Streamwise travelling waves for drag reduction on a transonic airfoil

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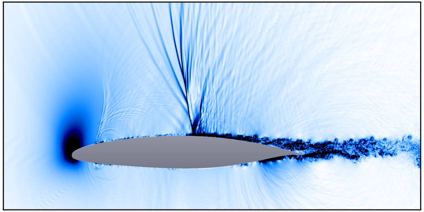
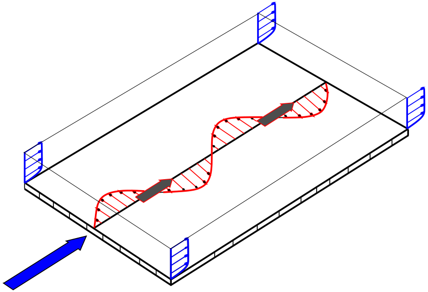


Reduction of friction drag

Streamwise travelling waves (StTW)

Incompressible plane flows:

- Inhibition of wall turbulence
- Large friction reduction
- Large net power savings



$$w(x,t) = A\sin(kx - \omega t)$$

Reduction of ~~friction~~ drag

What about pressure drag?

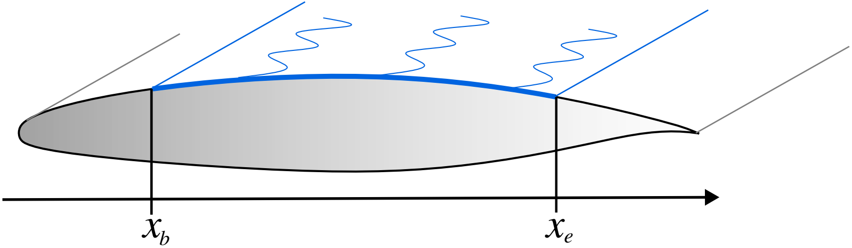
Are StTW beneficial in complex geometries?

Reduction of ~~friction~~ drag

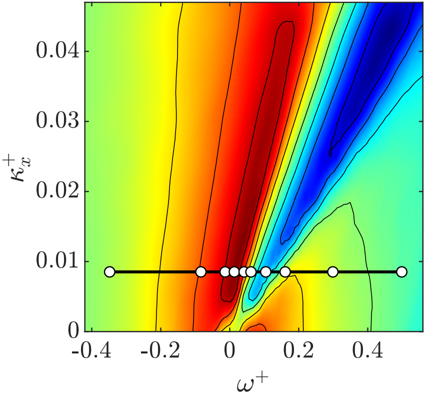
What about pressure drag?

Are StTW beneficial in complex geometries?

Transonic wing: friction drag + (shape drag + wave drag)



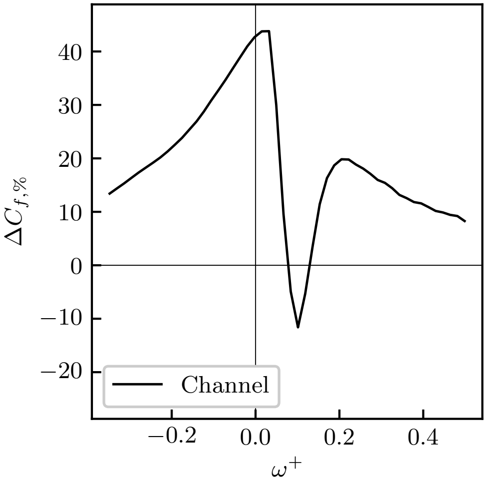
Construction of the numerical database



- Compressible DNS with 536M points (validation with 1.2B points)
- $\alpha = 4°$ $M_\infty = 0.7$ $Re_\infty = 300'000$
- Variation of control parameters (A, k, ω, x_b, x_e)

