HIGH-FIDELITY INTO PRELIMINARY AIRCRAFT DESIGNS FRAMEWORKS

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Associate Professor

4th Symposium on Collaboration in Aircraft Design (SCAD)
ONERA, Toulouse, November 25-27

Department of Mechanical Engineering

POLYTECHNIQUE MONTRÉAL

YESTERDAY'S SPEAKERS

- M. Daoud, Airbus
  - Intermediate fidelity modeling
  - 80% solution accuracy in very little wall-clock time
- Mr. Schneegans, Pace
  - Systems-based design
  - Redundancy, multi-spoilers, ice protection system

ACKNOWLEDGMENTS

- Bombardier Aerospace
- NSERC-CRSNG
- CRIAQ
- Compute Canada
- All students and collaborators

OUTLINE

- École Polytechnique at a Glance
- Research Activities
- High-Fidelity framework
- Low-Fidelity Non-Linear VLM model
  - Coupling procedures
  - 2.5D approach, transonic, high-lift and icing applications
  - Elliptic wing
  - Realistic configurations
- Expose few Canadian Financing Strategies

5 min.

UdeM – POLYTECHNIQUE – HEC CAMPUS

America’s largest French-language university campus

Canada’s 2nd-largest campus
2 640 professors

64 500 students
including 16 800 graduate students
7 900 international students

École Polytechnique

A STRONG PRESENCE IN KEY INDUSTRY SECTORS

Life sciences

Aviation

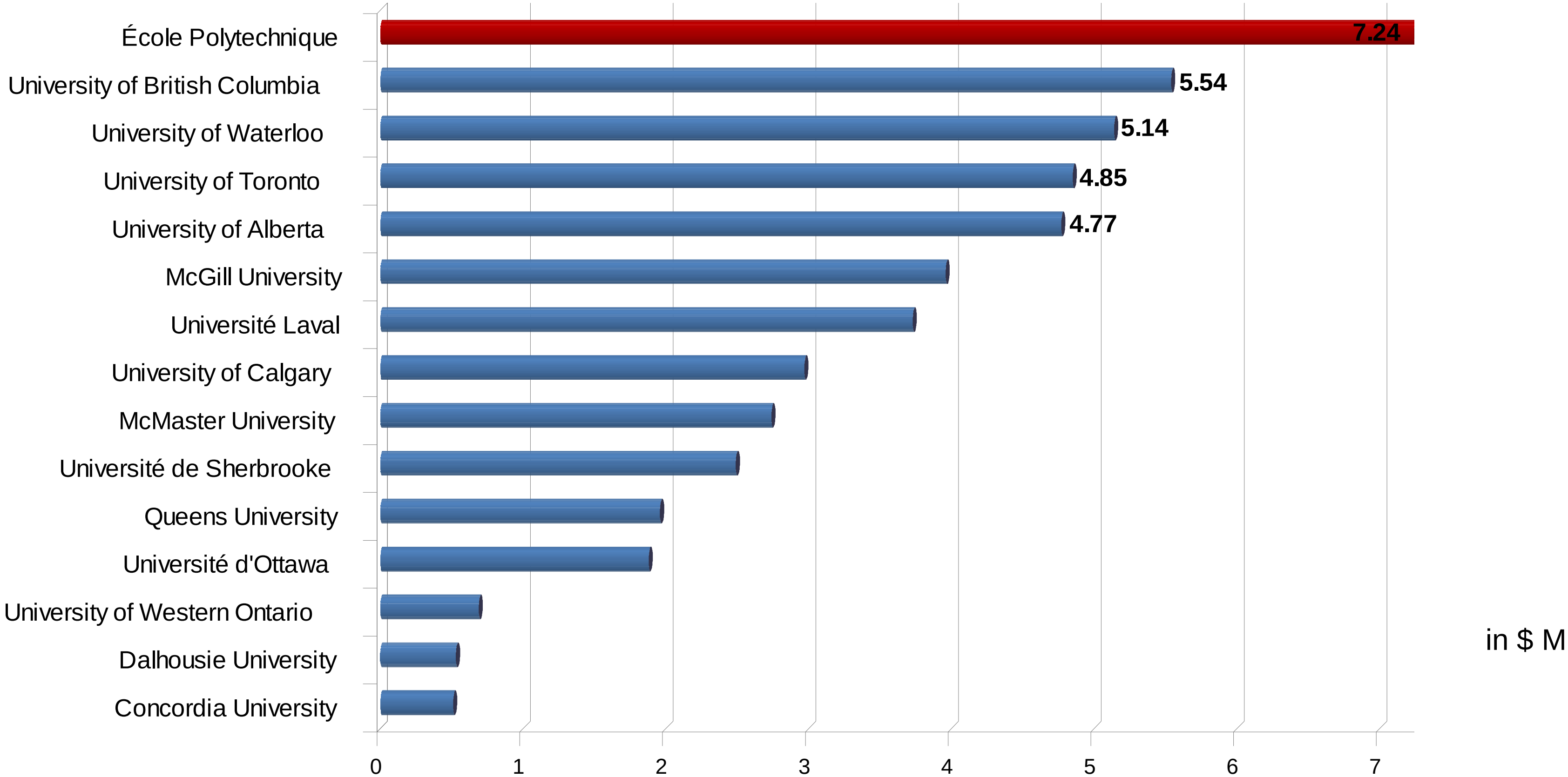
Nanotechnologies

Environment and sustainable development

Information technologies

NSERC RESEARCH GRANTS IN PARTNERSHIP WITH INDUSTRY

POLYTECHNIQUE LEADING THE PACK



Source: NSERC, 2006-2007

Undergraduate training

12 PROGRAMS

New programs

(1st in Quebec)

- **Aerospace Engineering**
- **Biomedical Engineering**

- Electrical Engineering
- Mechanical Engineering
- Geological Engineering
- Software Engineering
- Chemical Engineering
- Industrial Engineering
- Mining Engineering
- Civil Engineering
- Computer Engineering
- Engineering Physics

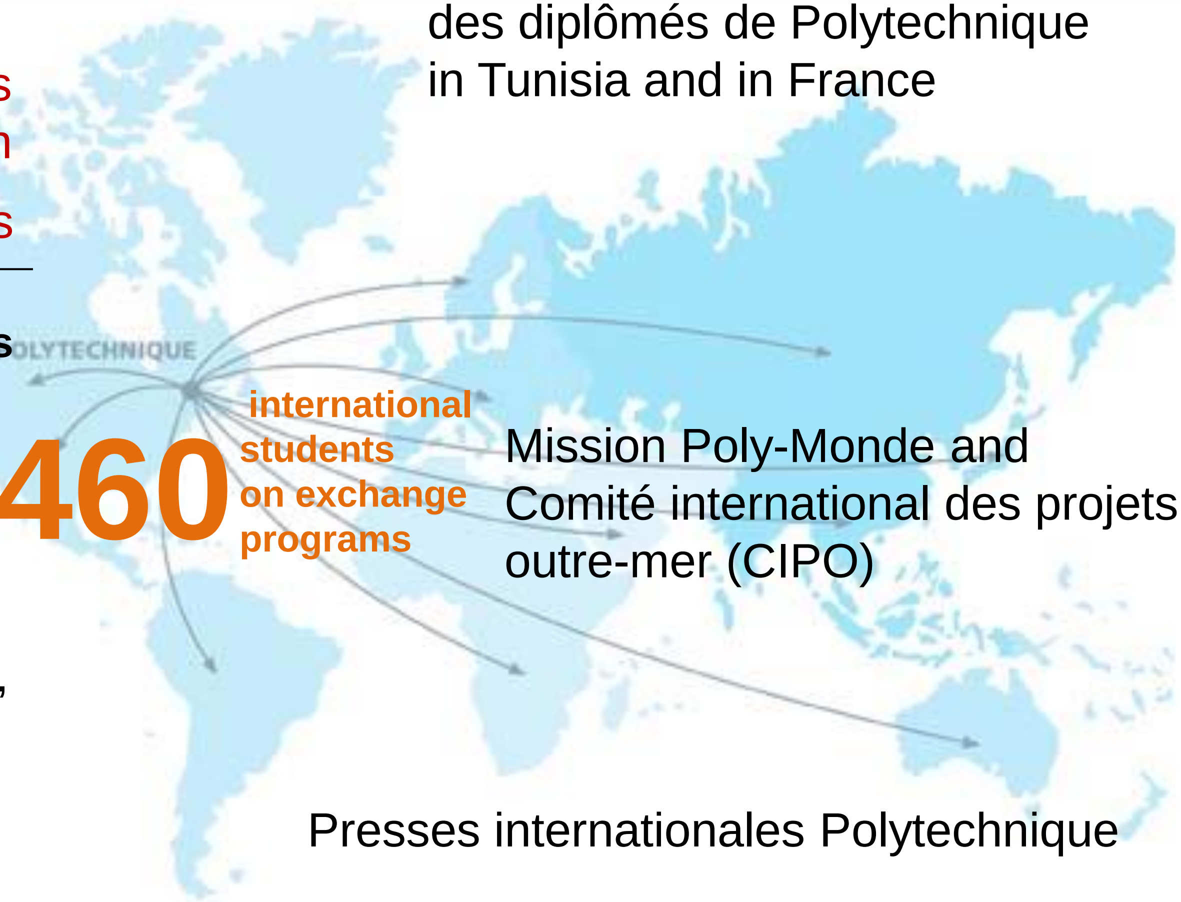
International Visibility

Bilateral exchange programs

250 agreements with institutions

15 countries

100 students on exchanges abroad



460 international students on exchange programs

Chapters of the Association des diplômés de Polytechnique in Tunisia and in France

Mission Poly-Monde and Comité international des projets outre-mer (CIPO)

Advisory role with embassies, Québec delegations, etc.

