CFD for Better Understanding of Wind Tunnel Tests

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Outline

- Introduction
- Where are those windward shocks coming from?
- Incipient separation criterion
- CFD for wind tunnel wall interference corrections
- Extrapolation and summary

Introduction

- **CFD solutions requires verification**
  - Algorithm accuracy
  - Grid type/resolution sensitivity
  - Convergence

- **CFD models require validation**
  - Unresolved physics: turbulence
  - New physical phenomena: micro/nano-fluidics (gas/liquids), chemical reaction rates, etc.

Introduction

- **Demands on wind tunnel investigation**
  - To understand basic flow physics (its traditional role)
  - To validate models used in CFD simulations, which is increasingly more and more difficult/expensive as the application of CFD expands to more and more complicated flow regimes

- **Wind tunnels have so far helped tremendously in CFD development, can CFD do more in return for wind tunnels to meet the challenges?**
  - A few examples how this may be achieved

A shock on the windward side ?

With Prince and Birch

M=1.8, α=14º, Re/D=6.6x10^5

- **Ogive slender bogy**
  - Wind tunnel tests by Birch
- **A weak feature appears on the windward side**
  - A model imperfection?
  - From wind tunnel wall?
  - A shock wave? Why?

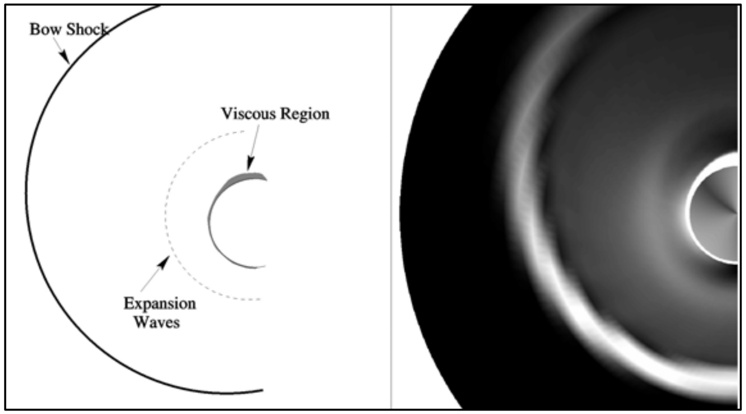
Cases with different cross flow Mach

Case	Ogive *l/D*	M_∞	Re_∞/D	α °	M_C
1	3.0	2.0	1.20×10^6	10.0	0.347
2	3.5	1.4	0.80×10^6	16.2	0.391
3	3.0	1.8	0.66×10^6	14.0	0.435
4	3.5	1.5	1.20×10^6	17.0	0.439
5	3.5	1.5	1.20×10^6	21.2	0.542
6	3.0	2.5	1.23×10^6	14.0	0.605

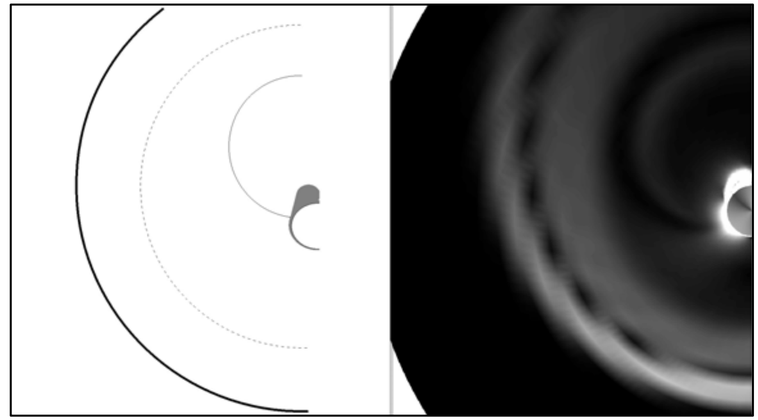
Solution

- **Parabolised Navier-Stokes**
- **Algebraic turbulence models for vortical flows**
  - Degani-Schiff
  - Curvature model
- **Riemann solver based discretisation**
- **Implicit space marching**
- **Non-adaptive grid: a weakness, which makes the capturing of unknown features difficult**
- **Relatively fine grid can be used due to the efficiency of PNS approach**

