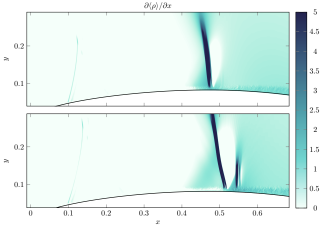


Drag reduction on a transonic airfoil

How does reducing friction drag reduce drag?

M. Quadrio[1], A. Chiarini[1], J. Banchetti[1], D. Gatti[2], A. Memmolo[3] & S. Pirozzoli[4]

EDRFCM 2022, Paris, Sept. 7

[1]Politecnico di Milano, [2]Karlsruhe Institute of Technology, [3]CINECA Interuniversity Consortium, [4]La Sapienza Università di Roma

A simple question for the drag reduction community

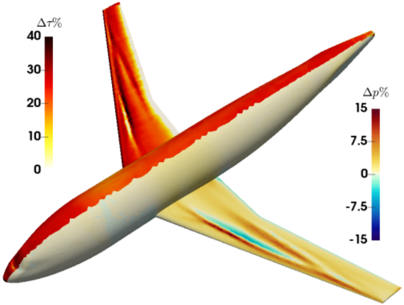
- Skin-friction drag reduction (DR) is often studied for low-*Re* flows in simple geometries
- For a complex body, skin-friction DR should be extrapolated to total DR
- The standard answer is: in proportion!

We answer differently, with a story told through EDRFCMs 2017-2022

Chap.1: EDRFCM 2017, Rome

Asking the question

- Preliminary study (coarse RANS, wall functions, DR model)
- Suggests that pressure distribution is affected
- Resemblance with similar studies for riblets

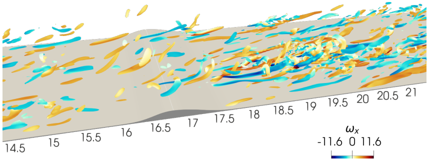


EDRFCM 2017: Drag reduction of a wing-body configuration via spanwise forcing, J.Banchetti, A.Gadda, G.Romanelli & M.Quadrio

Chap.2: EDRFCM 2019, Bad Herrenhalb

First answer, simple physics

- Reliable modelling (DNS, DR accounted for directly)
- Still simple physics
- Confirmation that skin-friction DR may led to pressure DR too

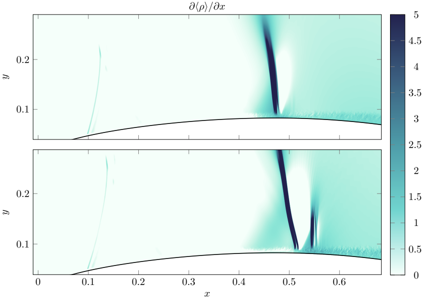


EDRFCM 2019: Turbulent drag reduction for a wall with a bump, J.Banchetti & M.Quadrio
Paper: J.Banchetti *et al*: Turbulent drag reduction over curved walls. J. Fluid Mech. 2020, **896** A10.

Chap.3: EDRFCM 2022, Paris

Final answer, richer physics

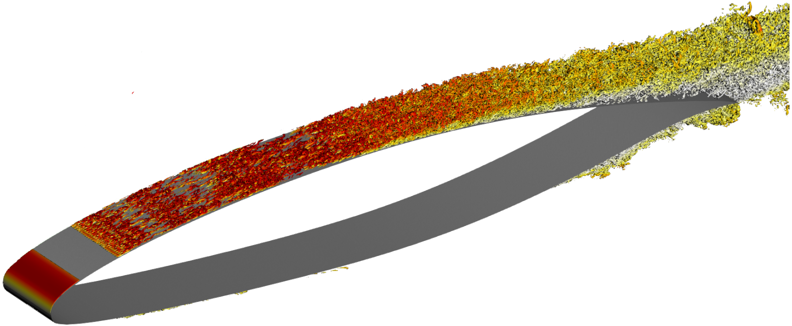
- Reliable modelling (DNS, DR accounted for directly)
- Richer physics (compressible flow over a transonic wing with shock wave)
- Extrapolation to the entire airplane



EDRFCM 2022: This talk
Paper: M.Quadrio *et al*: Drag reduction on a transonic airfoil. J. Fluid Mech. 2022, **942** R2.