Presses internationales Polytechnique

Background: Diplomas

- B.Eng. McGill (Montreal), 1989
  - Aeronautics option
- D.E.A. Sup'Aero (Toulouse), 1990
  - Thesis: aerodynamics of three surface configuration
- Internship ENSEEIHT (Toulouse), 1991
  - Aerospatiale, Advanced Design Department
  - 100 seater jet design
- Ph.D. University of Washington (Seattle), 1995
  - Thesis: Boundary-Layer Bleed Roughness
  - Financed by Gov. of. Quebec, U.W, NASA High Speed Civil Transport

Background: Bombardier Aerospace

- Bombardier Aerospace, 1996-2011
  - Advanced Aerodynamics
    - Lecturer Polytechnique Montreal (Aerodynamics)
    - CFD flow solvers, High Performance Computing
    - Boundary-Layer, transition
    - Aircraft aerodynamics
    - Book (Springer, 2005 with Cebeci, Kafyeke and Shao)
    - Head, Aerodynamic Research (ˈ05)
      - Icing, High-Lift, High-Speed, CAD, grid generation, Multi-Disciplinary Optimization
      - 7 aircraft programs: *CRJ700, CRJ900, CRJ1000, Challenger 300, Lear85, Série-C, Global 7/8000*

  - Strategic Technologies
    - Core Engineering R&D Portfolio
    - I.P.
    - University relations (including governance)
    - Boards/Committee: CFDSC president (2010-12)

Background: Responsibilities

- Polytechnique Montreal, since 2011
  - Associate Professor
  - Acting Director, Aerospace Engineering program
  - Thermodynamics, Aerodynamics, Projects (3rd, 4th year)

- Committees
  - Member, Compute Canada, Inaugural Advisory Committee on Research, Oct. 2013-2016 (Canadian Supercomputing)
  - Member, Aero-Montreal, Innovation Working group, Sept. 2012-now (Montreal Aerospace Cluster)
  - Scientific Committee, International Conference on High Performance Computing & Simulation HPCS 2015

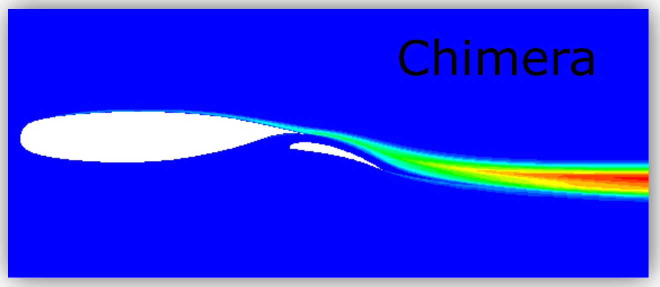
AREAS OF RESEARCH

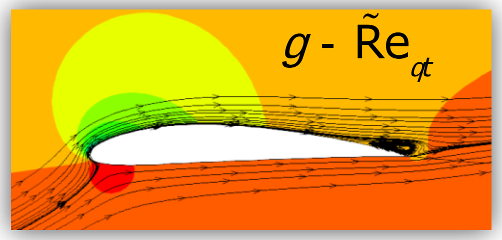
- High-Fidelity aerodynamic modeling
  - Chimera solvers, URANS (dual time-stepping, Non-Linear Frequency Domain), Turbulence modelling, FSI
  - Aero-Icing/Anti-Icing
  - Far-Field Drag predictions
  - Flow control: Laminar airfoil design (morphing, plasma)
  - Mesh Generation (out-of-CAD, in-CAD)
  - Frameworks
    - 3D NSMB (CFS Engineering, 7 European Universities)
    - 2D NSCODE (Ecole Polytechnique)
    - 3D/2D FANSC (Bombardier Aerospace)
    - CANICE (Polytechnique/Bombardier)
    - ANSYS, ICEM, Python, C, C++, Fortran 90/2003, OPEN-MP, MPI
- Low-Fidelity
  - Viscous-Inviscid coupling via Non-Linear VLM
    - 2D and 2.5D RANS models

INTRODUCTION TO NSCODE

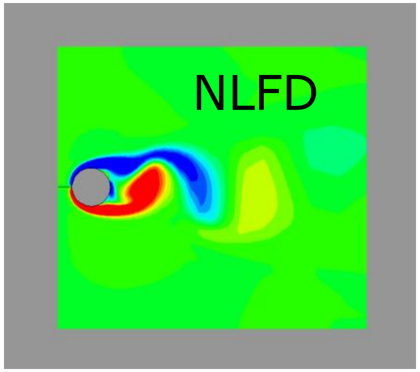
Platform for CFD research, developed at Ecole Polytechnique Montreal