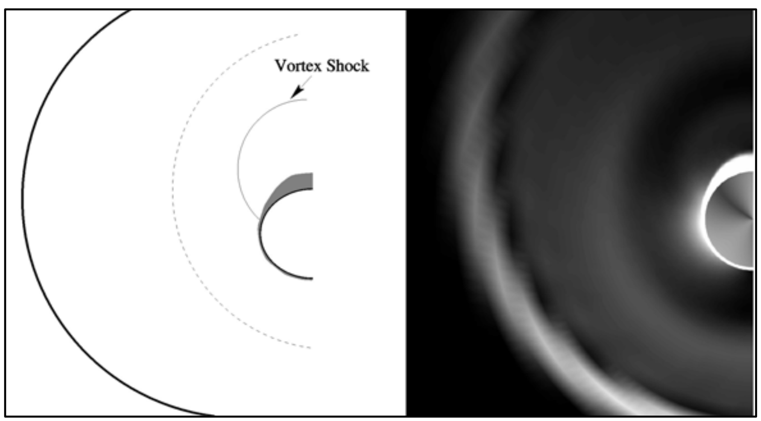
Cross flow development



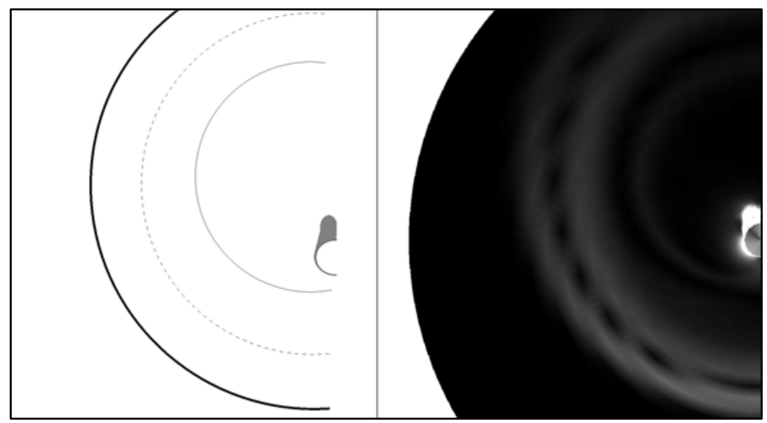
x/D=3.5



x/D=7.5



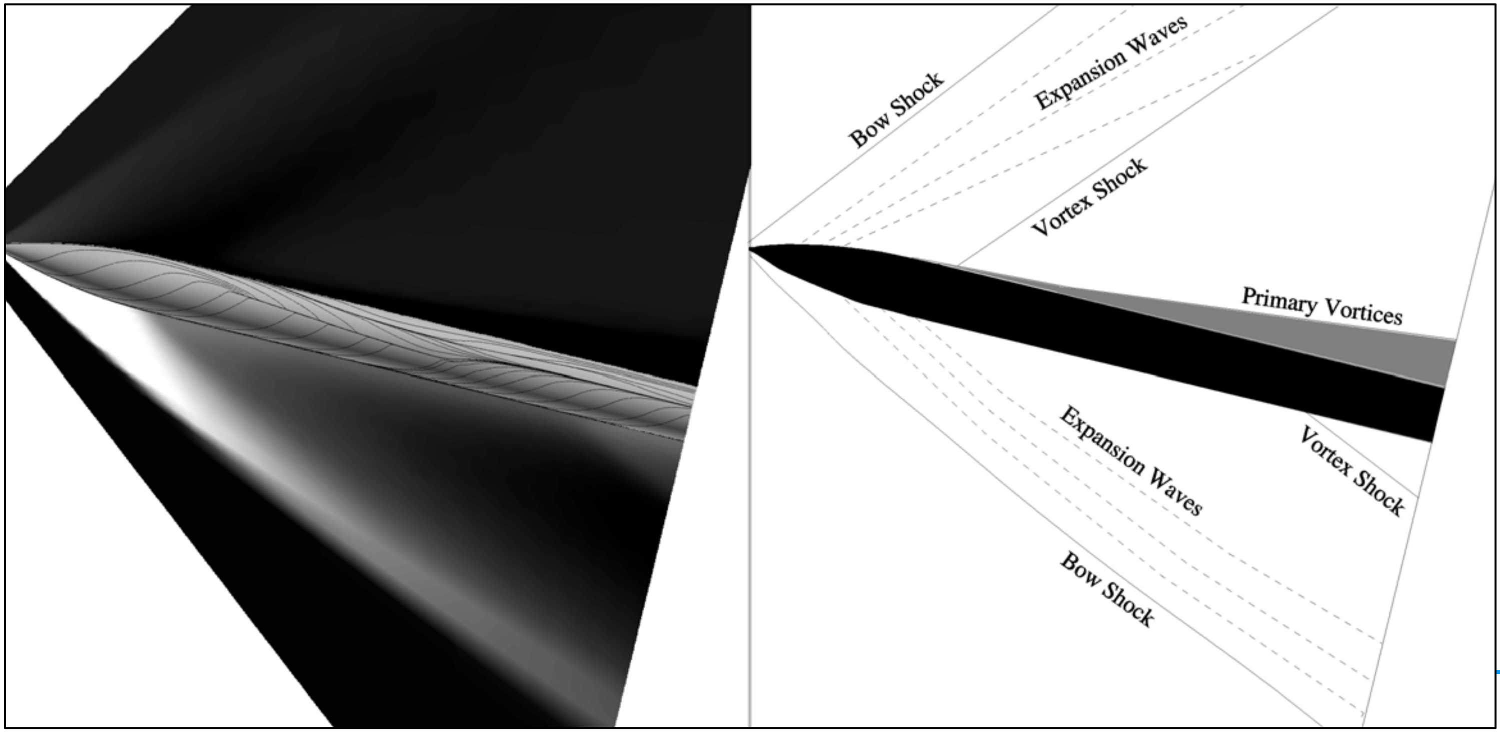
x/D=4.5



x/D=10

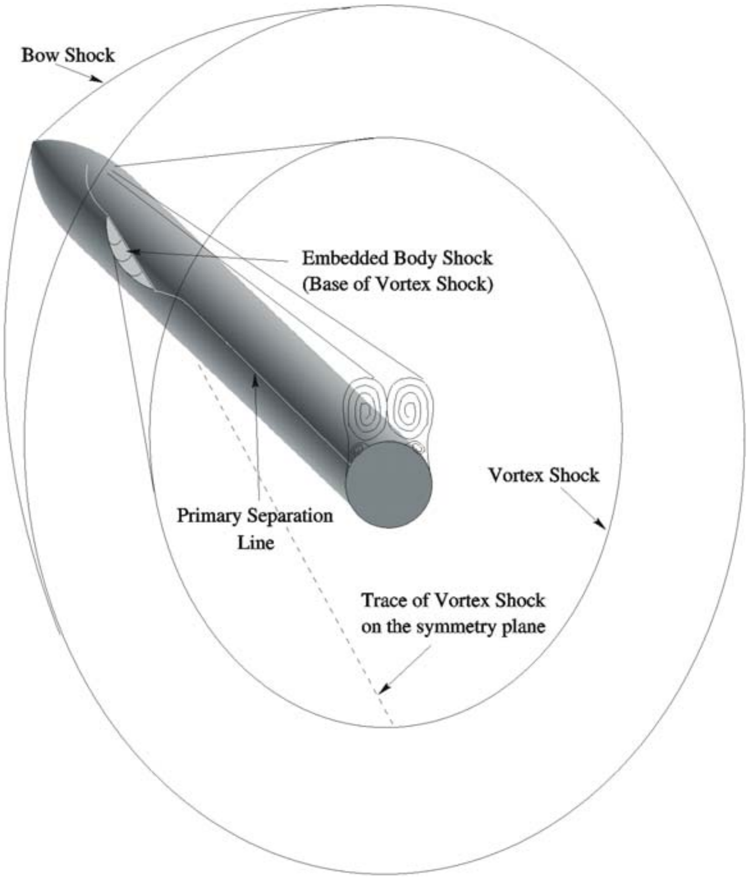
Symmetry plane trace

M=1.8, α=14º, Re/D=6.6x10^5, M_c =0.435

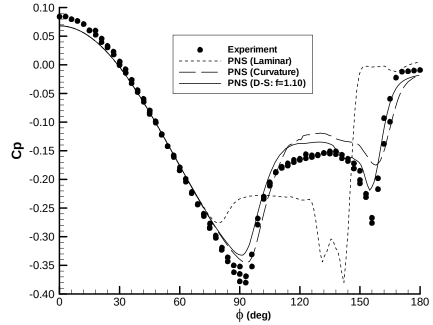


Vortex shock – an interpretation of the windward shock

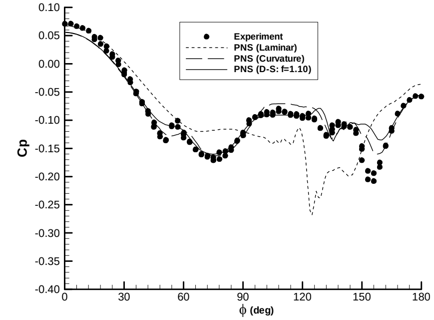
- ***The windward shock is the trace of a vortex shock, which forms as a result of the deflection of the supersonic flow caused by the double cone-like displacement effect of the primary vortices on the leeside of the body.***