Turbulent flow over a transonic airfoil

- Direct Numerical Simulation (up to 1.8 billions cells)
- Supercritical V2C airfoil
- $Re_\infty = 3 \times 10^5$, $M_\infty = 0.7$, $\alpha = 4°$
- Control by spanwise forcing (steady StTW)
- Only a portion of the suction side is controlled



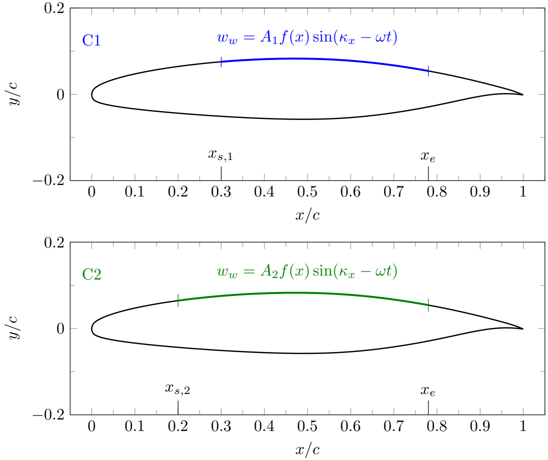
Two control layouts

For C1:

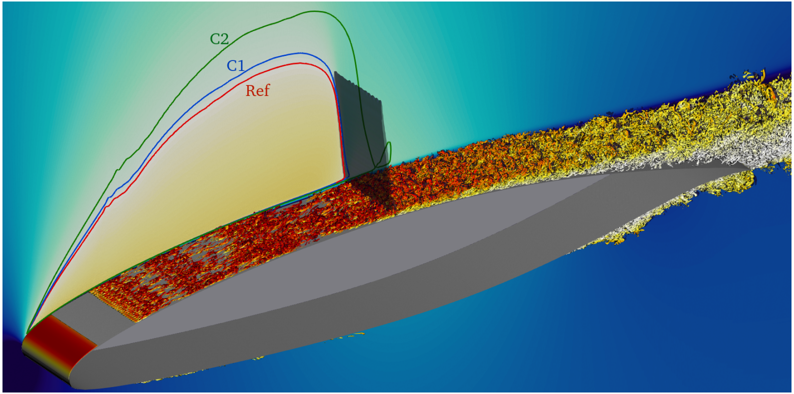
- $A_1 = 0.5$, $\omega = 11.3$, $\kappa_x = 161$
- $x_{s,1} = 0.3c$, $x_{e,1} = 0.78c$

For C2:

- $A_2 = 0.68$, $\omega = 11.3$, $\kappa_x = 161$
- $x_{s,2} = 0.2c$, $x_{e,2} = 0.78c$

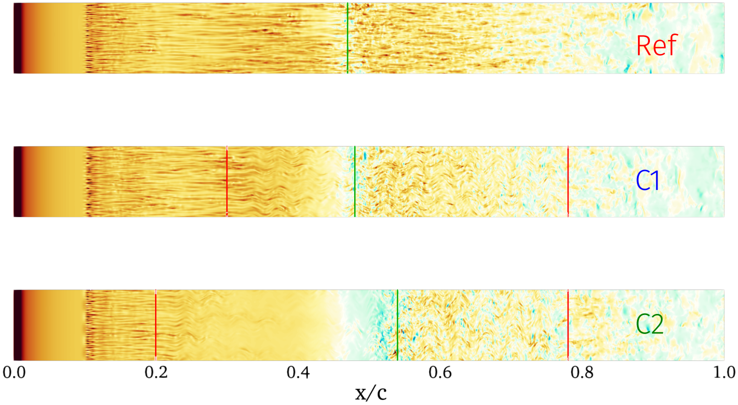


The mean flow



— $M = 1$ (Ref)
— $M = 1$ (C1)
— $M = 1$ (C2)

