Drag breakdown of *SU2* solutions around aircraft

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Objective

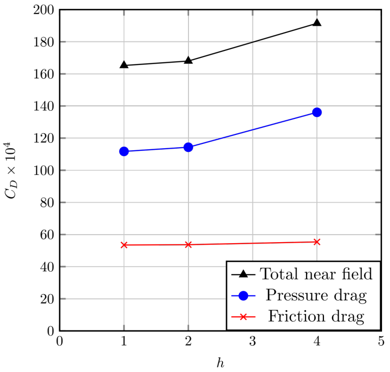
To provide a drag breakdown in physical components post-processing RANS solutions obtained by SU2.

Contents:

- Introduction.
- Far field methods.
- *BreakForce* code.
- Applications:
  - NASA CRM wing-body configuration,
  - High Lift wing configuration,
  - Distributed Electric Propulsion (DEP) configuration.
- Conclusions.

Introduction

Why drag breakdown from CFD analyses?



NACA 0012, $M_\infty = 0.7$, $Re_\infty = 9.0 \times 10^6$, $\alpha = 3.25°$. SU2 RANS solution, SA turbulence model. $h = 1,\ 2,\ 4$: $256,\ 128,\ 64$ cells around airfoil. NASA C-type grid.

Near Field aerodynamic force:

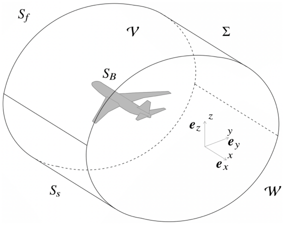
$$\boldsymbol{F}_{nf} = \int_{S_B} (p\boldsymbol{n} - \boldsymbol{\tau}_v \cdot \boldsymbol{n})\,\mathrm{d}S$$

Computed drag converges as mesh size h is reduced, but:

- Absolute accurate drag prediction only on extremely fine grids.
- Drag breakdown in pressure and friction components only.
- Aerodynamic designer interested in viscous, wave and lift-induced components.

Far Field Methods

Overview



Far Field aerodynamic drag:

$$D_{far} = -\int_{\Sigma} \left[\rho u \left(\boldsymbol{V} \cdot \boldsymbol{n}\right) + \left(p - p_{\infty}\right) n_x\right] \mathrm{d}S$$

- University of Naples (UniNa) started studies on 1998.
- At that time state-of-the-art well described by Van Dam (Prog. Aero. Sci., 1999).
- Van Dam et al. computed the drag of wings in transonic flow analyzing solutions of the Euler equations (JoA, 1995).
- Giles & Cummings proposed the computation of the entropy drag introduced by Oswatitsch via wake survey of RANS solutions (JoA, 1999).
- Schmitt & Destarac (AIAA paper, 1998) transonic Euler and potential flow analyses.

Thermodynamic Method

Far field equation allows to derive the irreversible part of the aerodynamic force (**entropy drag**).

Independently, Paparone & Tognaccini (AIAA J., 2003) and Destarac & van der Vooren (AST, 2004) proposed two thermodynamic methods which for the first time gave chance to:

- improve the accuracy in the computation of the total drag obtainable by RANS methods isolating at least part of the so-called **spurious drag** introduced by the discretization error of the numerical scheme;
- provide a breakdown of the entropy drag in its viscous and wave components.

Lift-induced drag only obtainable in an indirect way subtracting entropy drag to the total drag.

Entropy drag breakdown (1/2)

Thermodynamic Method

The **entropy drag** is given by:

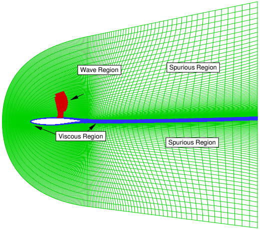
$$D_{\Delta s} = -V_\infty \int_{\mathcal{V}} \boldsymbol{\nabla} \cdot [\rho g (\Delta s) \boldsymbol{V}] \, \mathrm{d}\mathcal{V}$$

where $\mathcal{V}$ is the flow domain, Δs the entropy variation and

$$g(\Delta s) = f_{s1}\left(\frac{\Delta s}{R}\right) + f_{s2}\left(\frac{\Delta s}{R}\right)^2$$

with R the gas constant.

- Obtained breakdown in viscous and wave drag.
- Removal of the spurious drag improves computed drag accuracy.
- The selection of the flow regions is obtained using proper sensors.