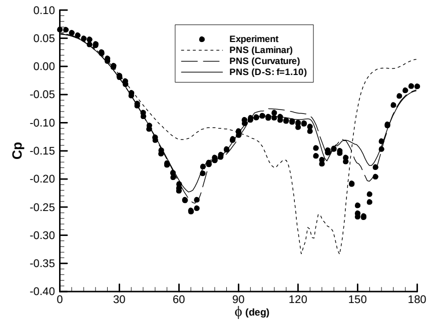
Trace on surface pressure



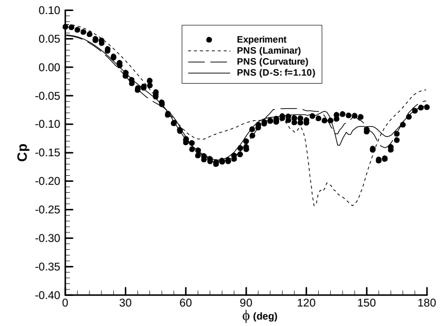
ϕ *x/D=4.4*



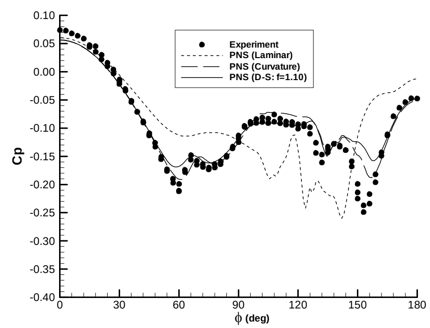
a)x/D=6.8



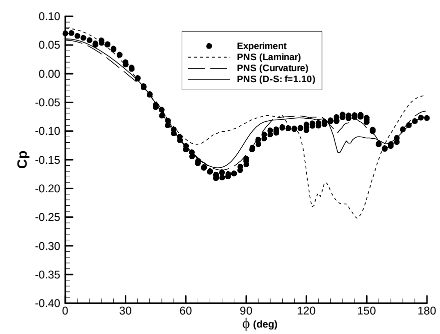
ϕ *x/D=6.2*



b)x/D=7.1



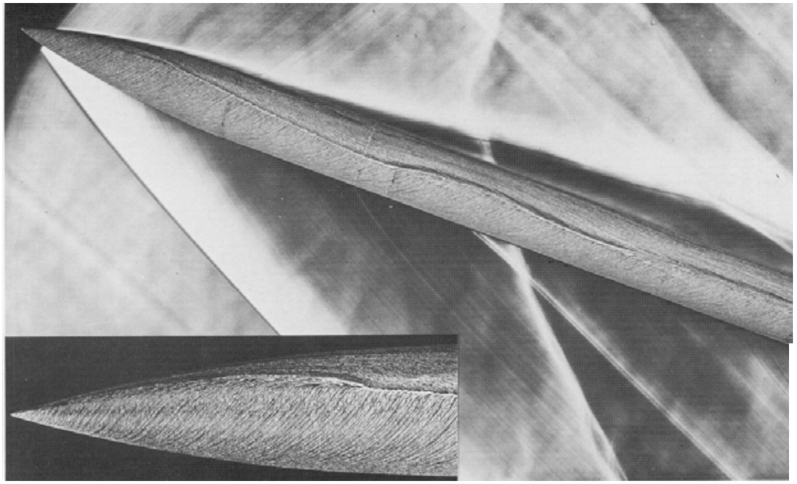
c) x/D=6.5

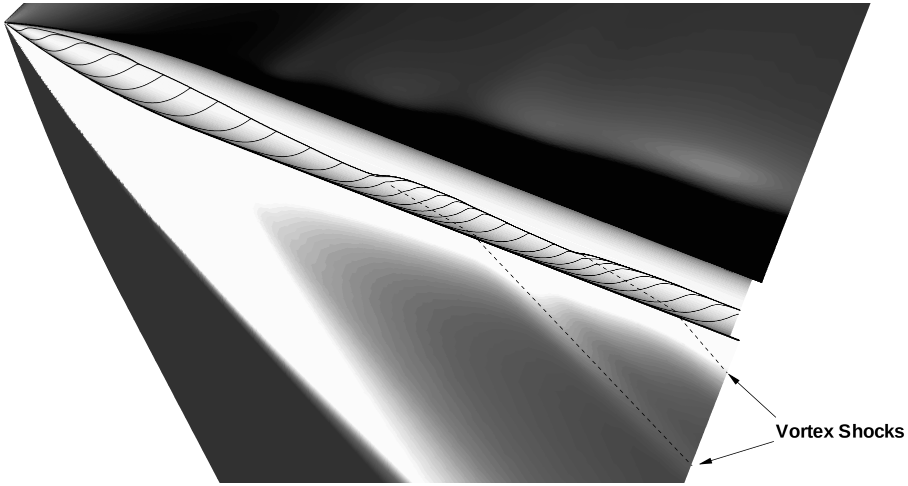


c)x/D=7.4

M=1.8, α=14º, Re/D=6.6x10^5

A case of multi vortex shocks

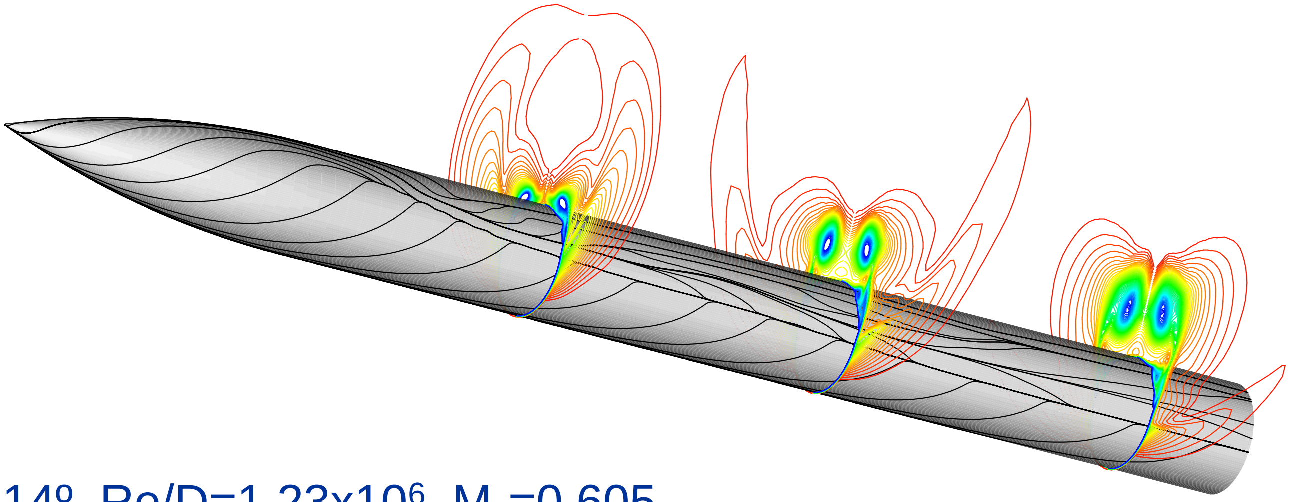




M=1.5, α=21.2^o, Re/D=1.2x10^6, M_c=0.542 (Esch)

Note the correspondence of the surface skin friction lines in exp and CFD, traces of double vortex shocks.

A case when the vortex shock does not appear on the windward side



M=2.5, α=14º, Re/D=1.23x10^6, M_c=0.605

The vortex shock is sustained along the whole length of the body, fixing the primary separation.

Summary and Extrapolation

- **CFD can be used to enhance our understanding of information obtained from wind tunnel tests**
- **Some weak features can be physically significant in design**
- **Flow features unknown beforehand can easily be overshadowed by poor resolution of grid**
- **Critical eyes are required in both experimental tests and CFD simulation**