- External Flows
- Mesh generation

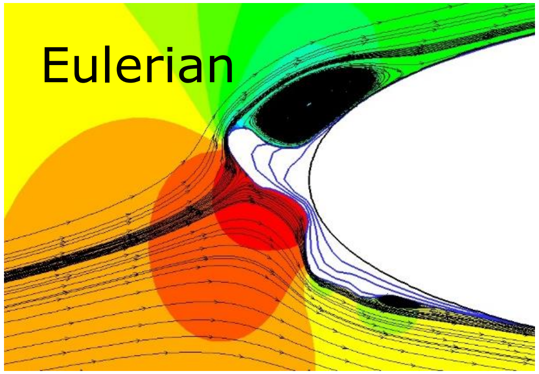




- Turbulence Modeling



- Steady/Unsteady Flows



- Ice Accretion

TRANSITIONAL RANS: MULTI-ELEMENT VALIDATION

MDA 30N-30P

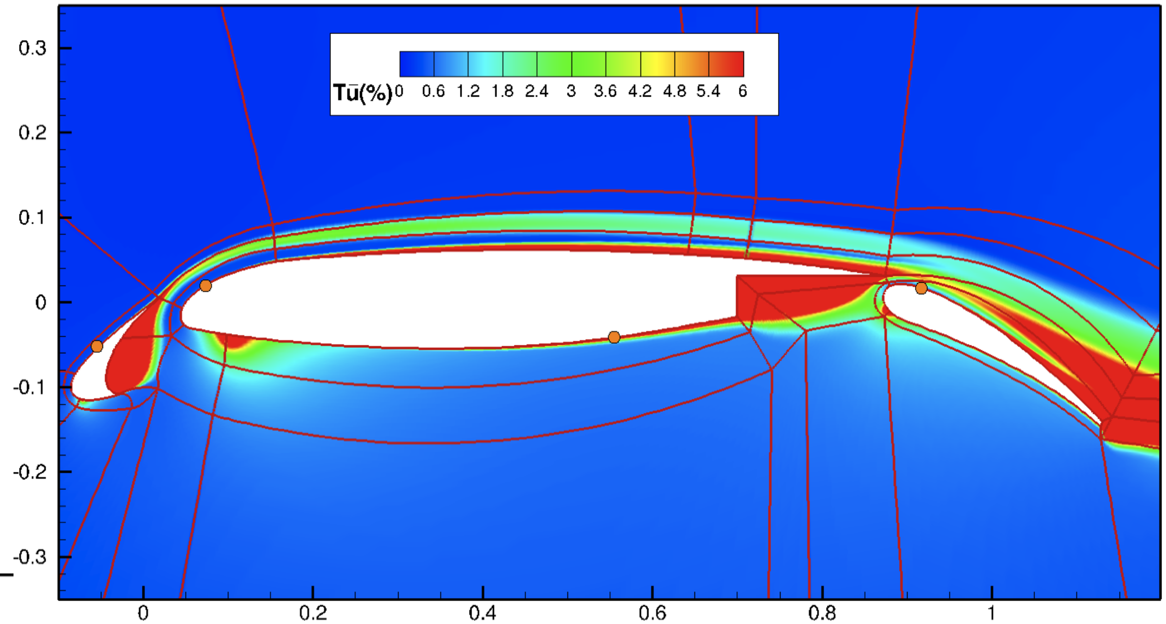
Re = 9´ 10^6

a = 8°

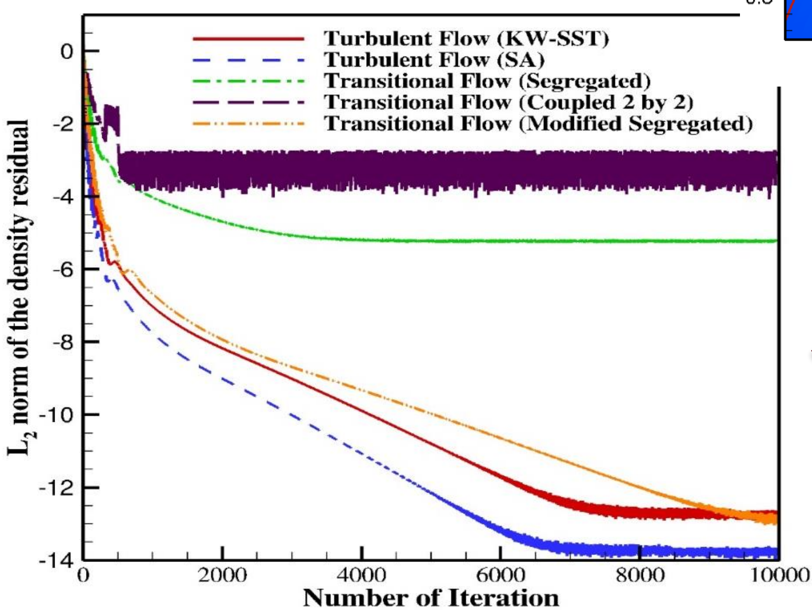
M = 0.2

$TI_{¥}$ = 0.25%

b = 10



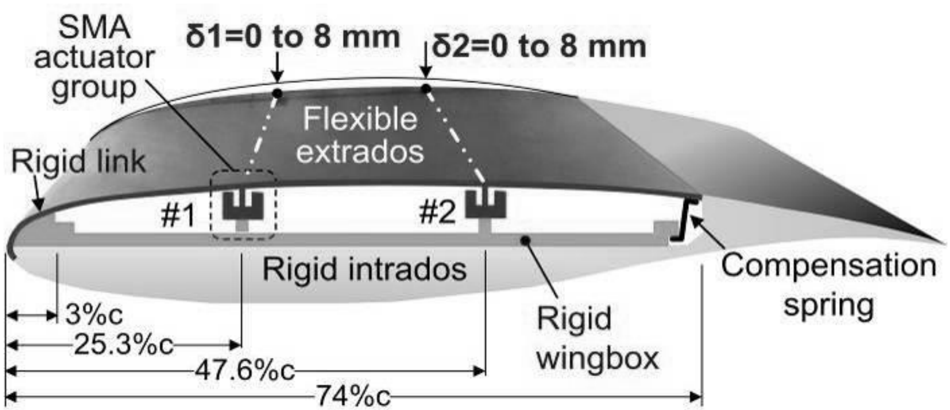
Turbulence Intensity Contour
(Transition Locations are indicated by circles)

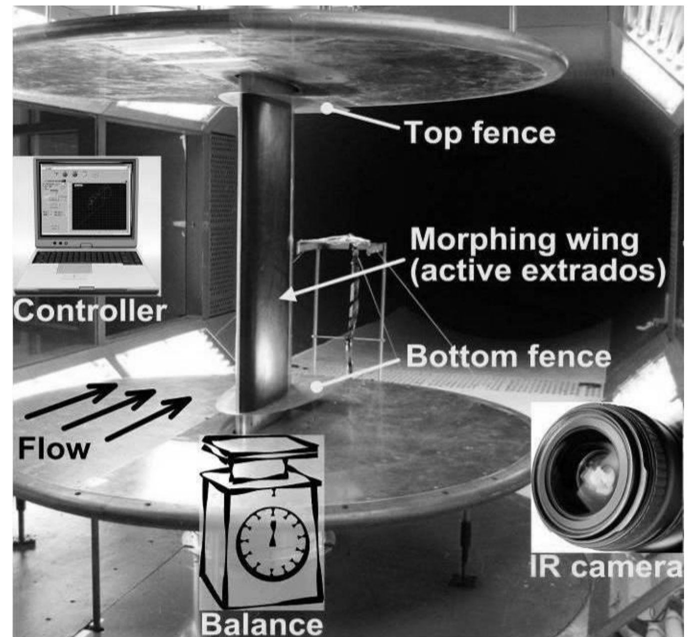


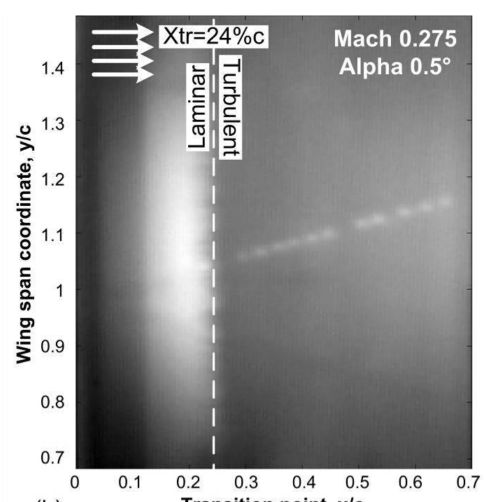
Machine-Level Convergence is achieved through Introduction of a modified segregated approach

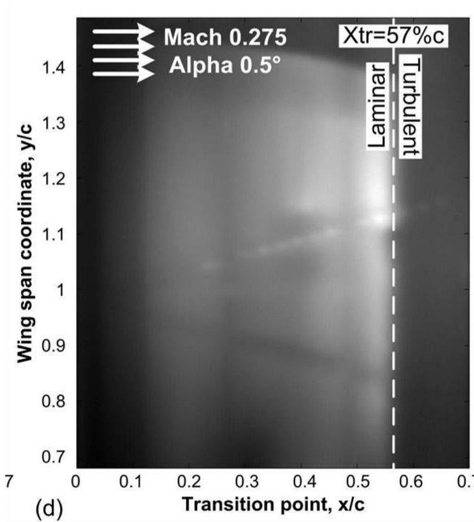
CONTROL: LAMINAR FLOW

- NSERC/CRIAQ/Bombardier/Alenia/ETS/Polytechnique/U. Naples









Improving airfoil aerodynamics by plasma actuation

With Prof. Vo and Mureithi (polytechnique), Sengupta (IIT Kampur)

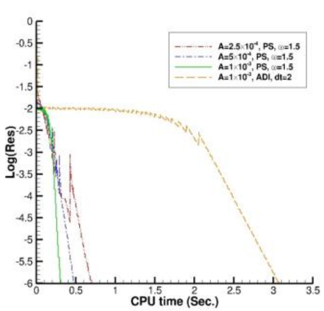
CRIAQ
NSERC CRSNG
BOMBARDIER
the evolution of mobility
POLYTECHNIQUE MONTRÉAL

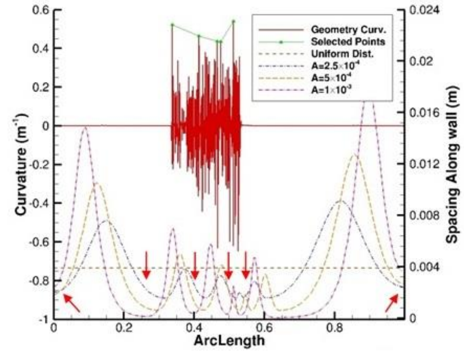
AERO-ICING

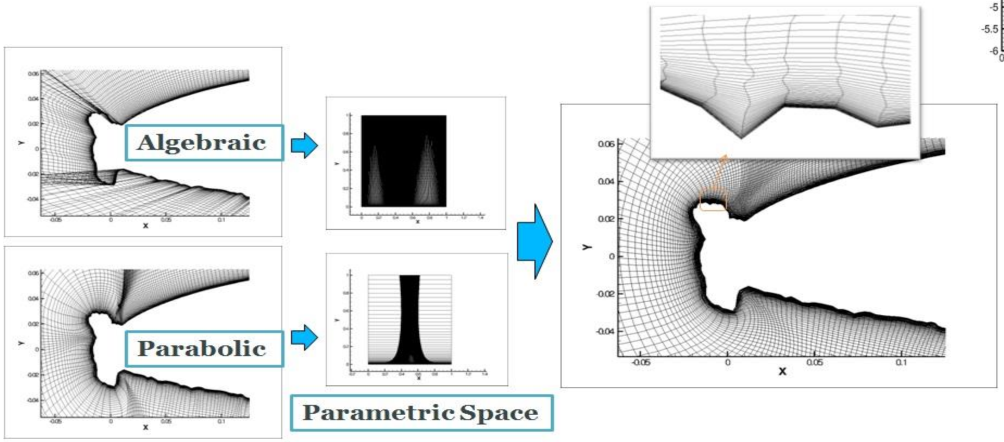
- NSERC/Bombardier/Polytechnique
  - Development of CANICE 2D/3D framework (since 1990's)
    - Methods used for certification by Transport Canada
    - Used for ice shape predictions, including water runback
    - Used for contaminated aerodynamic simulations
  - Development of NSCODE 2D framework
    - NSCODE/NSGRID/NSDROP/Implicit Thermodynamic
    - Multi-step calculations up to 160 layers
  - Lagrangian and Eulerian approaches, panel and NS solvers

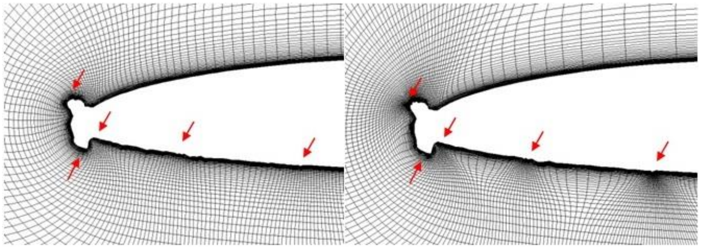
MESH GENERATION FOR ICE ACCRETION

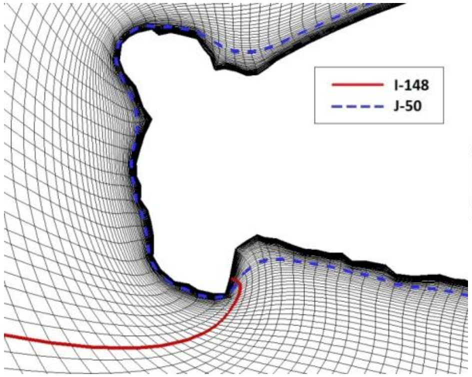
- **NSGRID2D**
  - NFL0414 ice 623
  - PDE Curv. based point dist.
  - Grid: RLS-SPS-Para