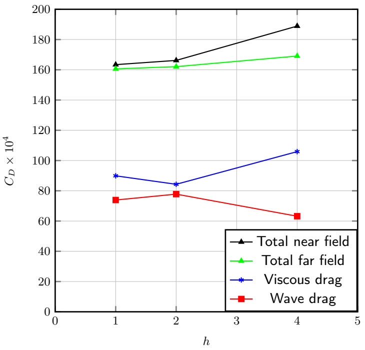
$$D_v = V_\infty \int_{\mathcal{V}_v} \boldsymbol{\nabla} \cdot (\rho g \boldsymbol{V}) \, \mathrm{d}\mathcal{V}$$

$$D_w = V_\infty \int_{\mathcal{V}_w} \boldsymbol{\nabla} \cdot (\rho g \boldsymbol{V}) \, \mathrm{d}\mathcal{V}$$

$$D_{sp} = V_\infty \int_{\mathcal{V}_{sp}} \boldsymbol{\nabla} \cdot (\rho g \boldsymbol{V}) \, \mathrm{d}\mathcal{V}$$

Entropy drag breakdown (2/2)

Thermodynamic Method



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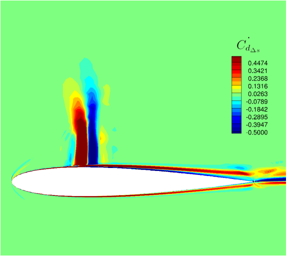


NACA 0012. Entropy drag production.

- Very weak sensitivity to mesh size of the computed total drag.
- Sufficient drag accuracy already on relatively rough grids.
- Obtained drag breakdown in viscous and wave components.

Vortex-Force Method

Why the need for a vortex-force method?

Spalart (JFM, 2008):*"An ambition which we have to wait is a rigorous definition of induced drag in viscous flow"*.

Thermodynamic method limits:

- only allowed the computation of the irreversible part of the aerodynamic force (associated with entropy production);
- unable to compute lift;
- lack of direct definition of lift-induced drag.

A paper of Wu et al. (JFM, 2007) gave us the chance to look for an answer to the Spalart's question.

The **Lamb vector** is responsible for the whole aerodynamic force:

$$\boldsymbol{\ell} = \boldsymbol{\omega} \times \boldsymbol{V}$$

Vortex-Force Method

High Reynolds number, compressible flow (Mele, Ostieri & Tognaccini, *AIAA J.*, 2016)

Vortex force:

$$\boldsymbol{F}_\ell = -\int_{\mathcal{V}} \rho \boldsymbol{\ell} \mathrm{d}\mathcal{V}$$

Aerodynamic force:

$$\boldsymbol{F} = \boldsymbol{F}_\ell + \boldsymbol{F}_{wk} + \boldsymbol{F}_{m_\rho}$$

$$\boldsymbol{F}_{wk} = -\int_{S_{far}} \hat{\boldsymbol{r}} \times (\boldsymbol{n} \times \rho \boldsymbol{\ell}\,)\,\mathrm{d}S, \quad \boldsymbol{F}_{m_\rho} = -\int_{\mathcal{V}} \boldsymbol{m}_\rho \mathrm{d}\mathcal{V}, \quad \boldsymbol{m}_\rho = \hat{\boldsymbol{r}} \times \left[\boldsymbol{\nabla}\rho \times \boldsymbol{\nabla}\left(\frac{V^2}{2}\right)\right].$$

Aerodynamic force given by the sum of a volume integral ($\boldsymbol{F}_\ell + \boldsymbol{F}_{m_\rho}$) and a surface integral on the aircraft wake $\boldsymbol{F}_{wk}$.

Vortex-Force Method

High Reynolds number, compressible flow (Mele, Ostieri & Tognaccini, *AIAA J.*, 2016)

$\boldsymbol{F}_{wk}$: irreversible part of the aerodynamic force.

