Skin-friction drag reduction in turbulent flows

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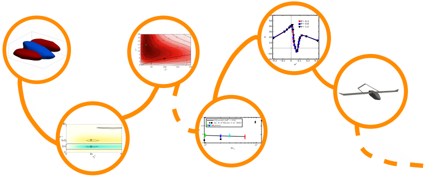
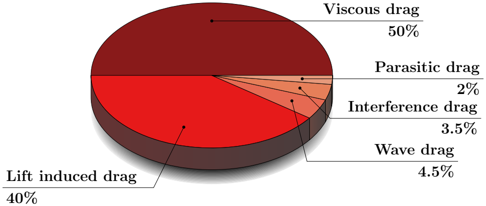


Motivation

- 50% of an aircraft's drag comes from viscous effects
- An efficient drag reduction ($\mathcal{R}$) technology would have huge economic and environmental benefits

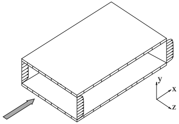
$$\mathcal{R} = \frac{C_{f,0} - C_f}{C_{f,0}}$$

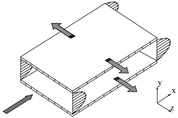


Roadmap

Understanding wall-bounded turbulence towards its control

- linear description
- complete description
- conceptual description

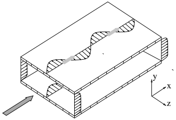




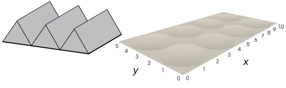
$$w_w = A \sin(\omega t)$$

Understanding controlled turbulence towards applications

- Re effect
- Mach effect
- complex configuration



$$w_w = A \sin(\kappa_x x - \omega t)$$



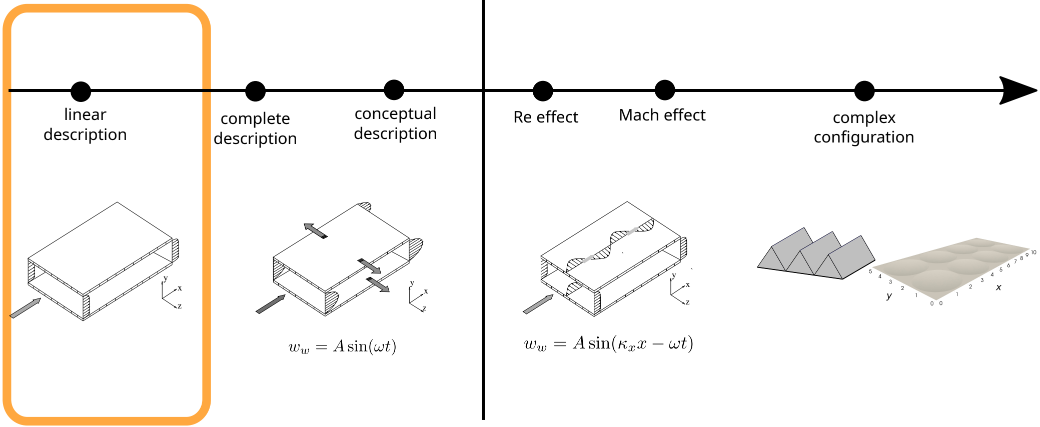
Part I:

Understanding wall-bounded turbulence towards its control

Understanding wall-bounded turbulence towards its control

Understanding wall-bounded turbulence towards its control

Understanding controlled turbulence towards applications

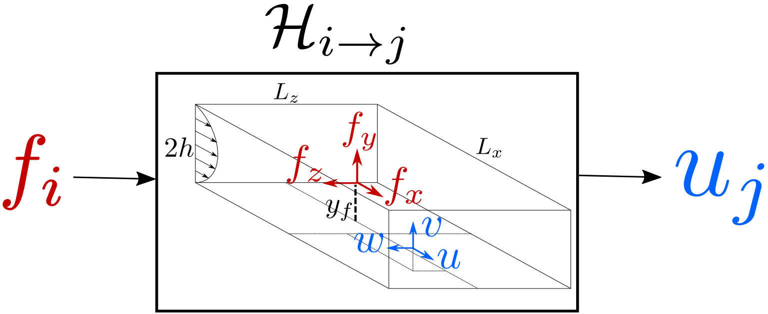


$$w_w = A\sin(\omega t)$$

$$w_w = A\sin(\kappa_x x - \omega t)$$

The linear impulse response function (LIRF)