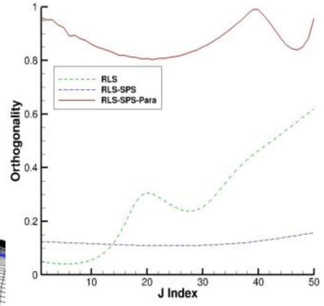




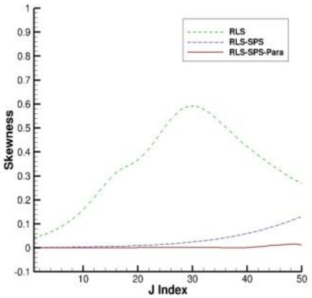




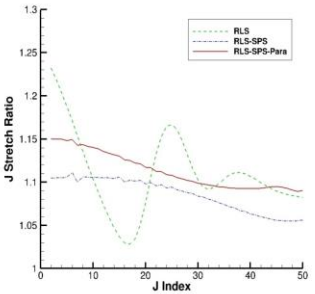




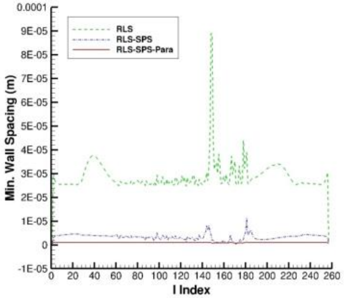
orthogonality



skewness



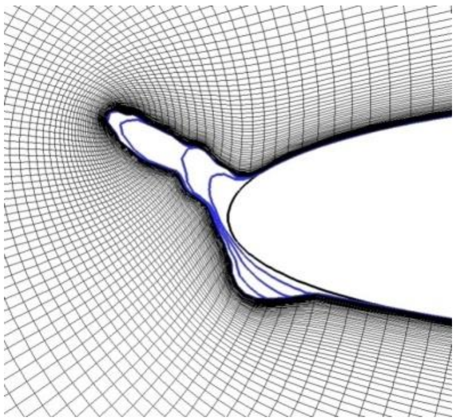
stretching



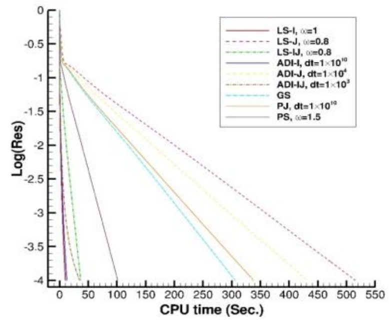
curvature

EULERIAN NSCODE FRAMEWORK (GLAZE)

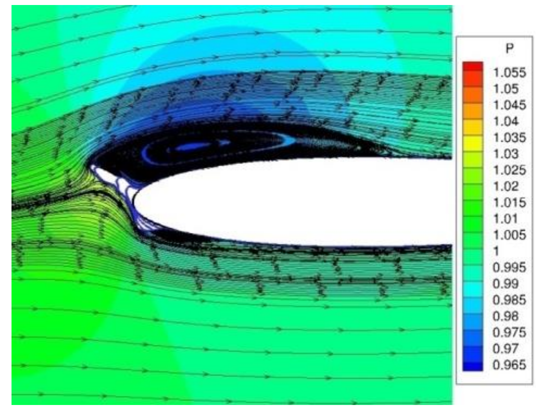
- **CANICE2D-NS (NSCODE2D/NSGRID2D)**
  - NATO C17, Intel I7-3900K 4-core



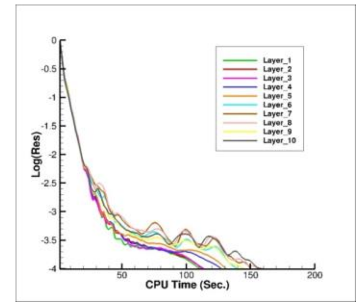
NSGRID2D



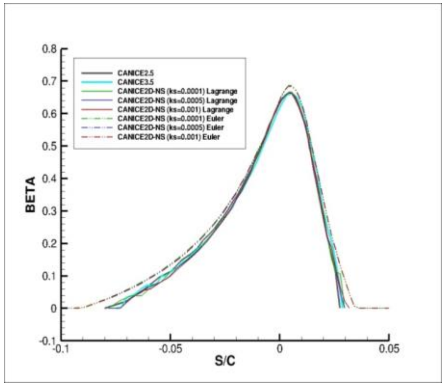
10 sec.



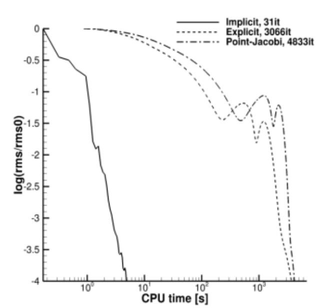
NSCODE2D



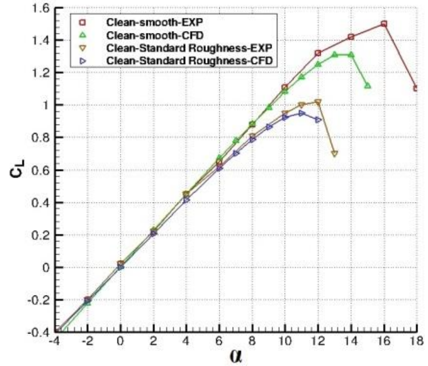
1 min.



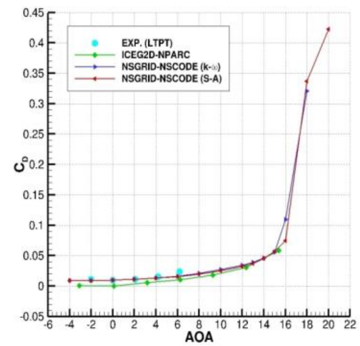
NSDROP2D



5 sec.



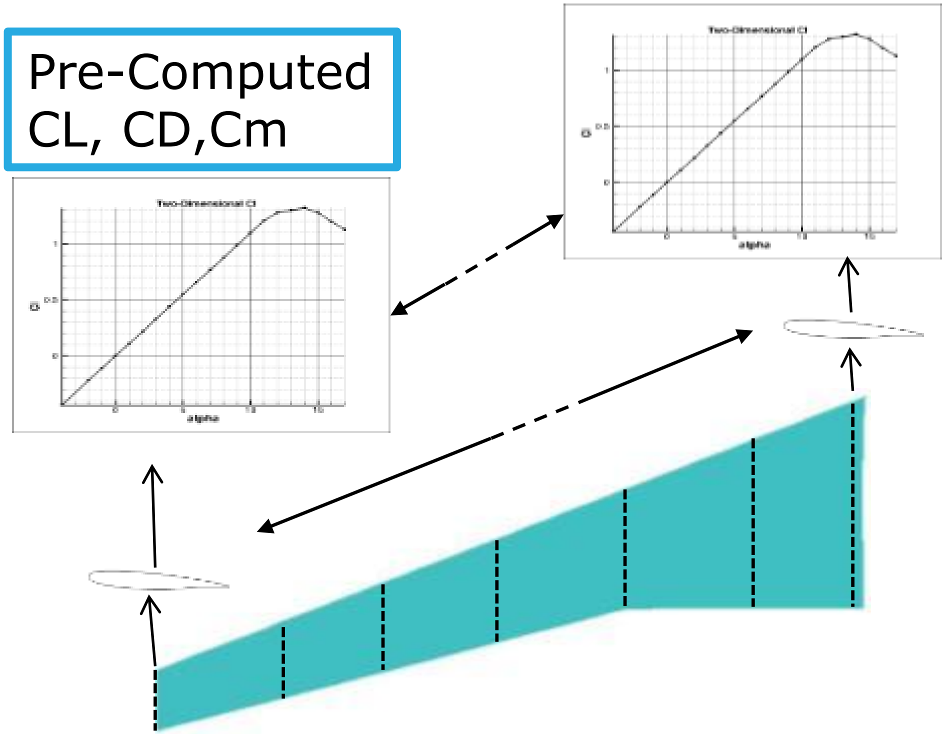
LIFT



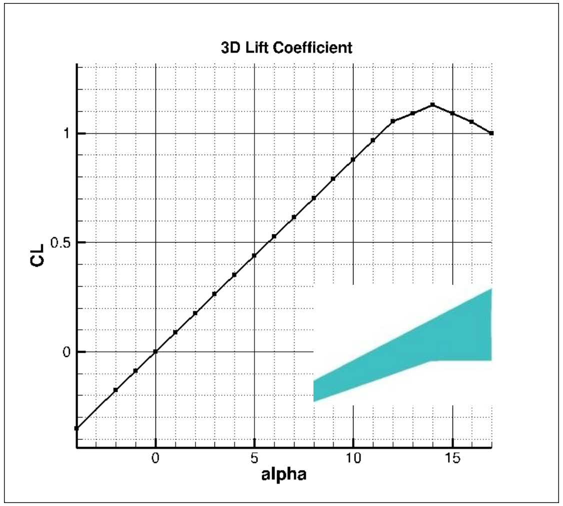
DRAG

NON-LINEAR COUPLING OVERVIEW

Pre-Computed
CL, CD,Cm



Iterative
Method



2D sectional properties
(includes high-lift devices)

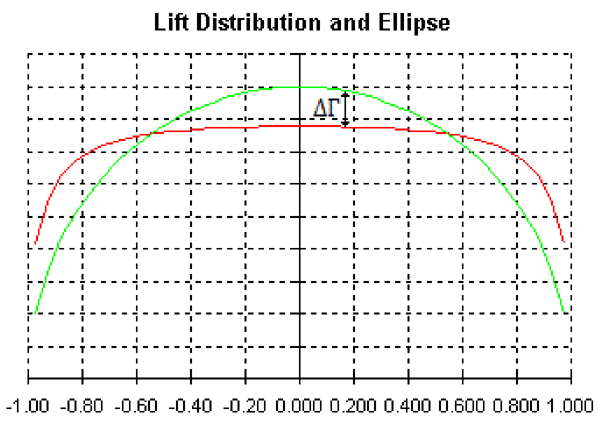
3D wing properties

Gallay, S., Ghasemi, S., Laurendeau, E., “Sweep effects on non-linear Lifting Line Theory near Stall”, AIAA Scitech, 52nd Aerospace Sciences Meeting, 13-17 January 2014, National Harbor, Maryland, AIAA 2014-0913, DOI: 10.2514/62014-0913