$\boldsymbol{F}_{\ell} + \boldsymbol{F}_{m_\rho}$: reversible part of the aerodynamic force (also present in inviscid subsonic flow)

Vortex force breakdown:

Viscous and wave drag: $\boldsymbol{D}_{vw} = \boldsymbol{F}_{wk}$

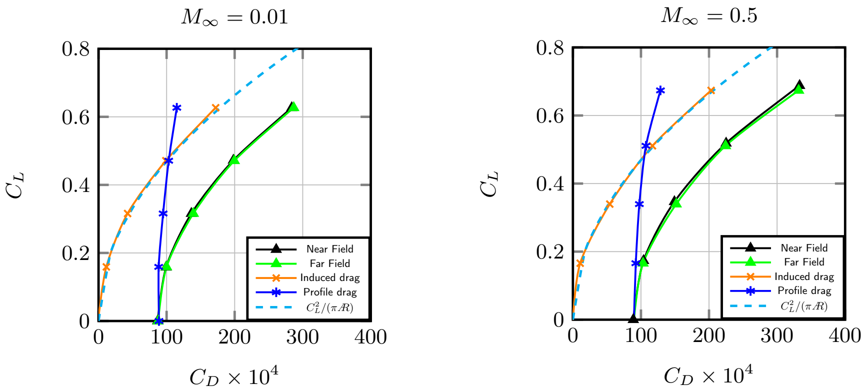
Lift: $\boldsymbol{L} = (\boldsymbol{F}_{\ell} + \boldsymbol{F}_{m_\rho})_{\perp \underline{\mathrm{V}}_\infty}$

Lift-induced drag: $\boldsymbol{D}_i = (\boldsymbol{F}_{\ell} + \boldsymbol{F}_{m_\rho})_{\parallel \underline{\mathrm{V}}_\infty}$

- Unambiguous direct definition of lift-induced drag even in transonic flow.

Elliptic wing in transonic flow, $Re_\infty = 3 \cdot 10^6$

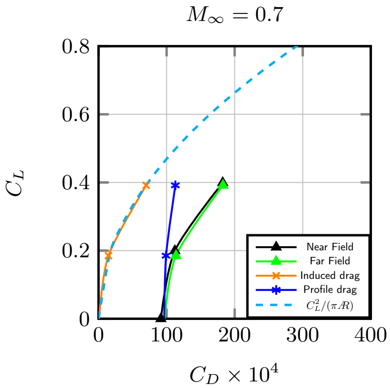
Vortex-Force Method

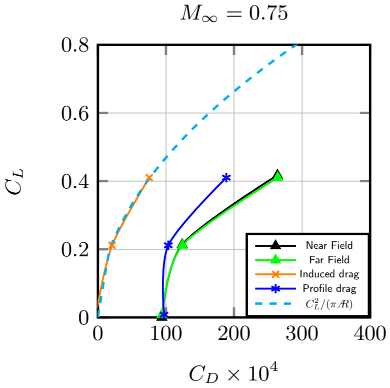


- In subsonic flow, vortex-force definition of lift-induced drag in agreement with celebrated Prandtl's formula.

Elliptic wing in transonic flow, $Re_\infty = 3 \cdot 10^6$

Vortex-Force Method

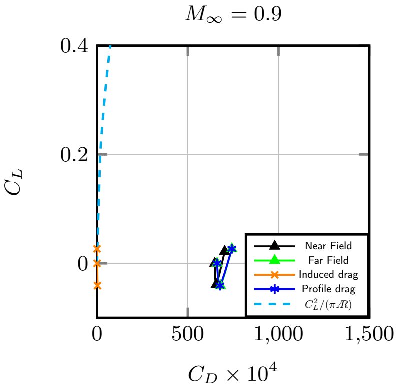


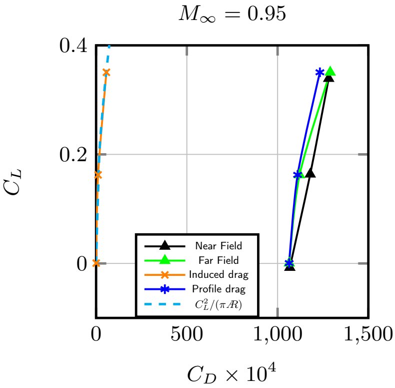


- Prandtl's formula correctly predicts lift-induced drag in transonic flow...

Elliptic wing in transonic flow, $Re_\infty = 3 \cdot 10^6$

Vortex-Force Method

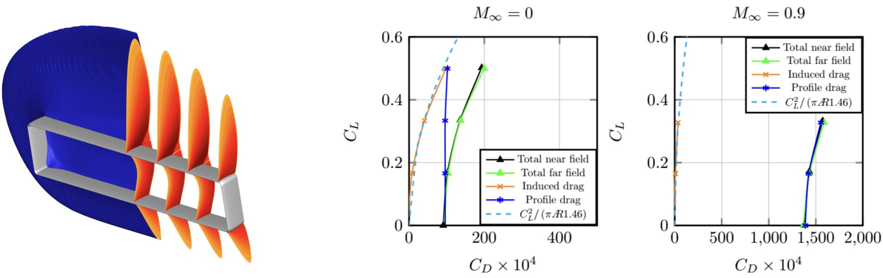




- ... even at $M_\infty = 0.95$!