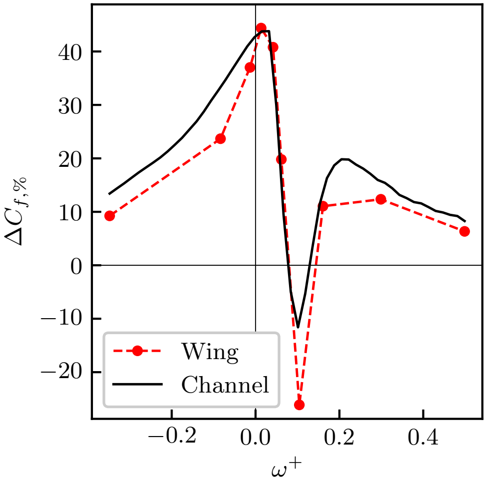
The comparison with the incompressible channel

- Max ΔC_f for slow, forward-traveling waves

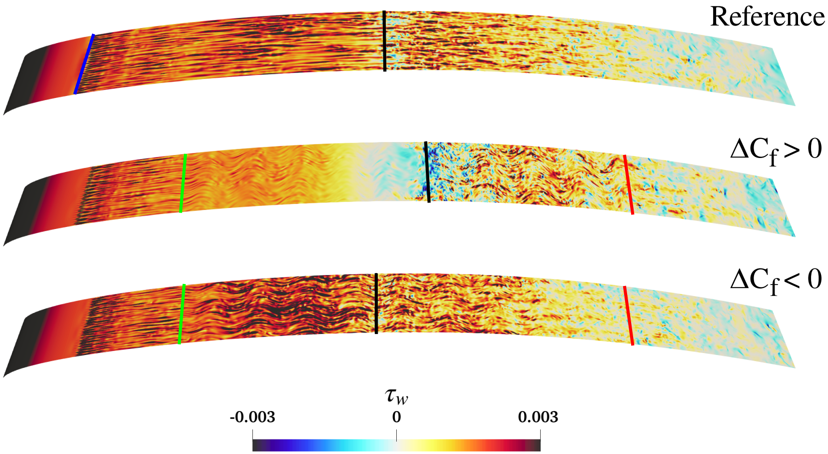


The comparison with the incompressible channel

- Max ΔC_f for slow, forward-traveling waves



The shear stresses on the transonic wing

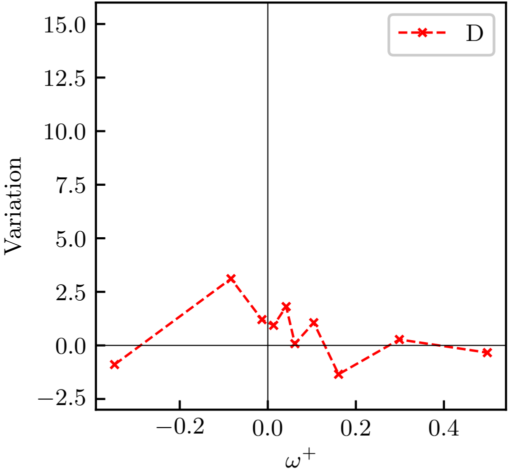


Global forces and moments

The integral of the surface stresses

Constant angle of attack α:

- Drag is (!) unaffected

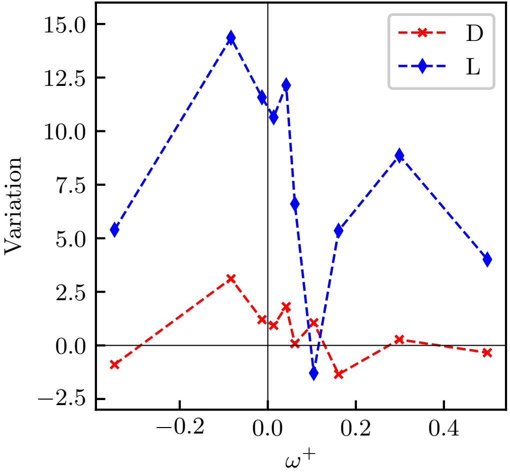


Global forces and moments

The integral of the surface stresses

Constant angle of attack α:

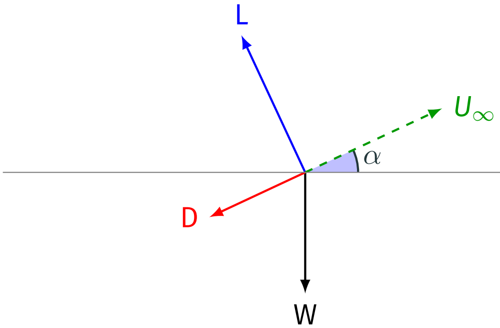
- Drag is (!) unaffected
- Lift is increased



The total drag of an aircraft

The extrapolation

StTW increase Lift, but in cruise conditions Lift is linked to Weight!



On the full aircraft, $\Delta D = 12\%$ with negligible actuation costs!

Conclusions

- Large drag reduction achieved!
- Limitation: Low Re_∞

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JFM PAPERS

Aerodynamic performance of a transonic airfoil with spanwise forcing

Niccolò Berizzi[1], Davide Gatti[2], Giulio Soldati[3], Sergio Pirozzoli[3] and Maurizio Quadrio[1]

The numerical code

- Full compressible Navier–Stokes solver [1]
- 2^{nd} order finite–volumes approach
- WENO[2] numerical flux, modified Ducros sensor for shock detection
- Low–storage, 3^{rd} order Runge–Kutta temporal scheme, $\Delta t = 1.2 \times 10^{-4} c/U_\infty$
- Numerical tripping [3] for turbulence at $x/c = 0.1$
- Averaging window for statistics: at least $40c/U_\infty$

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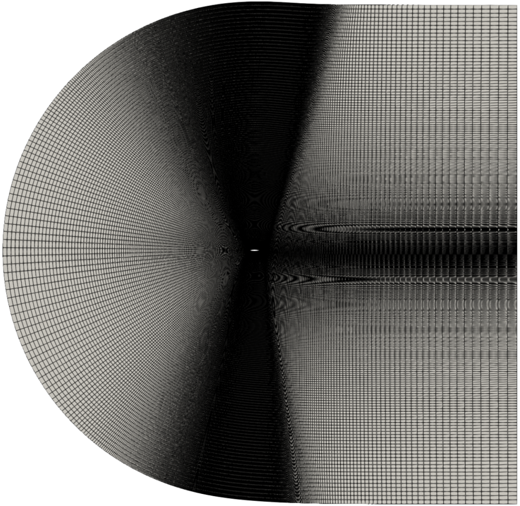
[1] Memmolo *et al.* IJNMHFF 2018

[2] Liu *et al.* JCP 1994

[3] Schlatter & Örlü, JFM 2012

Grid details



C-grid:

- Radius of 25c, outflow at 25c downstream, spanwise extrusion of 0.1c
- $4096 \times 512 \times 256 \approx 537 \times 10^6$ points
- Hyperbolic–tangent clustering in wall-normal direction, uniform extrusion in *z*
- Fully-resolved turbulent scales: $\Delta x^+ < 10, \Delta y^+ < 0.5, \Delta z^+ < 5$

Detecting the shock wave

The shock is present if the modified Ducros [4] Θ sensor satisfies:

$$\Theta \equiv \max\left(-\frac{\nabla \cdot \boldsymbol{u}}{\sqrt{(\nabla \cdot \boldsymbol{u})^2 + (\nabla \times \boldsymbol{u})^2 + (U_\infty / c)^2}}; 0\right) > 0.99$$

- x_s: closest point to the wall where $\Theta > 0.99$
- Shock intensity: wall normal average of M_{pre}/M_{post}