- **Adaptive gridding can help but need good thinking about the threshold so as not to miss those weak but significant flow features**

Empirical criteria in aerodynamics

- **Many simple but very useful empirical criteria have been developed based on wind tunnel tests, e.g. for separation onset, transition to turbulence, etc.**
- **It is interesting to revisit these criteria and possibly extend their usage to broader ranges**
- **Validated CFD may be used as numerical wind tunnels to discover new simple “empirical” criteria and rules**
- **Good understanding of aerodynamics is crucial in extracting/condensing the wind tunnel data or CFD results**

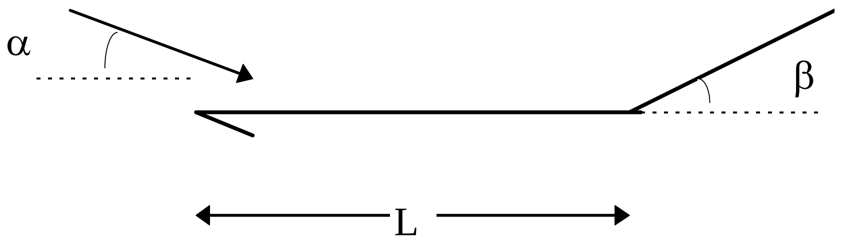
Incipient separation criterion: an example

- **Needlham, Stollery and Holden (1966)'s incipient separation criterion for hypersonic laminar flows:**

$$M\beta_i = k\chi^{\frac{1}{2}}$$

β	=	flap deflection angle in degrees
χ	=	viscous interaction parameter, $M^3 Re_L^{-1/2}$
k	=	70-80 depending on wall temperature condition
		74 according to Hankey.

Incipient separation criterion: the CFD formulation

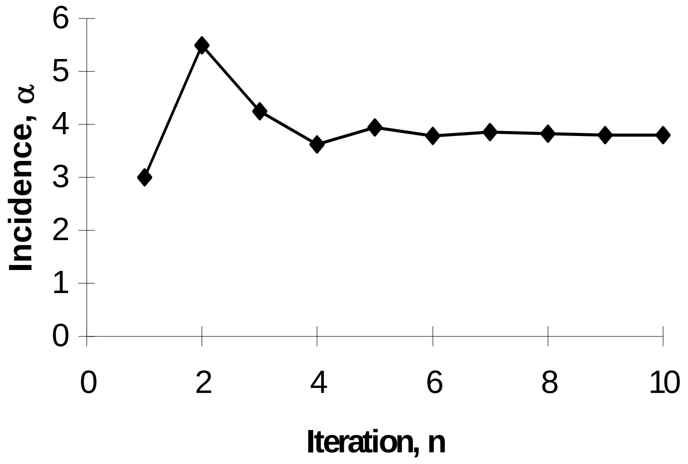


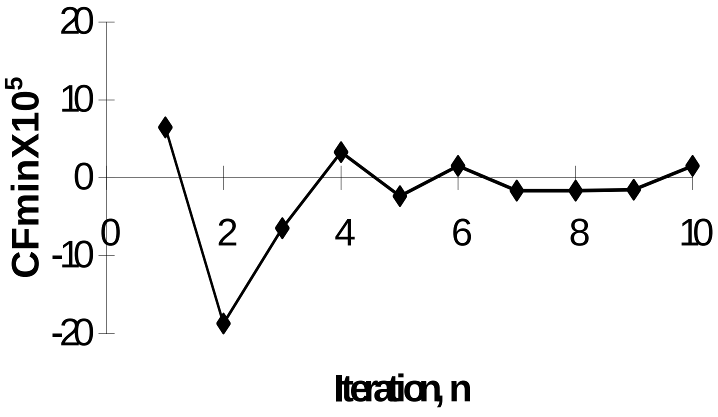
- **For a given β, there should be an α for the incipient separation condition, i.e. the following non-linear equation is satisfied,**