Box wing in transonic flow

Russo, Tognaccini & Demasi, *AIAA J.*, 2020

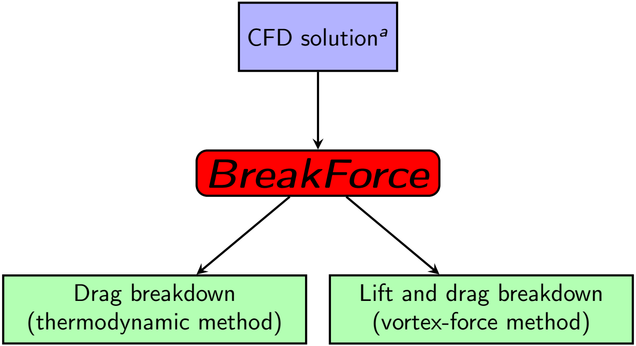


Box wing lift-drag polars. $Re_\infty = 1.0 \times 10^7$, $Æ = 6$.

- Span efficiency $\epsilon = 1.46$ in agreement with optimum (subsonic) theoretical value.
- The box wing is the best wing system (in terms of induced drag) also in transonic regime!

BreakForce code

- Developed by the Theoretical and Applied Aerodynamic Research Group (TAARG) at University of Naples (UniNa).
- Written in FORTRAN 90.
- Independent of CFD solver (being structured or unstructured).

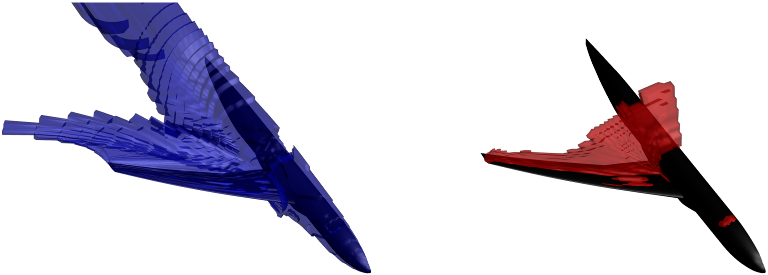


[a] Unstructured CGNS format.

NASA CRM Wing-Body Configuration

$M_\infty = 0.85$, $Re_\infty = 5.0 \times 10^6$, 1.3 million grid cells

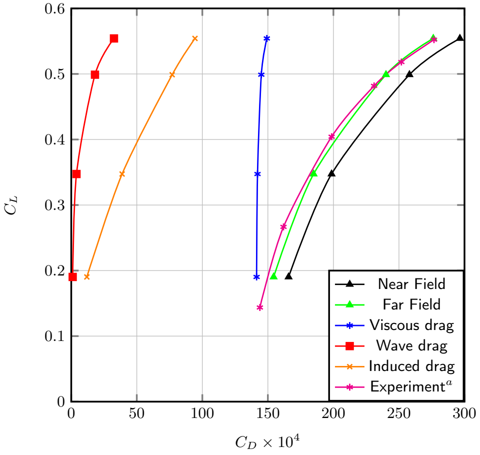
- 1.3 million cells coarse grid, 5^{th} AIAA drag prediction work-shop.
- RANS solution by *SU2* V7.1.1, SA turbulence model.



Selected boundary layer and shock wave regions ($C_L = 0.55$).

NASA CRM Wing-Body Configuration

$M_\infty = 0.85$, $Re_\infty = 5.0 \times 10^6$, 1.3 million grid cells



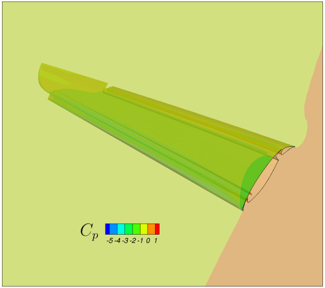
- On this coarse grid near field lift-drag polar far from experiment.
- Identification of spurious drag dramatically improves agreement with experiment.
- Reliable drag breakdown.

[a] NASA Ames 11ft wind-tunnel.