Instantaneous flow: near-wall fluctuations

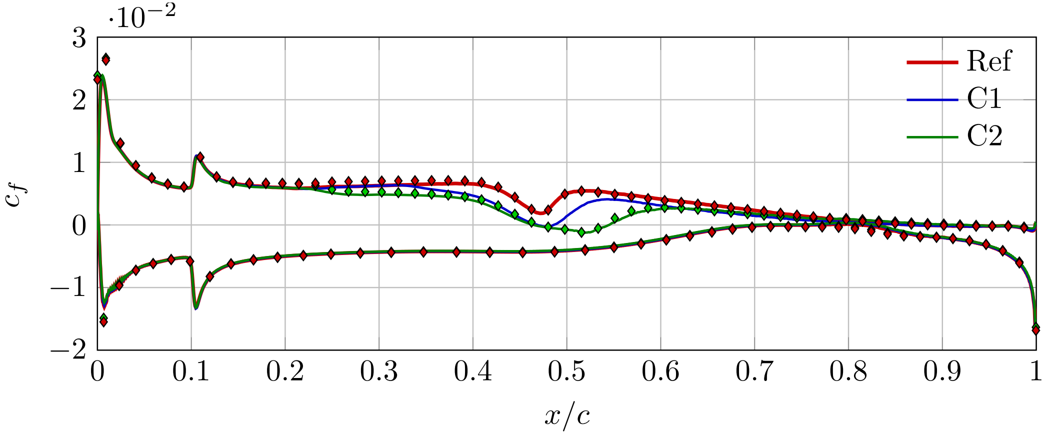


🟩 shock position

🟥 x_s and x_e

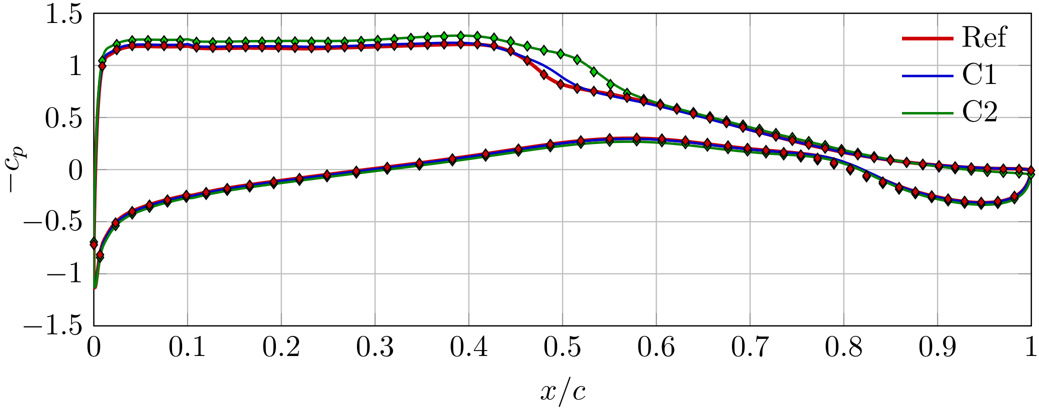
Friction coefficient

$$c_f = \frac{2\tau_w}{\rho_\infty U_\infty^2}$$



Pressure coefficient

$$c_p = \frac{2(p_w - p_\infty)}{\rho_\infty U_\infty^2}$$



Aerodynamic forces

At the same incidence angle $\alpha = 4°$

	Reference	C2	Δ_2	C2 $(\alpha = 3.45°)$	Δ_2
C_ℓ	0.740	0.825	+11.3%	0.730	-1.3%
C_d	0.0247	0.0245	-0.8%	0.0210	-15.0%
$C_{d,f}$	0.0082	0.0071	-13.4%	0.0074	-9.7%
$C_{d,p}$	0.0165	0.0174	+5.5%	0.0136	-17.6%
C_ℓ/C_d	29.7	33.7	+13.5%	34.8	+17.2%

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How does it scale to a full aircraft?

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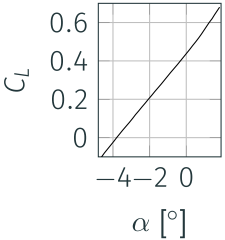
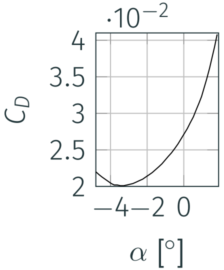
Assumptions:

- The wing is responsible for the entire lift and 1/3 of the non-lift-induced drag
- ΔC_ℓ and ΔC_d induced by control do not change along the wing span
- ΔC_ℓ and ΔC_d induced by control do not change with α, Re_∞ and M_∞

How does it scale to a full aircraft?