COUPLING: Γ-METHOD VS. α-METHOD

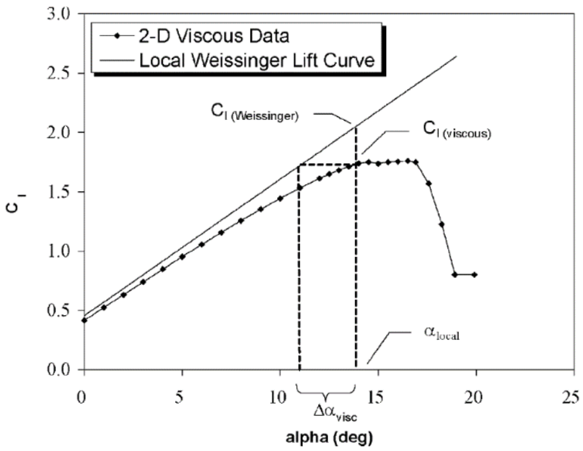
Γ-Method (Chattot):

- Correction of the lift distribution Γ
- Non uniqueness of the solution
- Require low relaxation



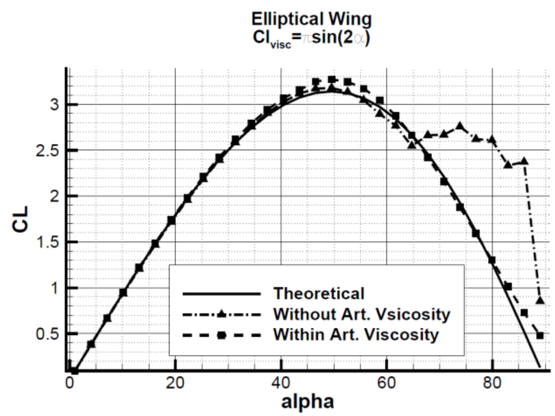
ɑ-Method (Van Dam):

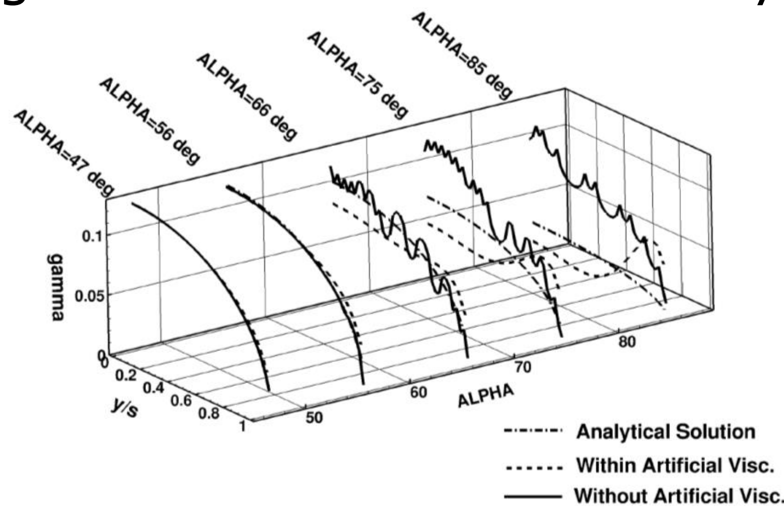
- Correction of the angle of attack
- Uniqueness of the solution
- Doesn't require relaxation



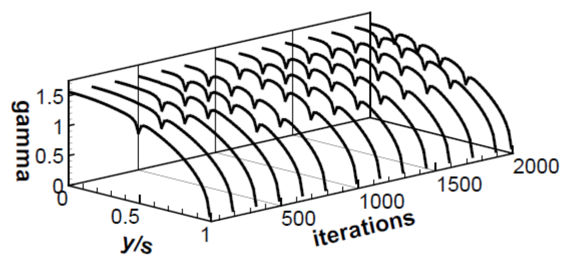
2D NS/3D VLM COUPLING (NO SWEEP)

- Loosely vs. Strongly Coupled Algorithms & Artificial Viscosity

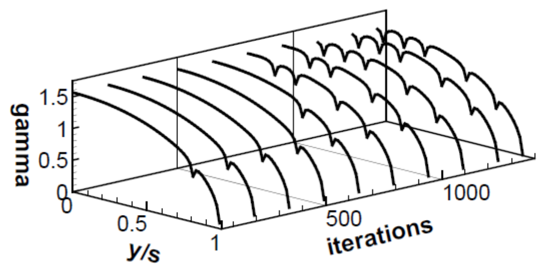




- Stability of the solution: pre/post Stall flows
- Stall Pattern



Perturbation at y=0.5s



Perturbation at y=0.75s

Similar to Spalart, private communication

2.5D COUPLING (SWEEP)

VLM/2D coupling is reported as ineffective for transonic flows

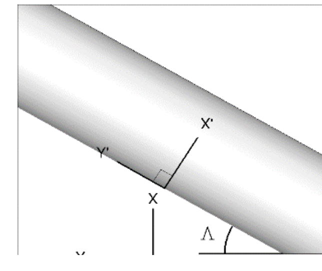
3D RANS equations

$$\vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\vec{\nabla} \cdot (\rho \vec{v} \times \vec{v}) = \vec{\nabla} P + \vec{\nabla} \cdot \bar{\bar{\tau}}$$

$$\vec{\nabla} \cdot \left((\rho e + P) \vec{v} \right) = \vec{\nabla} \cdot (\bar{\bar{\tau}} \cdot \vec{v})$$

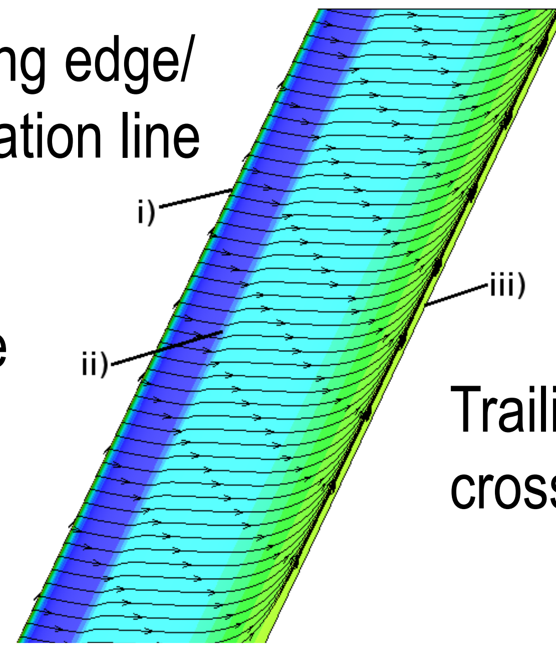
Standard and modified coordinate system



Leading edge/ stagnation line

Shock-wave R-H jump

Trailing edge cross-flow BL



Infinite sweep wing general assumption

$$\frac{\partial(*)}{\partial y'} = 0$$

Ghasemi, S., Mosahebi, A., Laurendeau, E., “A Two-Dimensional/Infinite Swept Wing Navier- Stokes Solver”, AIAA Scitech,52nd Aerospace Sciences Meeting, 13-17 January 2014, National Harbor, Maryland, AIAA 2014-0557.

EQUATIONS-SIMPLIFIED

$$\frac{(\partial \rho u')}{\partial x'} + \frac{(\partial \rho w')}{\partial z'} = 0$$

$$\frac{\partial(\rho u'^2)}{\partial x'} + \frac{\partial(\rho u' w')}{\partial z'} = \frac{-\partial P}{\partial x'} + \left[\frac{\partial}{\partial x'}(\tau xx) + \frac{\partial}{\partial z'}(\tau xz)\right]$$

$$\frac{\partial(\rho u' w')}{\partial x'} + \frac{\partial(\rho w'^2)}{\partial z'} = \frac{-\partial P}{\partial z'} + \left[\frac{\partial}{\partial x'}(\tau zx) + \frac{\partial}{\partial z'}(\tau zz)\right]$$

Decoupled 2D equation

$$\frac{\partial(\rho u' v')}{\partial x'} + \frac{\partial(\rho w' v')}{\partial z'} = \left[\frac{\partial}{\partial x'}(\tau yx) + \frac{\partial}{\partial z'}(\tau yz)\right]$$

Cross flow equation

$$\frac{\partial}{\partial x'}((\rho e + P)u') + \frac{\partial}{\partial z'}((\rho e + P)w') =$$
$$\frac{\partial}{\partial x'}(u'\,\tau xx + v'\,\tau xy + w'\,\tau xz) + \frac{\partial}{\partial z'}(u'\,\tau xz + v'\,\tau yz + w'\,\tau zz)$$

Coupled 3D equation

S-A turbulent model is unchanged (later comes out as good hypothesis!)