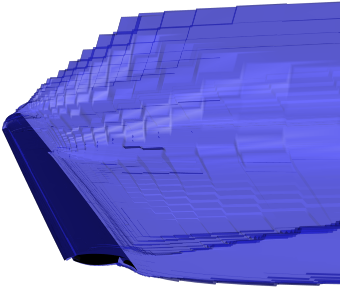
High Lift Wing Configuration

$M_\infty = 0.16$, $Re_\infty = 13.9 \times 10^6$

- Take-off high-lift system designed for a laminar wing (output of DeSiReH EU funded research).
- Configuration and grid provided by CIRA (4.5 million grid cells).
- *SU2* V7.0.6 runs.



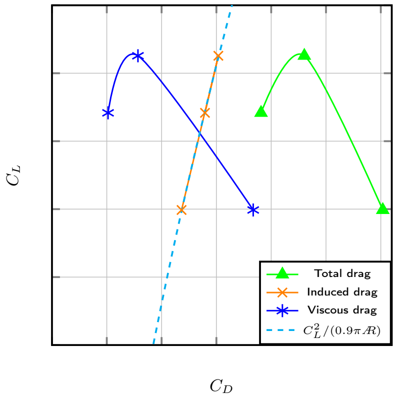
C_p contour, $\alpha = 14.0^\circ$.



Boundary layer region selected, $\alpha = 10.5^\circ$.

High Lift Wing Configuration

$M_\infty = 0.16,\ Re_\infty = 13.9 \times 10^6$

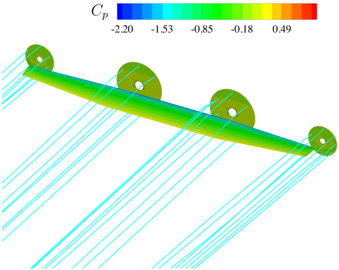


- Breakdown in viscous and lift-induced drag.
- Computed span efficiency ($\epsilon = 0.9$) even in this strongly non-linear regime.
- Parabolic law for the induced drag even in post-stall conditions!
- Evidenced the universality of classical wing theories (not limited to subsonic linear regime).

DEP Configuration

$M_\infty = 0.48,\ Re_\infty = 16.6 \times 10^6$

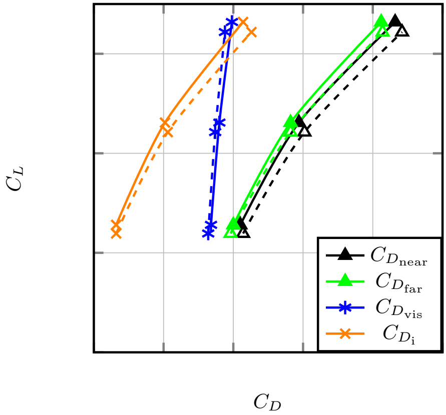
- The activity carried out in cooperation with CIRA within CS2 Iron EU funded research program.
- Configuration and grid provided by CIRA (3.3 million grid cells).
- *SU2* V7.0.7 runs, SA turbulence model.
- Propeller modelled by UniNa actuator disk model with variable load distribution and swirl.



$\alpha = 0.0°$

DEP Configuration

$M_\infty = 0.48,\ Re_\infty = 16.6 \times 10^6$



- Possibility to compare **Prop-on** (solid line) and **Prop-off** (dashed line) conditions.
- Lift increased and total drag decreased by DEP.
- Very small increase of viscous drag in Prop-on conditions.
- Increased span efficiency in Prop-on conditions due to reduction of tip-vortex intensity.

Conclusions

- Far field thermodynamic methods are today well-established and widely adopted in industries (at least in Europe).
- Contributed to the design of last generation jet transport.
- Thermodynamic methods limited to the calculation of the irreversible part of the aerodynamic force.
- Limitation overcome by vortex-force methods, which provide a direct definition of lift-induced drag.
- Vortex-force methods still not sufficiently mature.
- Showed post-processing of *SU2* RANS solutions by UniNa *BreakForce* code.

What's next?

Theory:

- Unsteady regime.
- Post-processing of LES/DNS data.
- Thrust-drag bookkeeping.
- Supersonic regime.

Software:

- We are thinking to develop an open-source version of *BreakForce* code.
- Strongly integrated with *SU2*, but able to post-process any CFD result.
- Verifying the interest of scientific community.

Acknowledgment: special thanks to Mauro Minervino (CIRA) providing some of the CFD analyses.