- DLR-F6 (Second AIAA CFD drag prediction workshop)
- Data from `https://aiaa-dpw.larc.nasa.gov`
- Control C2 in flight conditions: $M_\infty = 0.75$, $Re_\infty = 3 \times 10^6$





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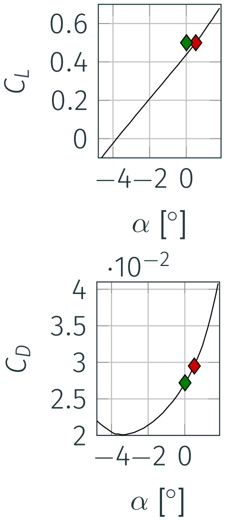
	Uncontrolled	Controlled
C_L	0.5	0.5
α	0.52°	0.0125°
C_D	0.0295	0.0272



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	Uncontrolled	Controlled
C_L	0.5	0.5
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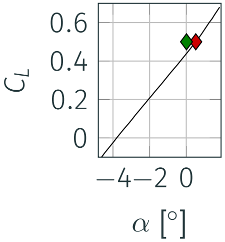
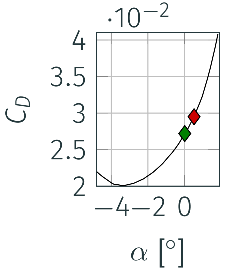
C_D	0.0295	0.0272

$\Delta C_D \approx 9.0\%$

actuation power ≈ 1% of the overall power expenditure

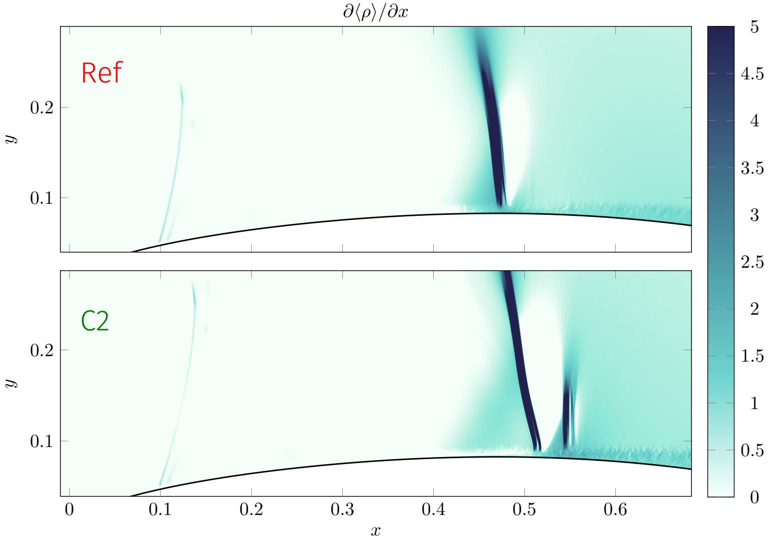




Conclusions

- The global aerodynamic performance of the wing is improved by locally reducing skin friction over a portion of the suction side
- We measure $\Delta C_d \approx 15\%$ and $\Delta C_D \approx 9\%$ (but more is possible!)
- Skin-friction drag reduction should be considered as a tool and not only as a goal

Mean flow: downstream shift of the shock



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At the same incidence angle $\alpha = 4°$

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C_ℓ	0.740	0.751	+1.5%	0.825	+11.3%	0.730	-1.3%
C_d	0.0247	0.0236	-4.5%	0.0245	-0.8%	0.0210	-15.0%
$C_{d,f}$	0.0082	0.0076	-7.3%	0.0071	-13.4%	0.0074	-9.7%
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Computational details

- compressible NS solver for a calorically perfect gas: second-order FV method, with locally 3rd-order WENO numerical flux with Ducros sensor
- domain with spanwise width $0.1c$, mesh radius $25c$
- incoming laminar flow, periodic spanwise boundary conditions
- baseline mesh $4096 \times 512 \times 256$
- resolution after Zauner, De Tullio & Sandham (2019) (but at lower *Re*), then checked a posteriori to obey requirements set forth by Hosseini et al. 2016
- statistics accumulated for $40c/U_\infty$