$$\mathrm{CFmin}(\alpha) = \min_{x} \ \mathrm{CF}(x, \alpha) = 0$$

Incipient separation criterion: the solution using the bi-section method

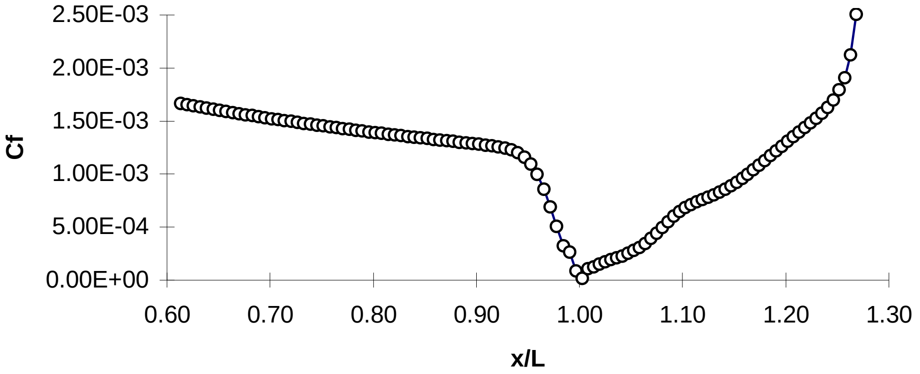
- **Convergence of incidence and CFmin to the incipient separation condition**

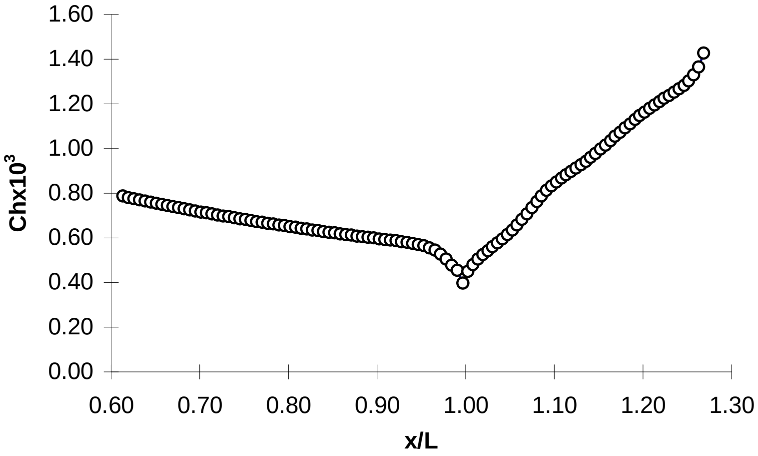




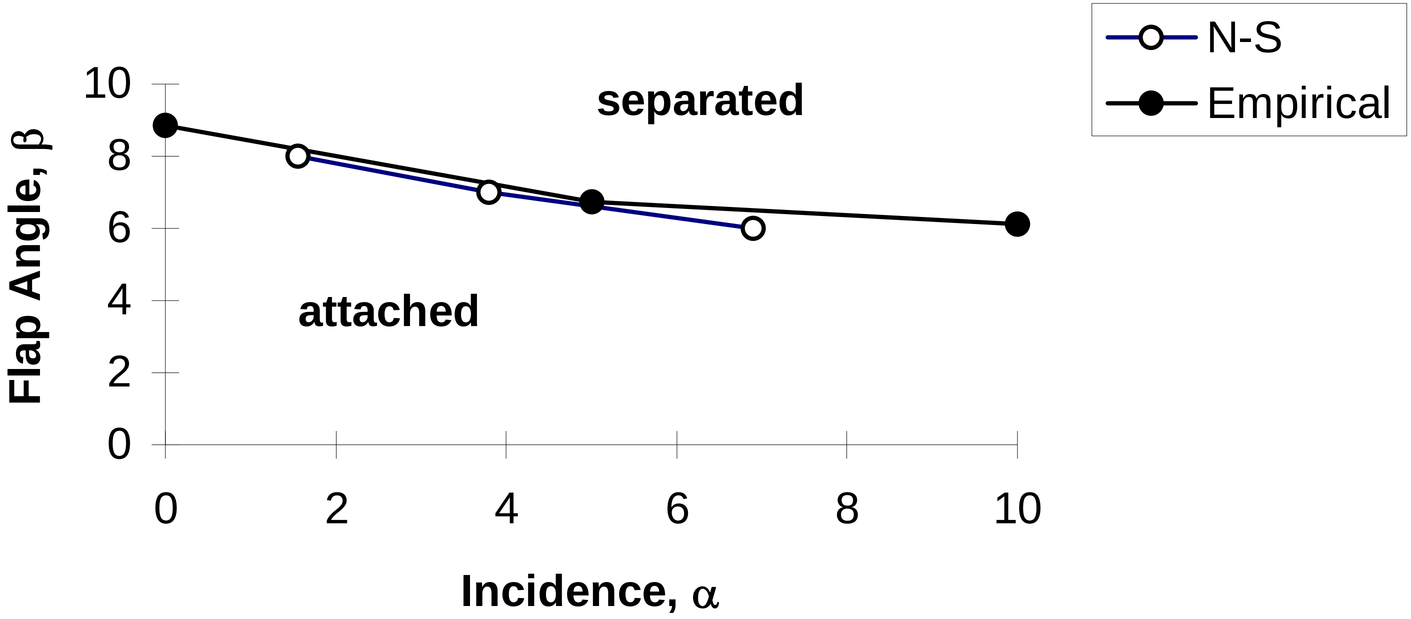
Incipient separation criterion:

Skin friction and heat transfer at incipient separation condition





Incipient separation criterion: comparison



Summary and extrapolation

- **The example demonstrates how CFD can be used to revisit an aerodynamic empirical rule**
- **CFD may be used to extend the criterion for more general case, e.g. including the wall temperature conditions, turbulent cases, buffet boundary, flow bifurcation, self excited shock oscillation, etc.**
- **If early aerodynamists can derive simple and useful “rules” from wind tunnel data, there is no reason why we cannot do the same combining the two.**
- **Deriving such CFD based “empirical” aerodynamic rules is not easy but can be very rewarding**