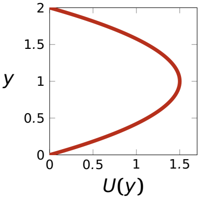
Relationship between each volume force and each velocity component



$$\langle u_j(\alpha, y, \beta, t; y_f)\rangle = \int_{-\infty}^{+\infty} \langle \mathcal{H}_{i\to j}(\alpha, y, \beta, t-\tau; y_f) \;\; \epsilon \; \mathrm{f}_i(\alpha, \beta, \tau; y_f)\rangle \; d\tau$$

How to define and measure the LIRF

Laminar



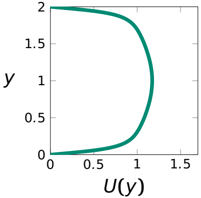
- ϵ needs to be small enough for the response to be linear

Previous work

- Stability theory: Jovanovic & Bamieh 2005, JFM
- Control theory: Höpffner et al. 2005, JFM

How to define and measure the LIRF

Pseudo-turbulent



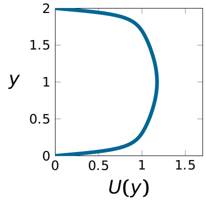
- ϵ needs to be small enough for the response to be linear

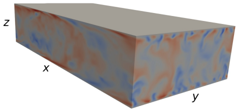
Previous work

- Resolvent analysis: McKeon & Sharma 2010, JFM
  Vararevu et al. 2019, JFM

How to define and measure the LIRF

Turbulent





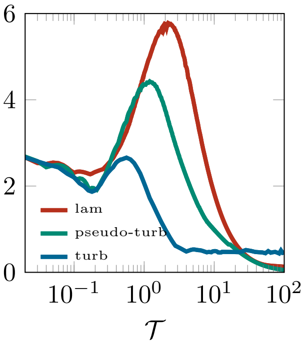
- ϵ needs to be small enough for the response to be linear
- ϵ too small compared to turbulent fluctuations
- LIRF can be computed as an ensamble average
- LIRF can be computed as an input-output correlation

Previous work

- Luchini et al. 2006, PoF

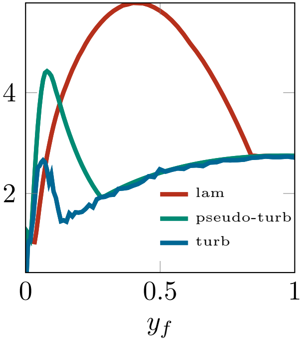
Result: $\mathcal{H}_{y\to u}$

$\max_{\alpha,y,\beta,y_f} |\mathcal{H}_{y\to u}(\alpha, y, \beta, t; y_f)|$



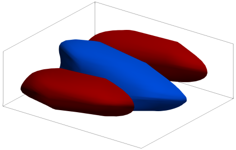
- transient growth
- $T^+_{\text{turb}} \approx 5$

$\max_{\alpha,\beta,t,y_f} |\mathcal{H}_{y\to u}(\alpha, y, \beta, t; y_f)|$



- buffer layer
- $y^+_{f,\text{turb}} \approx 10$

$\mathcal{H}_{y\to u}(x, y, z, t; y_f^+ \approx 10)|$



- streaks

Understanding wall-bounded turbulence towards its control

Understanding wall-bounded turbulence towards its control

Understanding controlled turbulence towards applications

linear description

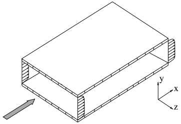
complete description

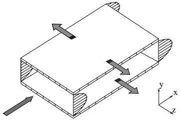
conceptual description

Re effect

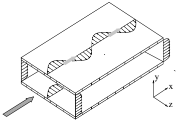
Mach effect

complex configuration

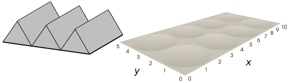




$$w_w = A\sin(\omega t)$$



$$w_w = A\sin(\kappa_x x - \omega t)$$

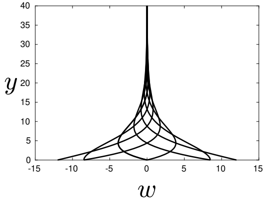


The oscillating wall (Jung et al. 1992, PoF)