IMPLEMENTATION-CROSS FLOW SOLVER

Similarity with Spalart-Almaras turbulent equation

$$\frac{\partial(\rho v')}{\partial t}+\frac{\partial(\rho u' v')}{\partial x'}+\frac{\partial(\rho w' v')}{\partial z'}=\left[\frac{\partial}{\partial x'}\left(\mu\frac{\partial v'}{\partial x'}\right)+\frac{\partial}{\partial z'}\left(\mu\frac{\partial v'}{\partial z'}\right)\right]$$

Cross flow equation

$$\frac{\partial(\rho\hat{\upsilon})}{\partial t}+\frac{\partial(\rho u'\hat{\upsilon})}{\partial x'}+\frac{\partial(\rho w'\hat{\upsilon})}{\partial z'}=c_{b1}(1-f_{t2})\hat{S}\hat{\upsilon}-\left[c_{w1}f_w-\frac{c_{b1}}{\kappa^2}f_{t2}\right]\left(\frac{\hat{\upsilon}}{d}\right)^2+\frac{1}{\sigma}\left[\frac{\partial}{\partial x'}\left([\mu+\hat{\mu}]\frac{\partial\hat{\upsilon}}{\partial x'}\right)+\frac{\partial}{\partial z'}\left([\mu+\hat{\mu}]\frac{\partial\hat{\upsilon}}{\partial z'}\right)\right]+\frac{1}{\sigma}c_{b2}\left[\frac{\partial(\hat{\upsilon})}{\partial x_i'}\frac{\partial(\hat{\upsilon})}{\partial x_i'}\right]$$

S-A equation

- Similar equation after simplification
- Similar method of resolution can be used
  - ADI implicit solver -> fast
  - Loosely coupled;
  - simple multigrid treatment (only restriction)
  - Can be implemented in any 2D code

IMPLEMENTATION-STEPS REQUIRED

Step 1: Adjustment of 2D section airfoil

$x' = x \cdot \cos(\Lambda)$ Only in X direction

Step 2: Adjustment of boundary conditions

$$U'_\infty = U_\infty \cdot \cos(\alpha) \cdot \cos(\Lambda)$$
$$W'_\infty = U_\infty \cdot \sin(\alpha)$$

Original 2D variable

$$V'_\infty = U_\infty \cdot \cos(\alpha) \cdot \sin(\Lambda)$$

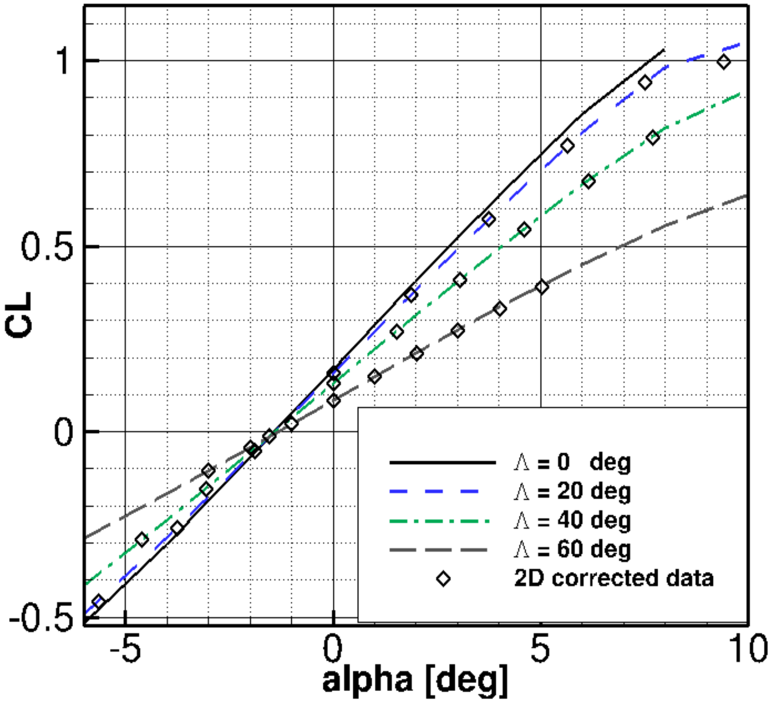
Cross flow

Step 3: Adjustment of aerodynamic forces

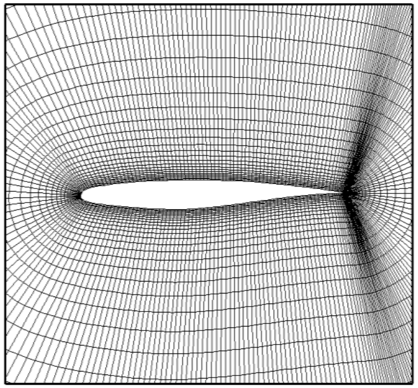
$$Cl = (-Cx' \times \sin(\alpha)\cos(\Lambda) + Cz' \times \cos(\alpha) - Cy' \times \sin(\alpha)\sin(\Lambda)) / \cos(\Lambda)$$
$$Cd = (Cx' \times \cos(\alpha)\cos(\Lambda) + Cz' \times \sin(\alpha) + Cy' \times \cos(\alpha)\sin(\Lambda)) / \cos(\Lambda)$$

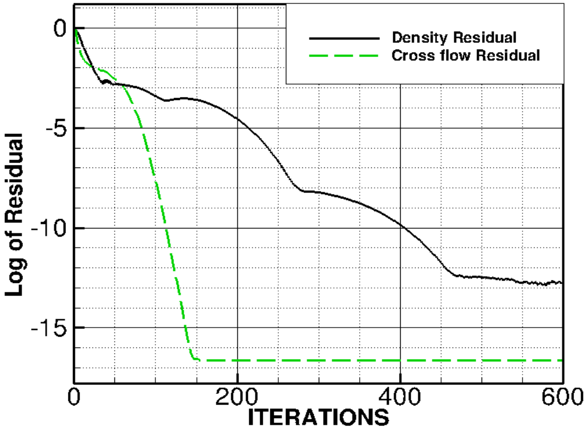
RESULT- INVISCID CASE : LOVELL SECTION AIRFOIL/ M0.22

$$Cl_{\propto,3D} = Cl_{\propto,2D} \times cos^2(\lambda)$$ ← Kuchemann sweep correction

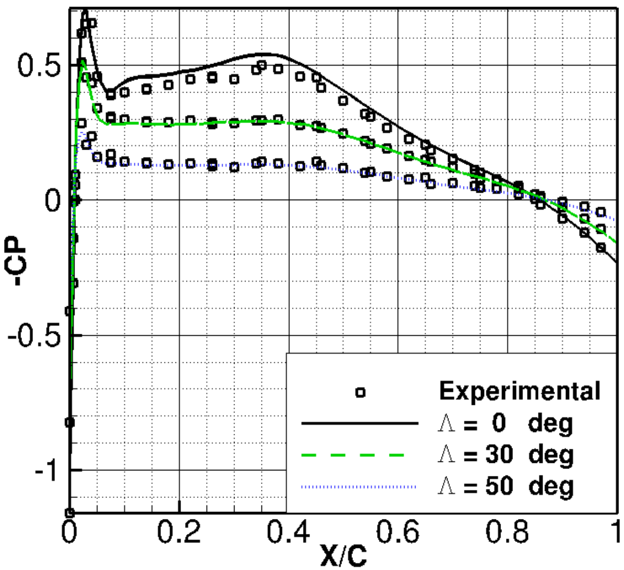


257X65
mesh





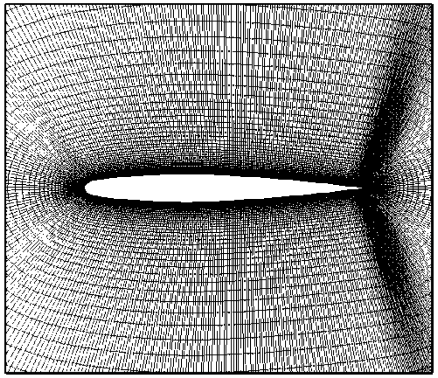
RESULT- VISCOUS FLOWS: EXPERIMENTAL DATA ON ONERA-D WING



*Experimental data from AGARD AR-138 report, Section B-2

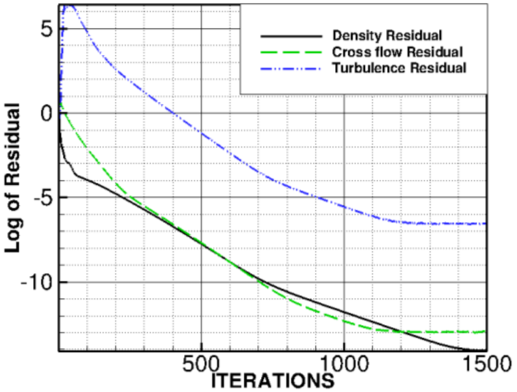
<u>Experimental</u>

- Simulations at $\alpha = 0^o$
- $\Lambda = 0^o, 30^o, 50^o$
- Untapered wing
- CP extracted at $\frac{y}{b}$ = 0.6
- M0.78/ Re 2.5e6