CFD for Wind Tunnel Wall Interference Correction

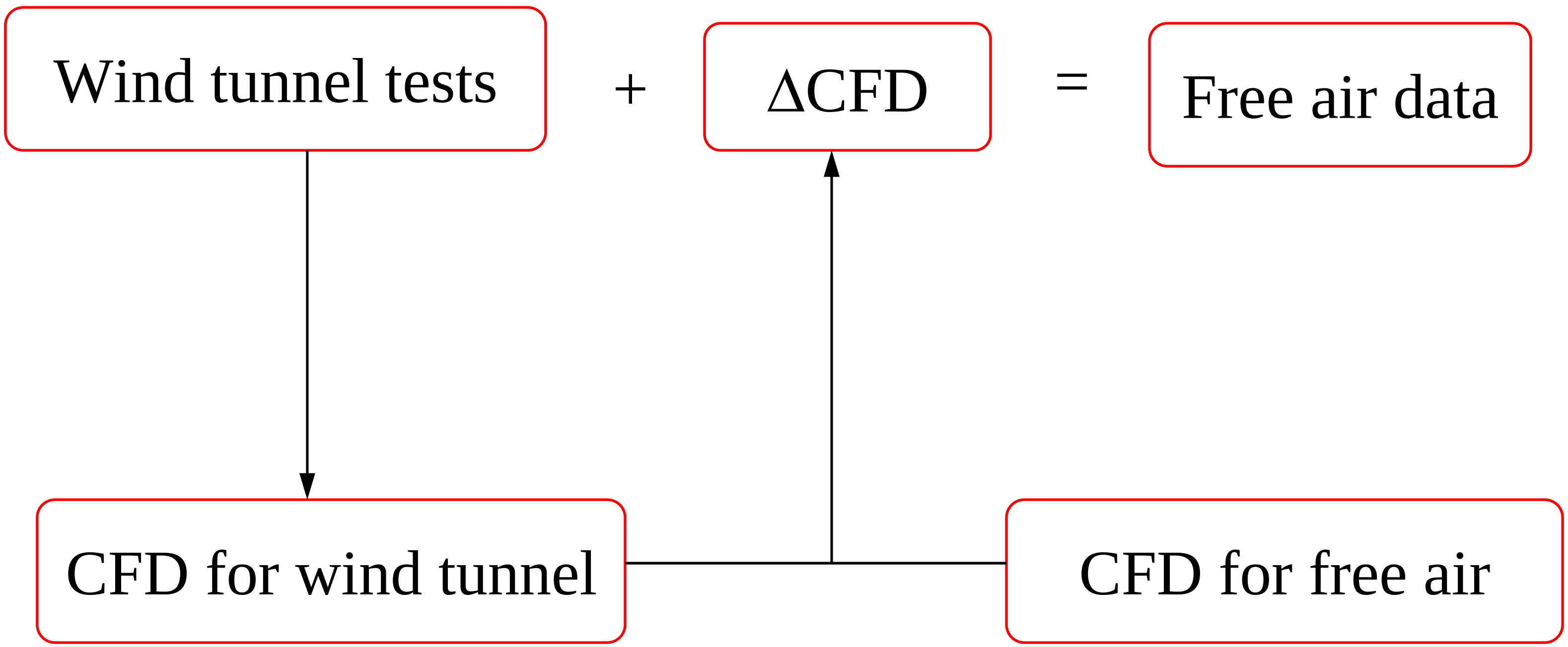
A series of Cranfield MSc projects with BAE collaboration
Shadbolt, Farnibanda, Putze, Burton and Cross

- **Objectives:**
  - Better use of small tunnels for large models (closer Re to flight conditions);
  - Reliable wall interference correction for transonic range, especially, when supercritical flow reaches the tunnel wall;
  - Use of modern CFD tools to assess and correct the interference.

Background

- **The RAE semi-empirical corrections (Ashill)**
- **The MDA approach (Crites and Rueger)**
  - modelling of wall boundary conditions for porous walls
  - correlation based on v_w, C_p and δ^* for a range of porous surfaces
- **The AEDC approach (Jacocks)**
  - modelling of wall (1) pre-test prediction (2) measured wall C_p
  - correlation between $dC_p/d\theta$ and δ^* for AEDC tunnel
- **The NASA LRC approach**
  - slotted wall boundary conditions for NTF

Use of CFD for WIAC



Correctability

- **Conventional correction**
  - Mach number and incidence correction
  - “uncorrectable” cases

- **MDA approach using modern CFD**
  - address “uncorrectable” cases
  - fixed Mach number and incidence

    Free Air = Wind Tunnel + ΔCFD

What are required for the correction

- **For computation: inviscid boundary conditions at wall**
  - tunnel wall pressure distribution
  - equivalent normal velocity at wall including the effect of porous wall conditions
  - tunnel wall initial δ^*
- **Extra wind tunnel measurement required**
  - tunnel wall pressure
  - displacement thickness at the entrance of tunnel wall

Wall correction: what to match?

- **Conventional correction**
  - match C_l, correct M and α

- **MDA approach**
  - match M and α, correct surface pressure etc.

Shadbold's Experiments

- Wing 9: 2D wing 14% thick and 12" chord
- Porous side walls, solid top/bottom walls, vertical model
- Measurement on the model: surface pressure measurement with 26 pressure tappings on the upper surface and 18 on the lower surface
- Measurement on the wall: p on both side of the wall
- M=0.695, Re per meter 18.5 million