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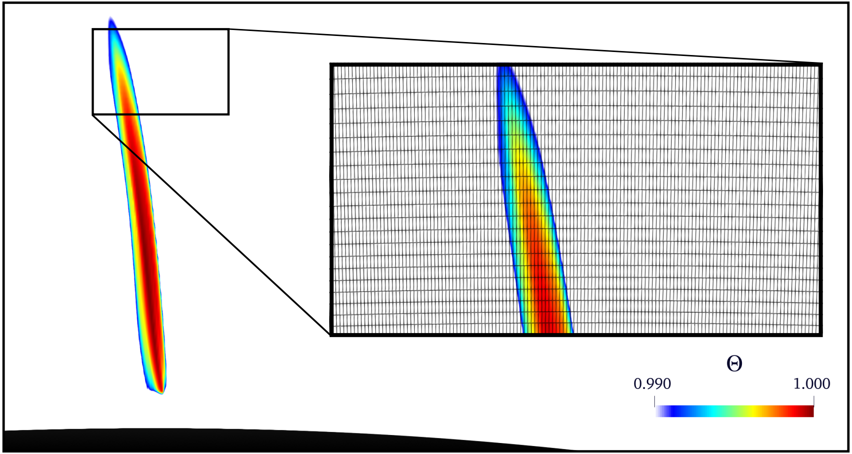
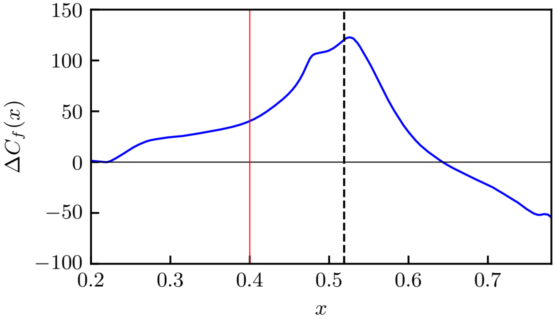
[4] Pirozzoli, ARFM 2011

Detecting the shock wave



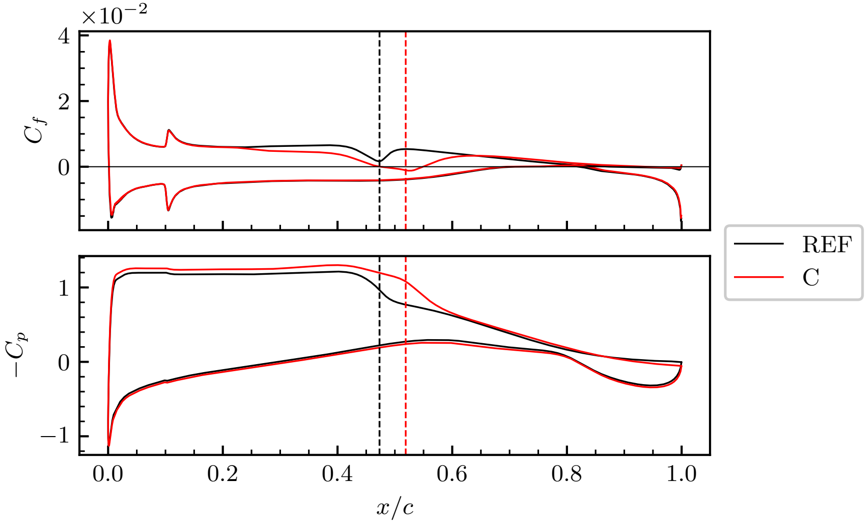
Friction: a compromise

- Low Reynolds $\Rightarrow$ artificial tripping
- Laminar–to–turbulent transition
- Non–constant $\Delta C_f(x)$
- Non–costant shock position



