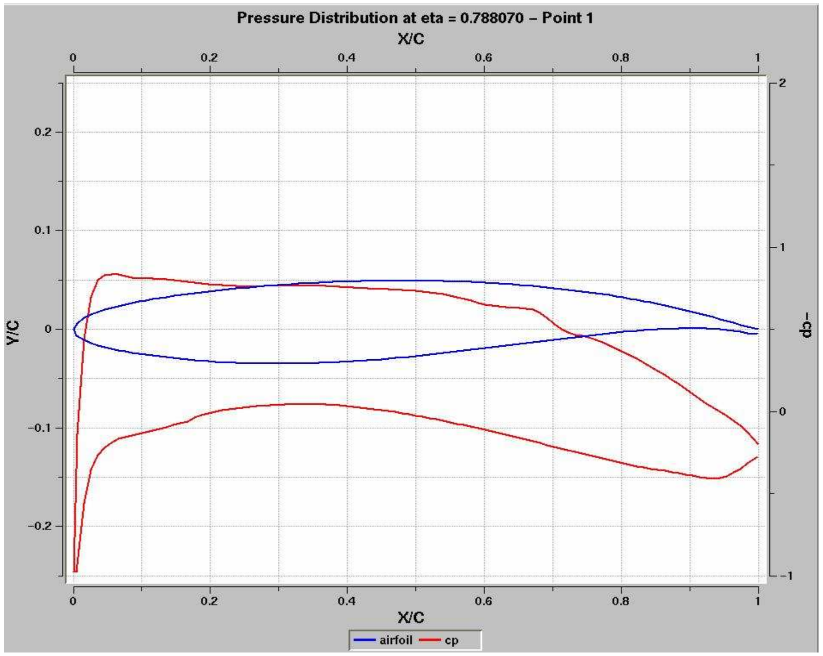
Eta=0.4

Applications

Aero-Structural Optimization results



Before MDO

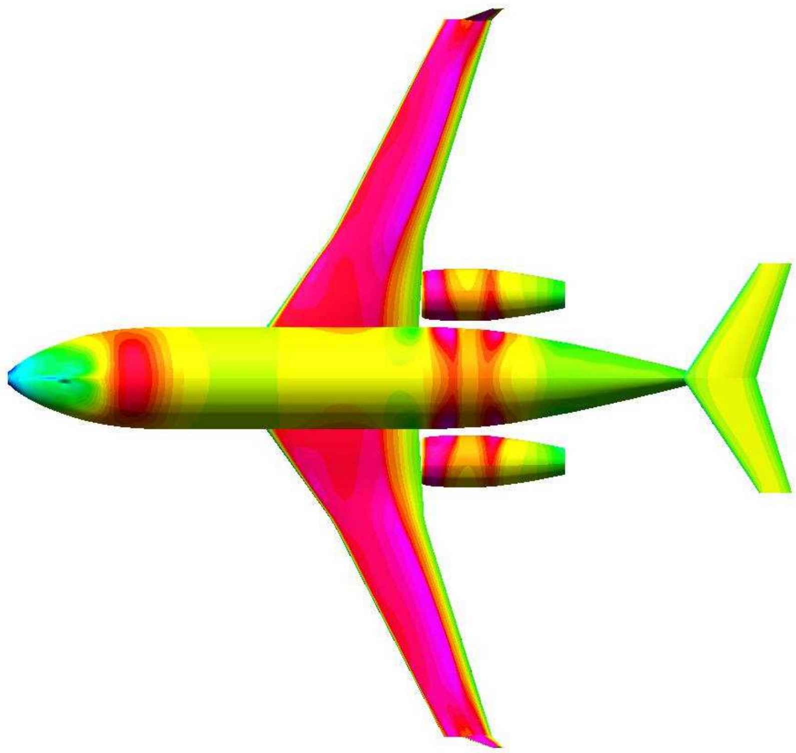


After MDO

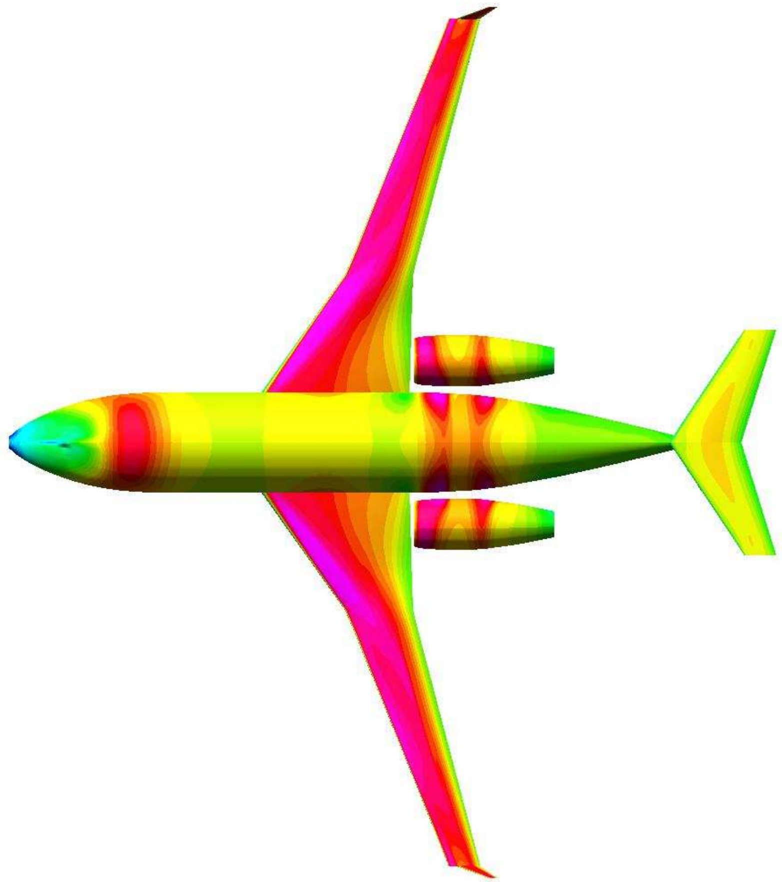
Eta=0.8

MDO Application

Aero-Structural Optimization results



Initial geometry



Optimized Geometry

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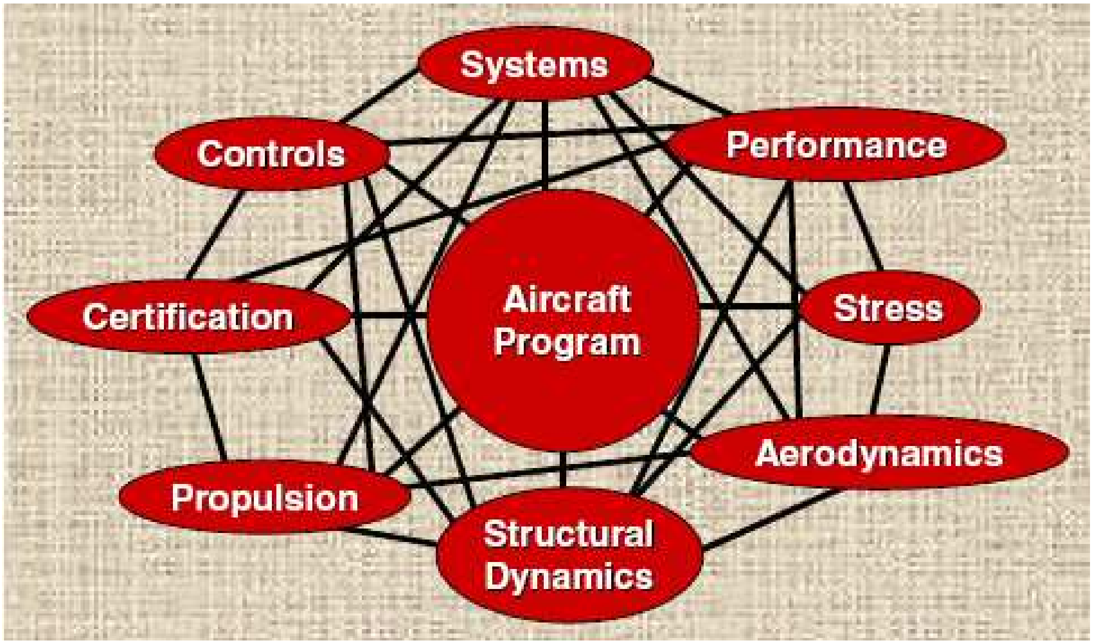
Deployment of MDO at Bombardier Aerospace



In order to further improve Bombardier's aircraft design process, MDO must begin at Conceptual Design stage, involve all key disciplines, and be an integral part of the aircraft design process until the aircraft configuration is frozen

Organizational Challenges of MDO

- The implementation of a coordinated MDO effort involving multiple engineering departments presents both technical and organizational challenges

- The organizational challenges stem from the greater level of integration required between disciplines, and the inevitable overlap in skill sets, processes and tools

- In parallel, the inherent complexity of aircraft design will continue to require a high-degree of specialization of the staff in each discipline

- The parallel requirements of integration and specialization suggest that the best approach to MDO is to form a cross-functional team consisting of members residing in the various departments

- The cross-functional MDO team should not be separate from the specialized design teams from each discipline, but rather include experienced designers from each discipline

Managing MDO Technologies

- MDO brings fundamental changes to the engineering process:
  - Utilization of higher-fidelity tools at the conceptual design stage
  - Use of process integration & optimization technologies
  - Interdisciplinary tools & processes
  - New paradigm: overlapping skill-sets & capabilities

- What MDO should NOT change
  - Clearly defined mandate & deliverables for each department:
    - Advanced Design: A/C size & concept
    - Aerodynamics: A/C aerodynamics
    - Structures / Stress: A/C structure
    - etc.