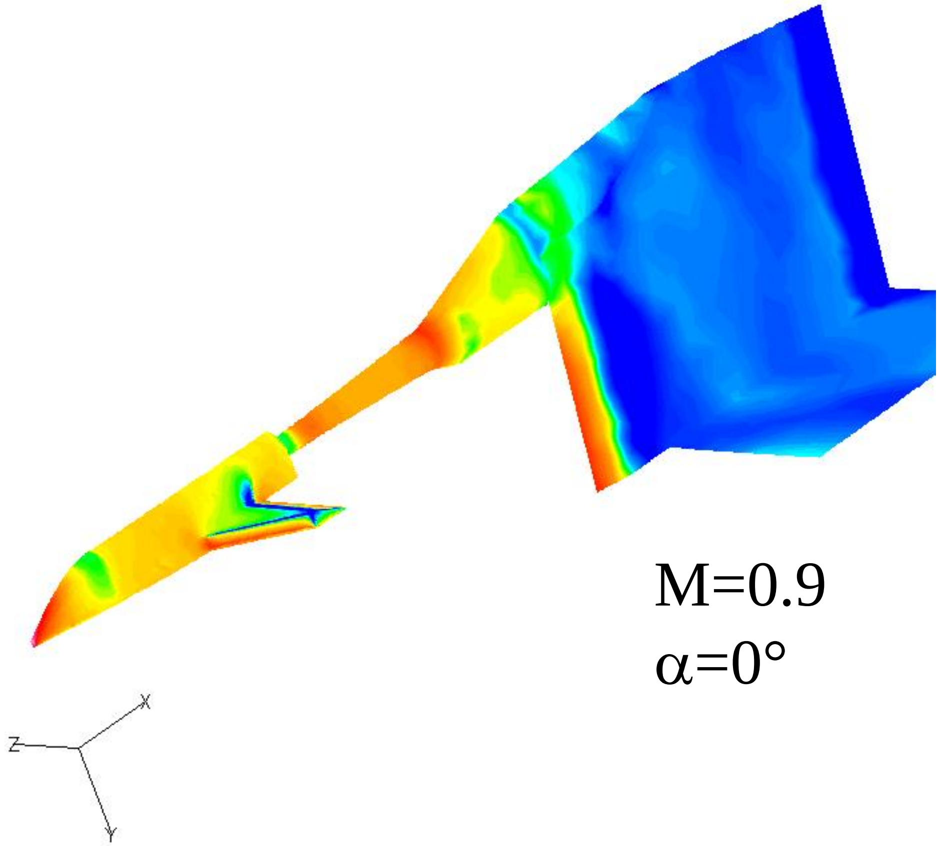
Fanibanda's 2D Study

- **CFD study of Shadbolt's experimental cases**
  - free air case
  - solid wall case
  - "ideal wall" case with boundary conditions set from the free air case
- **Results**
  - big difference between free air and solid wall cases
  - ideal wall case is much closer to free air case but discrepancies remain, indicating problem with B.C.
  - attempted to model porous wall

Puetz's 3D Study

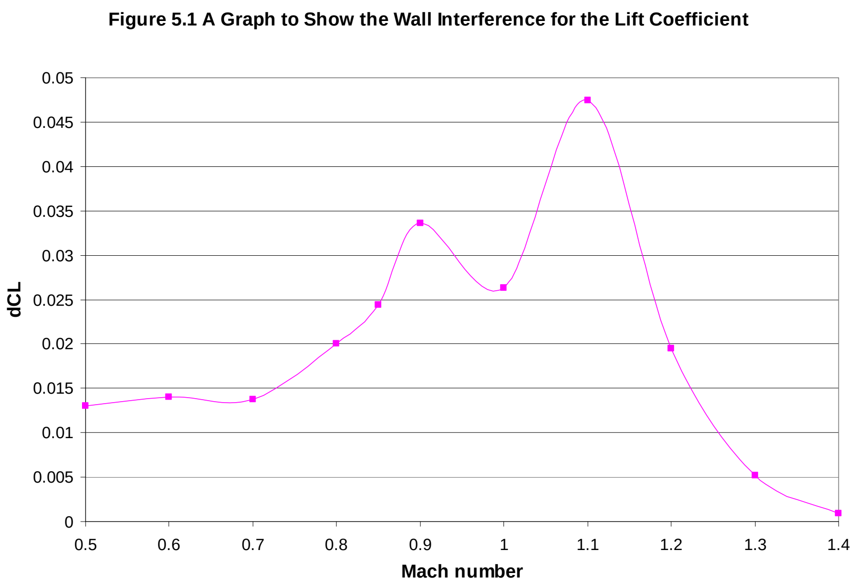
- **CFD study of TWIG cases: 0.5 < M < 1.4, α=0º, 20º**
  - free air cases
  - solid wall without support structure
  - solid wall with support structure
- **Results**
  - significant difference between free air and *solid wall* without support cases through the transonic region in HSWT
  - free air results are close to porous wall wind tunnel data at $\alpha=0°$ but significantly different at $\alpha=20°$
  - solid wall with support structure created a blockage effect for M>0.8