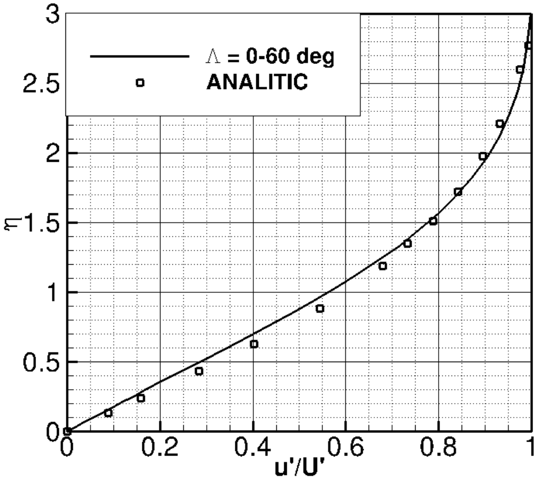


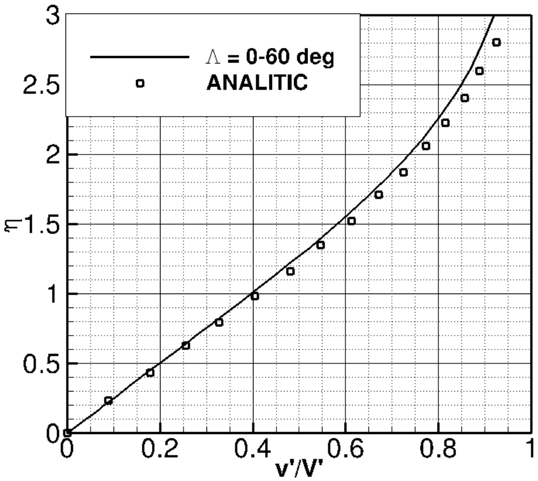
<u>Proposed method</u>

- 513X129 mesh
- First cell spacing 10e-6
- 4 level multigrid
- CP extracted at $\frac{y}{b}$ = 0.6



RESULT- ANALYTICAL SOLUTION OF YAWED CYLINDER

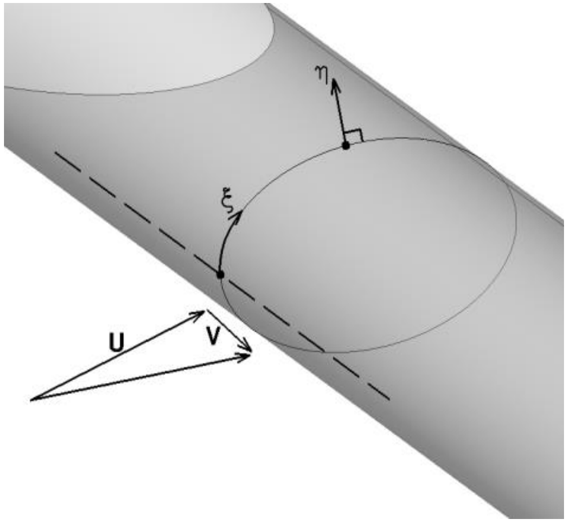


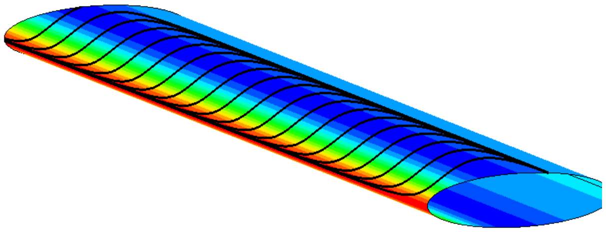


*Analytical data from Sears, W R. 1948

- Mach 0.2
- $Re_{\perp LE} = 100$
- $\xi = 0.5\ (90\ deg.)$

Coordinate system

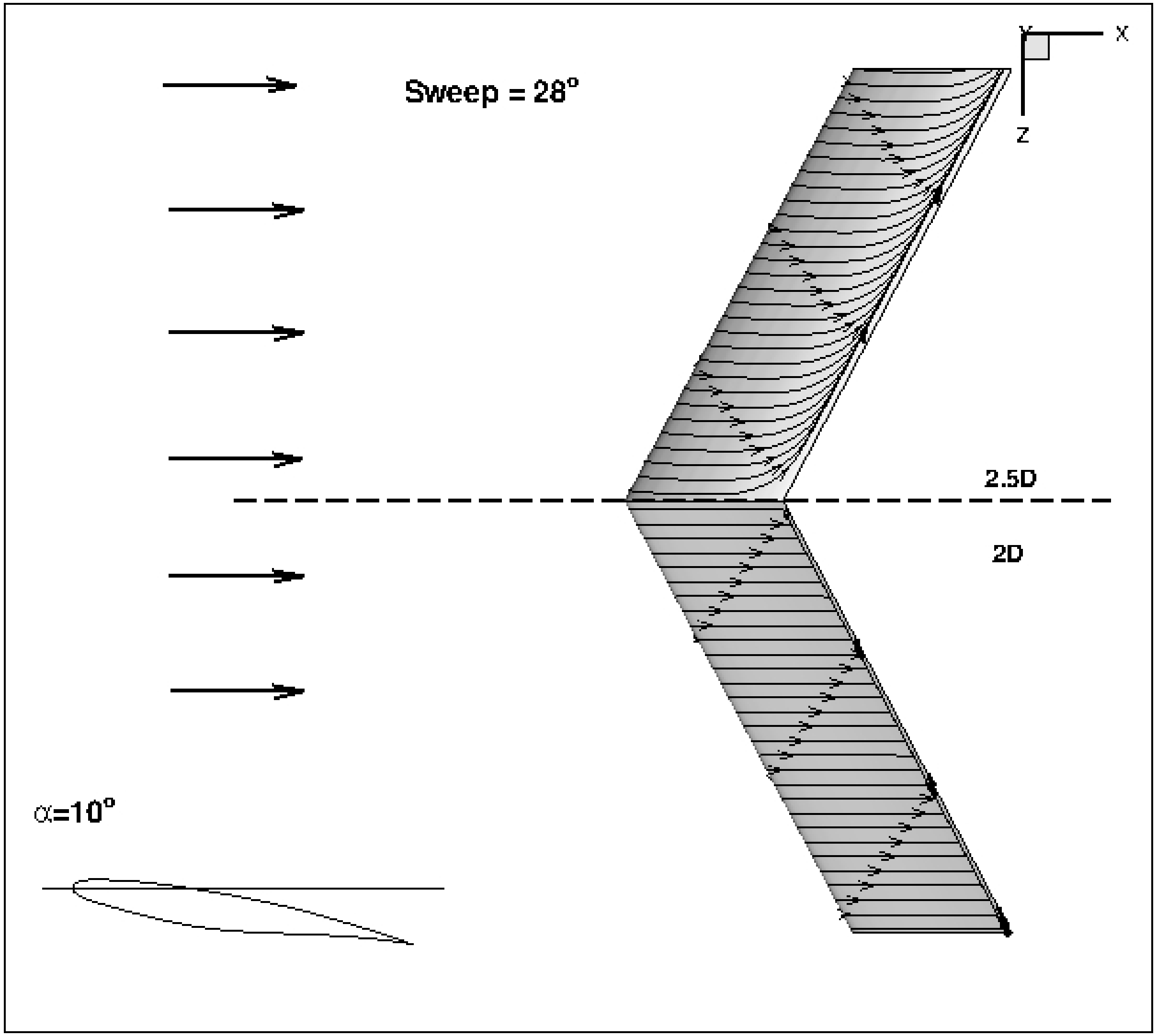




Streamline

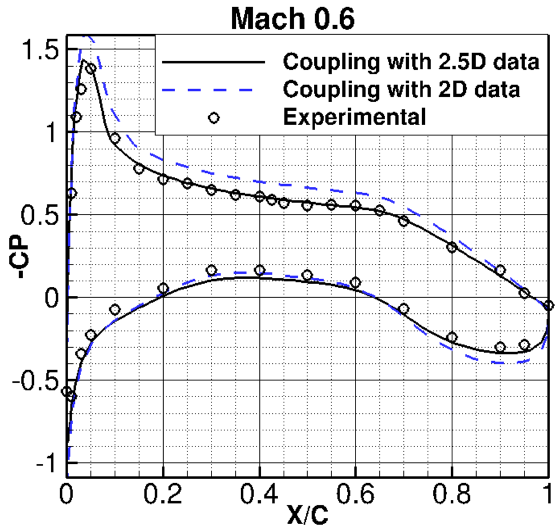
- Falkner-Skan-Cooke transformations

RESULT- SKIN-FRICTION LINES ON LOVELL AIRFOIL

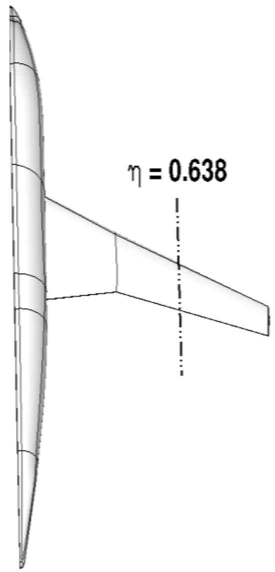


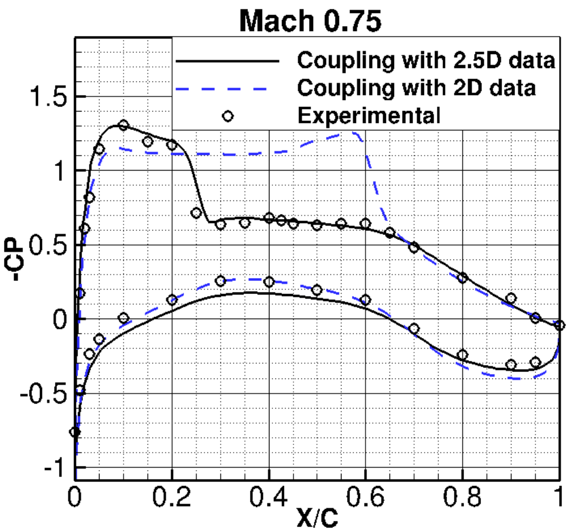
Note:
Extruded
2.5D
solutions

RESULTS-3D VALIDATION WITH DLRF4 WING OF THE 1ST AIAA DRAG WORKSHOP



- 3D effect capture by using Non-Linear Vortex Lattice Method (Van Dam, 2000)
- CP compared at $\eta = 0.638$
- Aircraft $C_L = 0.5$
  - $\alpha = 0.62^o$ for M0.6
  - $\alpha = 0.2^o$ for M0.75
- 2D results obtained at same α than 2.5D results