Function of each department is not defined by its tools & processes, but by its mandate & deliverables

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Aircraft Design Stages & MDO

§ Ideally, a fully developed MDO capability should employ only high-fidelity tools from all disciplines, and a fully integrated design should be accomplished early in the design cycle

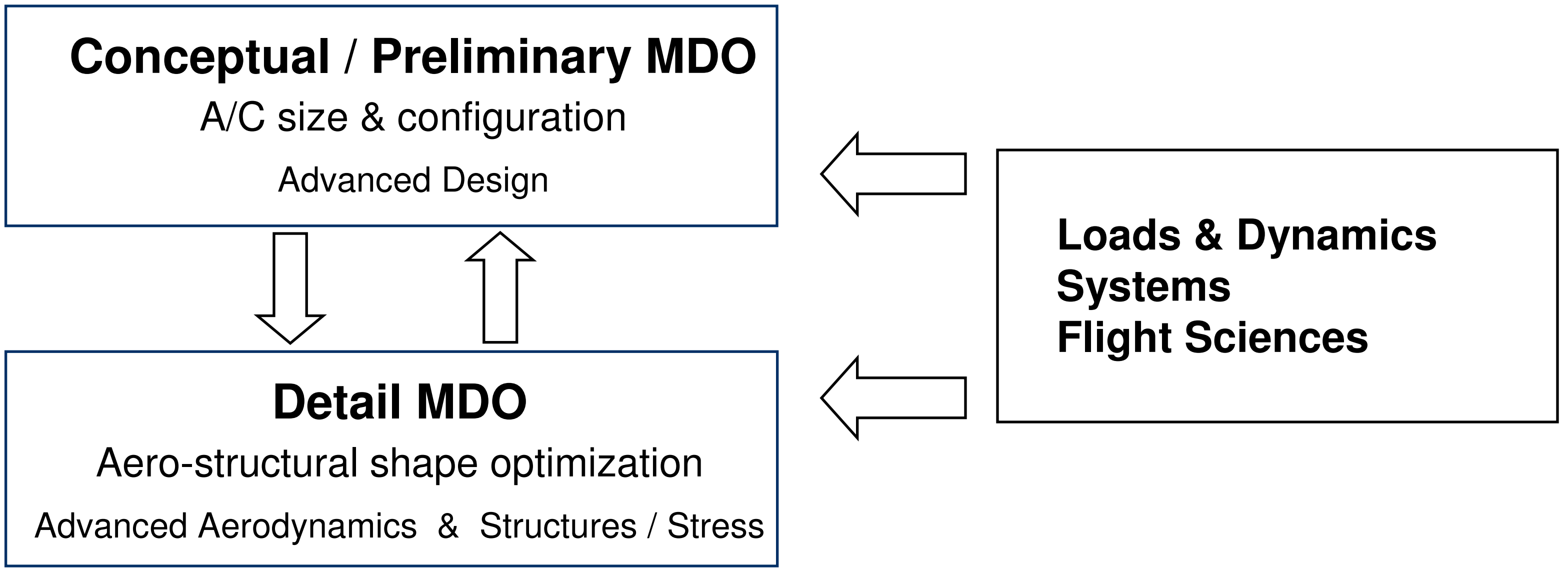
§ However, the inherent complexity of the aircraft design makes it a highly intractable problem for any single solution methodology, for a number of reasons:

- Aircraft design is an intrinsically iterative process, with little information available at the outset and an enormous amount of detail generated at the end
- Computers are very good at number crunching, but very bad at making conceptual choices/decisions based on incomplete information
- Even the most sophisticated optimization algorithms have limited capabilities when navigating a highly complex design space; manual intervention will always be required

§ Therefore there will always be a need to decompose the aircraft design problem into the conceptual / preliminary and detail design stages, and each stage will require a different type of MDO study, wherein each MDO step lays the groundwork for the next level of optimization

§ Each step in the MDO process will typically be focused primarily on one aspect of the design problem, i.e. one engineering discipline

Integrated MDO at Bombardier Aerospace



- Integrated MDO will have two-levels: Conceptual MDO & Detail MDO
- At each level, various disciplines (Loads & Dynamics, Systems, Flight Sciences etc.) will contribute the appropriate analysis modules

Conclusions

- MDO technologies are being developed at Bombardier Aerospace to enhance the aircraft design process; MDO expands the toolset available to designers

- Current capability can be used to perform constrained, aero-structural optimization of a wing

- Optimization technologies & strategies and turn-around times need to be reduced further to make MDO a more effective technology in a real aircraft design process

- Ongoing developments:

  - Implementation of 3D Navier-Stokes adjoint capability
  - Implementation of automated wing full FEM model
  - Expansion of MDO to Conceptual Design & other disciplines
  - Implementation of designer-based solution techniques in optimization
  - Enhancement of realism in aircraft definition & constraints in MDO process


Questions ?