Surface pressure distribution

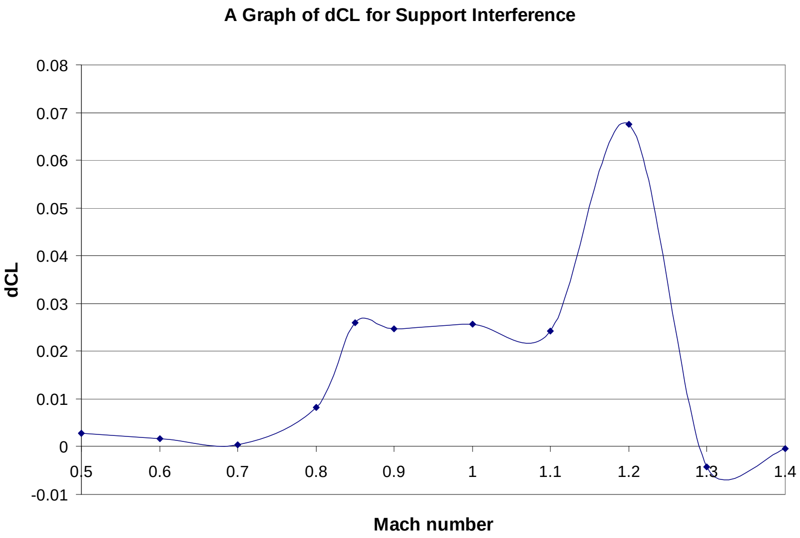


M=0.9
$\alpha=0°$

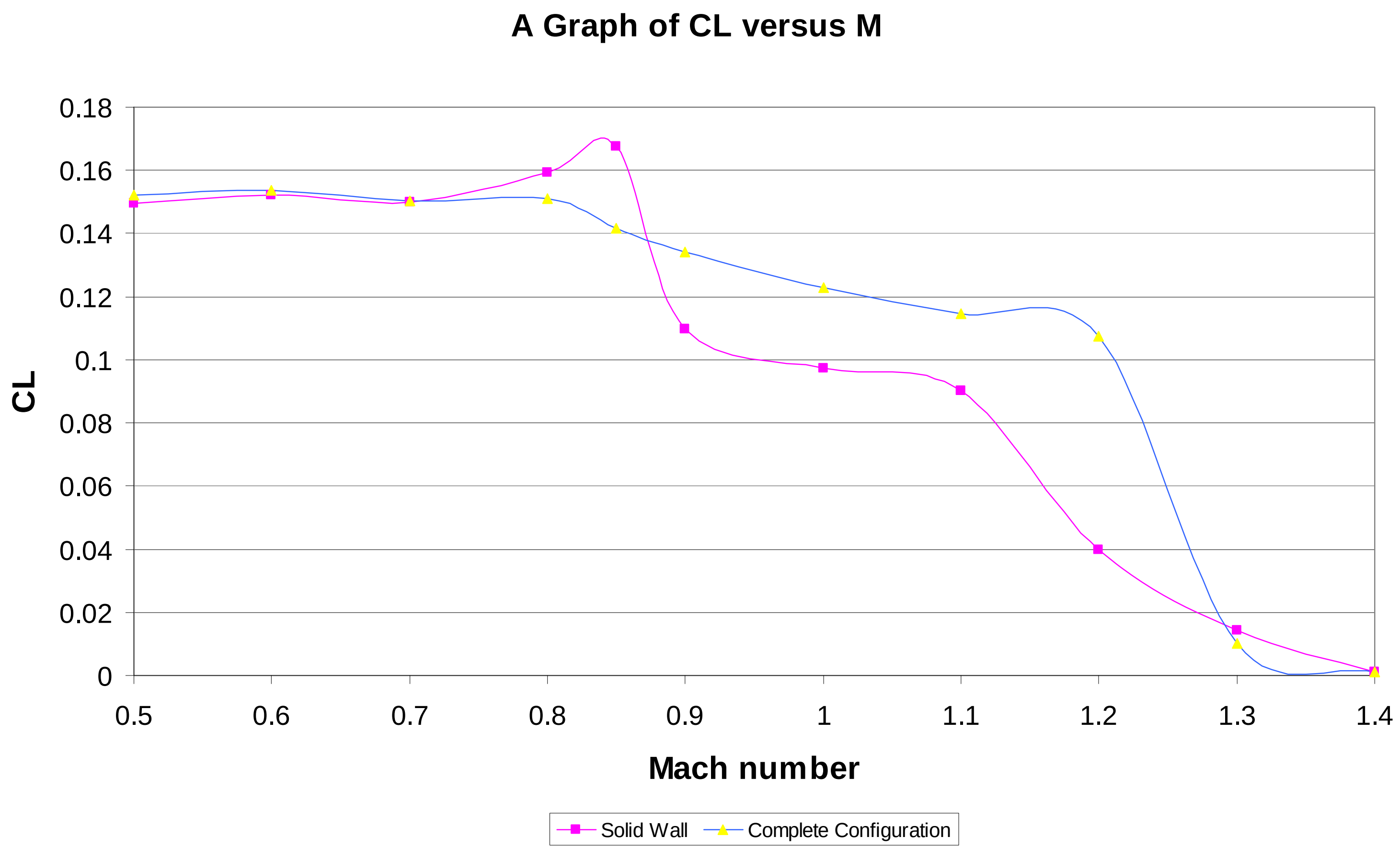
Solid wall interference



Additional support interference

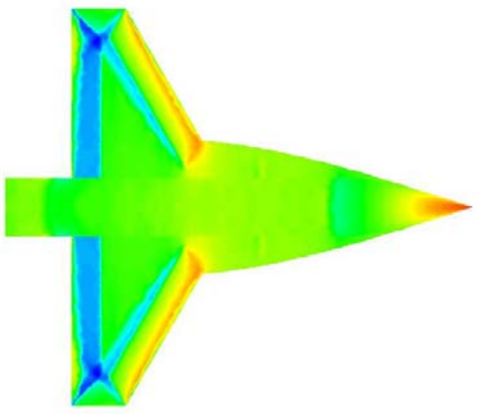


Solid wall with and without support

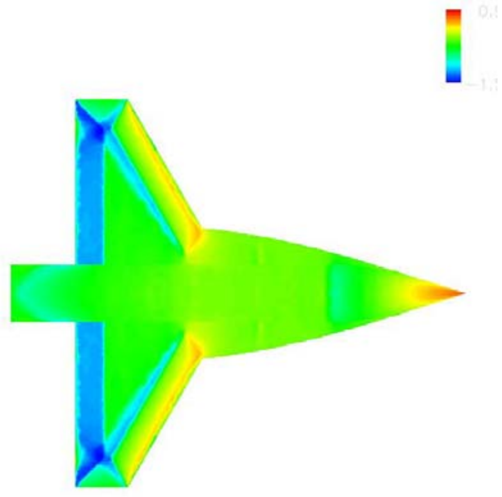


Surface pressure distribution M=0.9, α=0

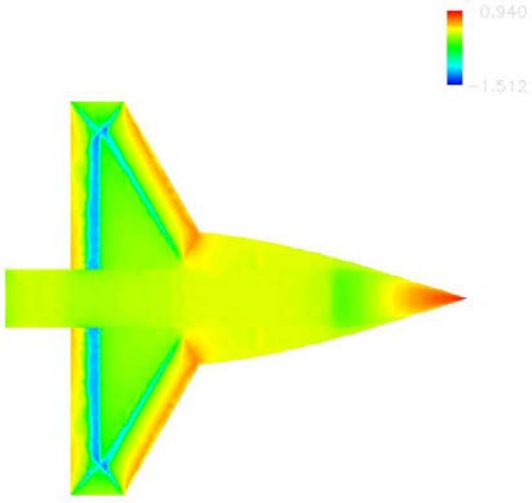
Free Air



Solid Wall



Complete



Summary and Extrapolation

- **The projects confirmed that the wall interference is most significant in the transonic range (high subsonic).**
- **The model support structure has a strong interference at low supersonic range.**
- **CFD can be used for WIAC improving the accuracy and the effective range of Reynolds number in wind tunnel tests (larger models in existing tunnels).**
- **Require further development of proper CFD boundary condition for the WIAC study.**

Conclusion

The three examples presented here highlight some potential use of CFD to help wind tunnel experimental investigation.

A lot needs to be done to achieve this!