Advantage

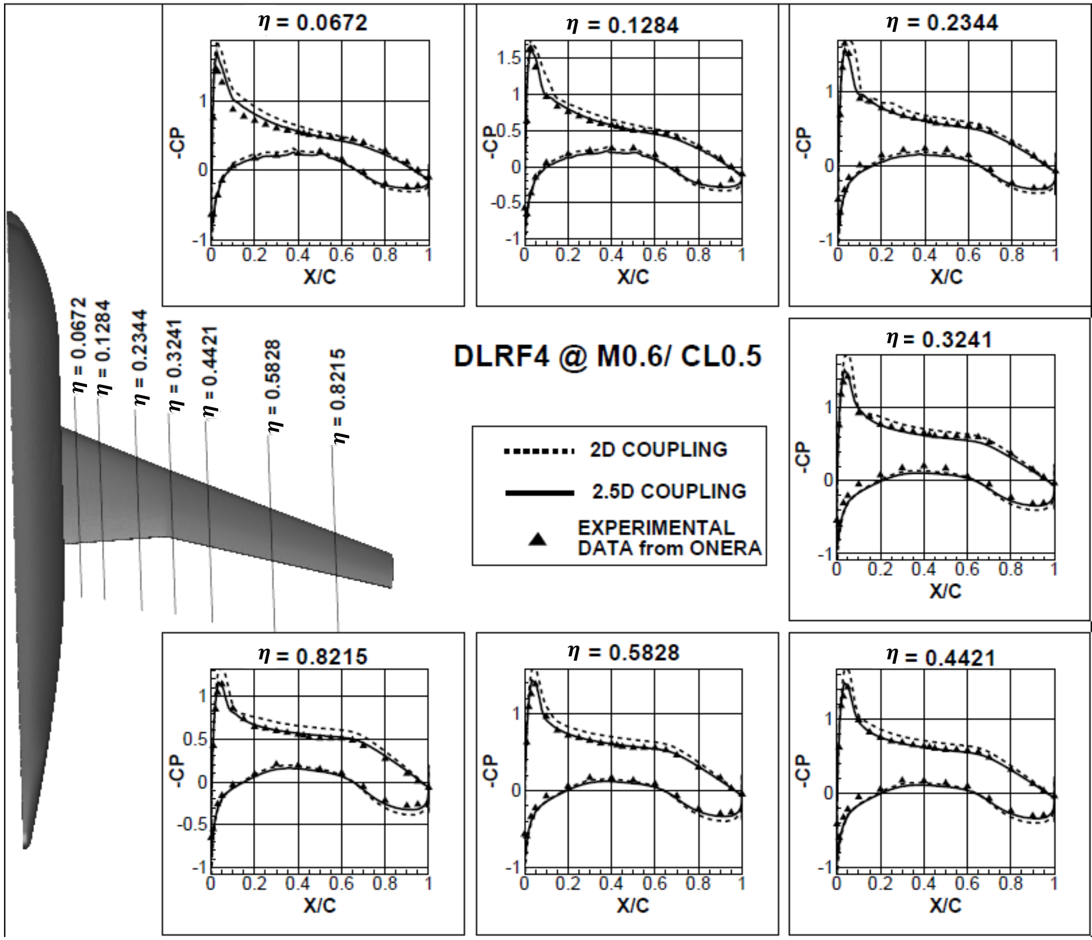
- 2D data overestimates lift
- Position of shock wave well captured
- Lower cove region effect well captured
- 2D Turbulence model adequate!

VALIDATION CASE: DLR-F4, TRANSONIC

- DPW1 Case
- Re= 5,0 Million, Mach=0,75
- Wing Body Configuration
- 9 sections on the wing
- Root correction (symmetry effects)

AIAA DPW1: DLR-F4, M=0,6, RE=5 M

- Using loosely coupling algorithm (2D/2,5D data):
  - Effective angle of attack calculated matching CL=0,5
- Pressure Coefficients calculated at these specific angles of attack

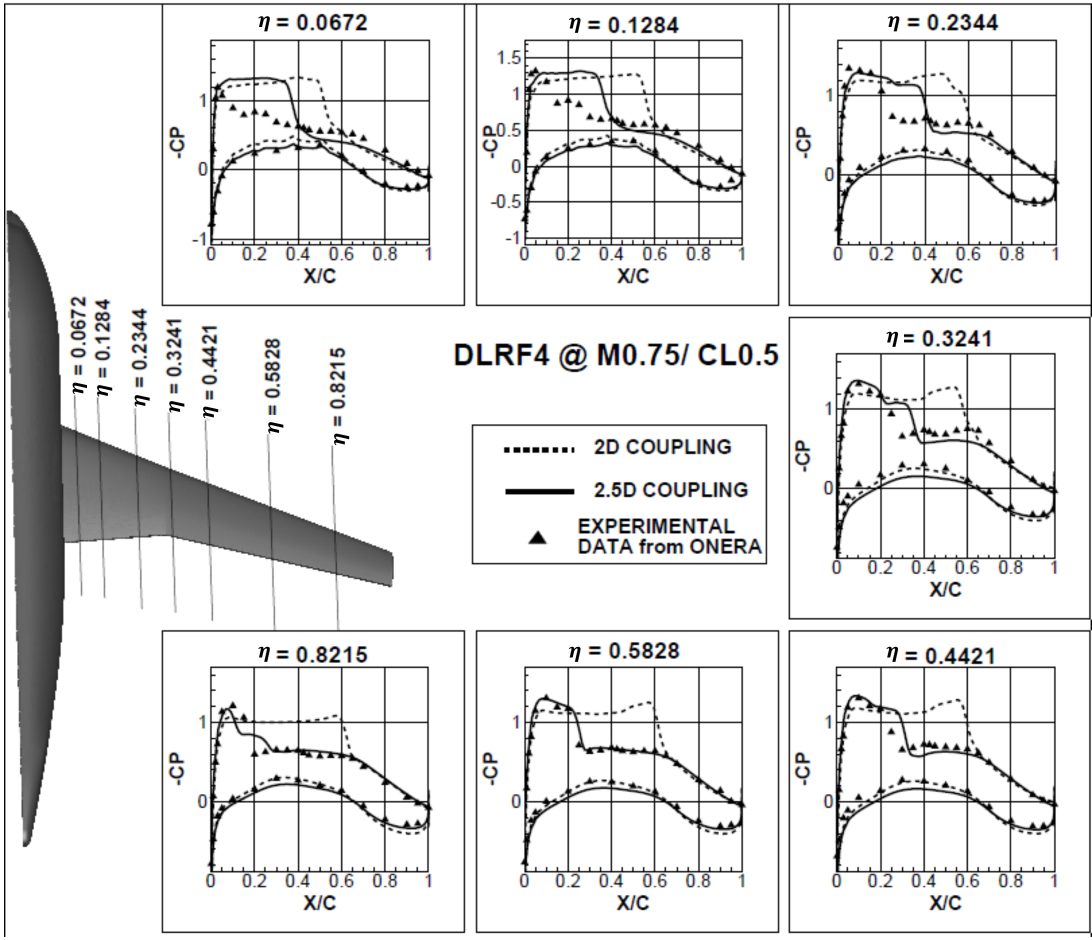


2,5 data improve the prediction of the Pressure Coefficients at CL=0,5

AIAA DPW1: DLR-F4, M=0,75, RE=5 M

2,5 data improve the prediction of the Pressure Coefficients at CL=0,5

Shock close to the wing root not accurately predicted: fuselage effects neglected



EXCELLENT PHYSICS-BASED REDUCE ORDER MODEL

- 2.5D calculations are performed upstream of any calculations
- Coupling procedure runs in seconds for entire AoA range
  - Excellent performance of GPU-based VLM for increased efficiency
- Allows simple incorporation of multi-physics considerations:
  - Icing
  - Transtitional flows
  - Aero-elasticity
  - S&C (i.e. spoilers, ailerons)
  - High-speed transonic and high-lift (high-aspect ratio only)
- Can easily be integrated in VLM-based optimisation frameworks
  - How many slat sections need anti-icing, including failure scenarios?
  - What is the optimal positions of control surfaces?
  - Where does stall occurs, and does it progresses inboard or outboard?

R&D FINANCING

- NSERC Discovery grant (TRL 1-3)
  - 4 students
- NSERC/Bombardier (TRL 3-6)
  - 7 students

- NSERC graduate students awards
  - 4 students in 2015 i.e. can work on anything!
- MITACS grants (visiting professor, MSc and PhD's for Canadian as well as foreign nationals, student study abroad)
- Compute Canada Cluster awards (can be as high as $1M, 1500 cores-years)

- Possibility of joining submitted NERC/Bombardier grants within collaborative project
  - Horizon 2020 CANNAPE calls (50% success rate)
  - French ANR
  - Double-Diplomas with individual professors (2 PhD's with France)

R&D FINANCING VIA EDUCATION

- Ecole Polytechnique is examining an academic graduate program (similar to Germany or UK programs) targeting Simulation-based Engineering
  - Funds injected to finance graduate courses and graduate students;
  - Great for ensuring use of multi-discipline collaborative frameworks like CEASIOM.
- Ecole Polytechnique is modifying it’s programs to fit within the Bologna agreements
  - Will allow easier alignment of double-diploma degrees, capstone projects or final Master research project with Europe
    - i.e. 20 Students in Montreal mounting wind-tunnel vibration test at ISAE;
  - CEASIOM already used at Polytechnique (R&D), but could be used in formal university program as well.

Thank you for your attention