Data is extracted at $x/c = 0.4$

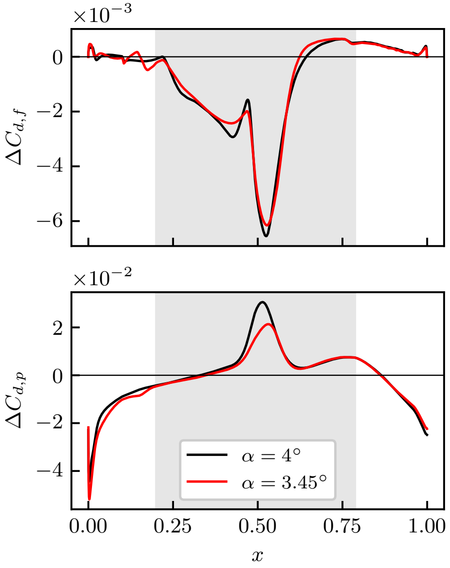
Friction and pressure coefficients



Effect on friction and pressure drag

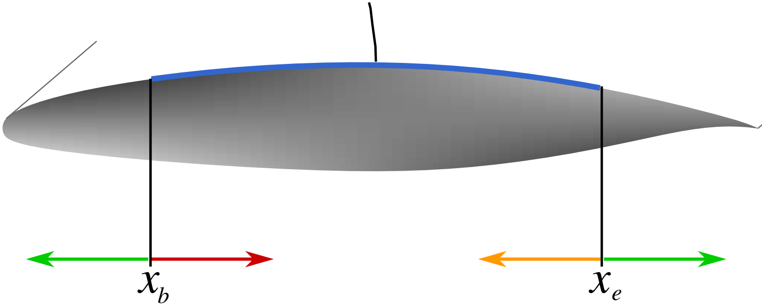
Suction side:

- $\Delta C_{d,f}$ does not depend on α
- $\Delta C_{d,p}$ is larger with larger α



Control position and extension

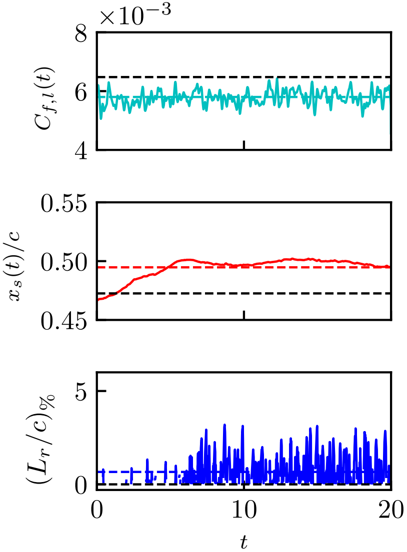
A non-trivial choice



The control effects must be developed **before** interacting with the shock!

The response to sudden StTW activation

1. The turbulent activity is inhibited:
   $C_f \Downarrow$
2. The shock is shifted downstream:
   $x_s \Uparrow$
3. A recirculation bubble of length L_r
   settles in the mean flow



Extrapolation to the Full Aircraft

The hypotheses adopted

1. Lift is only generated by the wing
2. Changes in C_L, C_D are constant along the wing and with $Re_\infty, M_\infty, \alpha$
3. Lift-induced Drag = 2/3 of the overall Drag
4. $S_{act} = S/12$

Extrapolation to the Full Aircraft

The aircraft

- DLR-F6 wing-body configuration [5]
- $\alpha_0 = 0.52^\circ \qquad Re_\infty = 3 \times 10^6 \qquad M_\infty = 0.75$
- $C_{L,0} = 0.5 \qquad C_{D,0} = 0.0295$

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[5] Laflin *et al. JA 2005*, *`https://aiaa-dpw.larc.nasa.gov/Workshop2/DPW_forces_WB_375`*

Extrapolation to the Full Aircraft

The procedure

1. The new C_L at α_0 is computed
2. The α_{new} yielding the original lift is computed
3. The new uncontrolled C_D is computed from the DLR-F6 $C_D - \alpha$ curve
4. The final drag coefficient is augmented by the StTW direct effect at α_{new}

$$\Delta C_D^{\alpha} = 8\% \qquad \Delta C_D^{C} = 4.4\%$$

Flow separation

- As the shock is shifted downstream, the adverse ∇p intensifies
- A separation with length L_r ensues

L_r is related to ΔC_f and x_s