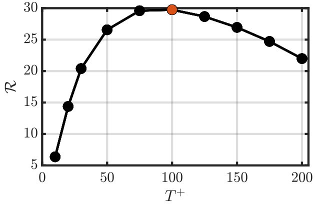
$$w_w = A \sin(\omega t) \qquad \omega = \frac{2\pi}{T}$$

The Stokes Layer

$$w(y) = A e^{y/\sqrt{\nu T/\pi}} \sin\left(\frac{2\pi}{T} t - \frac{y}{\sqrt{\nu T/\pi}}\right)$$

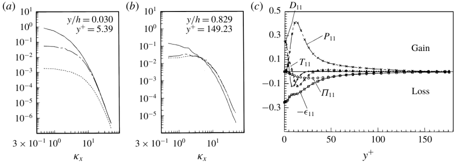


Optimum oscillation period



Phase-aware Anisotropic Generalised Kolmogorov Equations (φAGKE)

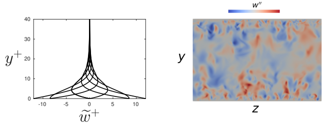
- Anisotropic flows (Gatti et al. 2020, JFM)



$\delta u_i' \delta u_j' =$

$(u_i'(X + r/2, t) - u_i'(X - r/2, t))(u_j'(X + r/2, t) - u_j'(X - r/2, t))$

- Periodic/coherent flows



$$u_i = U_i + \underbrace{\tilde{u}_i + u_i''}_{u_i'}$$

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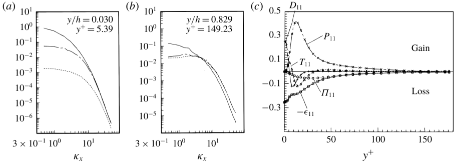

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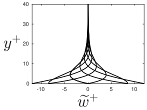
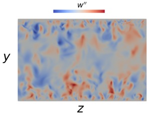




$$u_i = U_i + \underbrace{\tilde{u}_i + u_i''}_{u_i'}$$

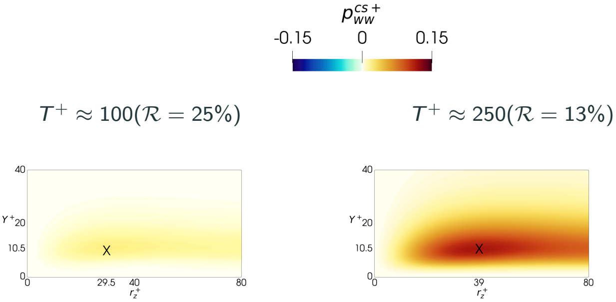
$$\frac{2\pi}{T}\frac{\partial \overline{\delta \tilde{u}_i \delta \tilde{u}_j}}{\partial \varphi} + \frac{\partial \phi^c_{k,ij}}{\partial r_k} + \frac{\partial \psi^c_{k,ij}}{\partial X_k} = p^{mc}_{ij} - p^{cs}_{ij} + \pi^c_{ij} + d^c_{ij} + \zeta^c_{ij}$$

$$\frac{2\pi}{T}\frac{\partial \overline{\delta u_i'' \delta u_j''}}{\partial \varphi} + \frac{\partial \phi^s_{k,ij}}{\partial r_k} + \frac{\partial \psi^s_{k,ij}}{\partial X_k} = p^{ms}_{ij} + p^{cs}_{ij} + \pi^s_{ij} + d^s_{ij}$$

$$p^{cs}_{ww} = -2\overline{\delta v'' \delta w''}\frac{d\tilde{w}}{dy}$$

Interaction between the control and the turbulence

$$\sum_{\varphi} p_{ww}^{cs}$$



p_{ww}^{cs+}

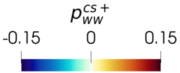
$T^+ \approx 100(\mathcal{R} = 25\%)$

$T^+ \approx 250(\mathcal{R} = 13\%)$

One way interaction:

coherent → stochastic

Interaction between the control and the turbulence

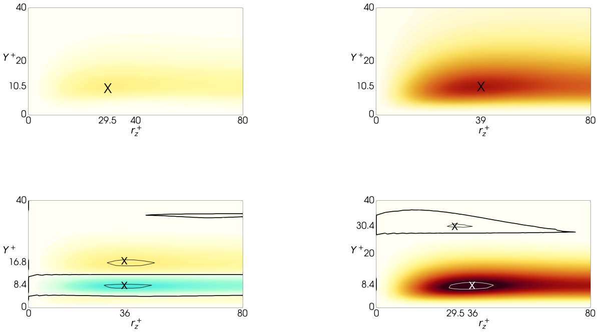


$T^+ \approx 100 (\mathcal{R} = 25\%)$

$T^+ \approx 250 (\mathcal{R} = 13\%)$

$\sum_{\varphi} p_{ww}^{cs}$

$p_{ww}^{cs}(\varphi = \frac{2\pi}{4} T)$



One way interaction:

coherent → stochastic

Two ways interaction:

coherent ↔ stochastic

Interpretations of the oscillating wall optimal parameter

Maximum $\mathcal{R}$: $T^+_{opt} \approx 100$

Possible interpretations:

- Time scale
- Longitudinal length scale
- Lateral displacement
- Penetration depth length scale

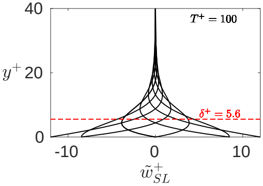
Conceptual description: a thought experiment

Oscillating wall:

Periodic movement of the wall

$$\tilde{w}_{SL} = A e^{y/\delta_{SL}} \sin\left(\frac{2\pi}{T} t - \frac{y}{\delta_{SL}}\right)$$

$$\delta_{SL} = \sqrt{\frac{\nu T}{\pi}}$$

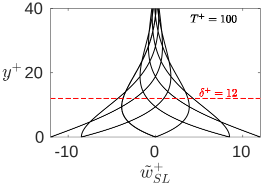


Extended Stokes Layer:

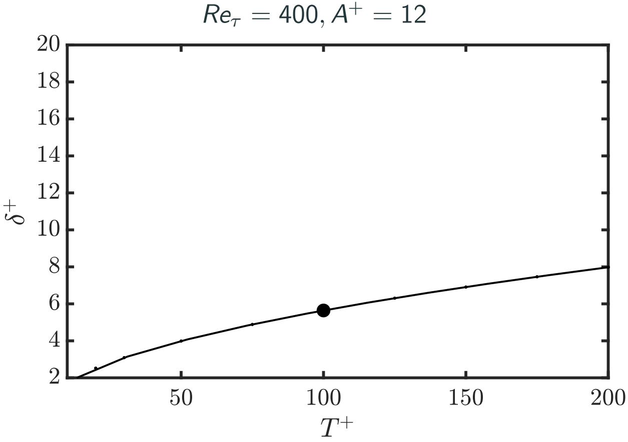
Imposition of velocity profile $w_{ESL}(y, t)$

$$\tilde{w}_{ESL} = A e^{y/\delta_{ESL}} \sin\left(\frac{2\pi}{T} t - \frac{y}{\delta_{ESL}}\right)$$

$$\delta_{ESL} \neq \sqrt{\frac{\nu T}{\pi}}$$



Control parameters: Drag reduction map



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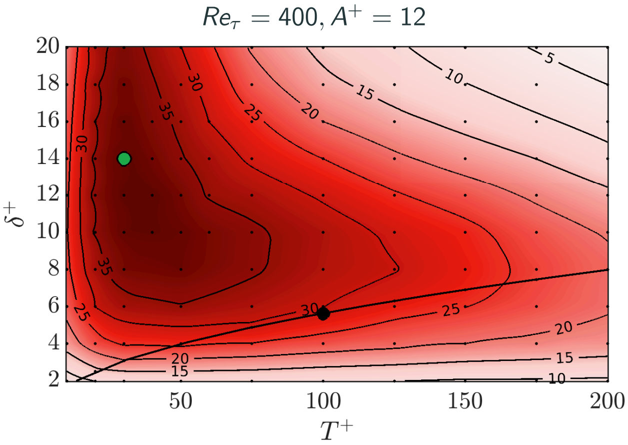
$T^+_{opt} = 100, \delta^+_{opt} \approx 6 \rightarrow \mathcal{R} \approx 30\%$

Control parameters: Drag reduction map



●

$T^+_{opt} = 100, \delta^+_{opt} \approx 6 \rightarrow \mathcal{R} \approx 30\%$

🟢

$T^+_{opt} = 30, \delta^+_{opt} = 14 \rightarrow \mathcal{R} \approx 40\%$

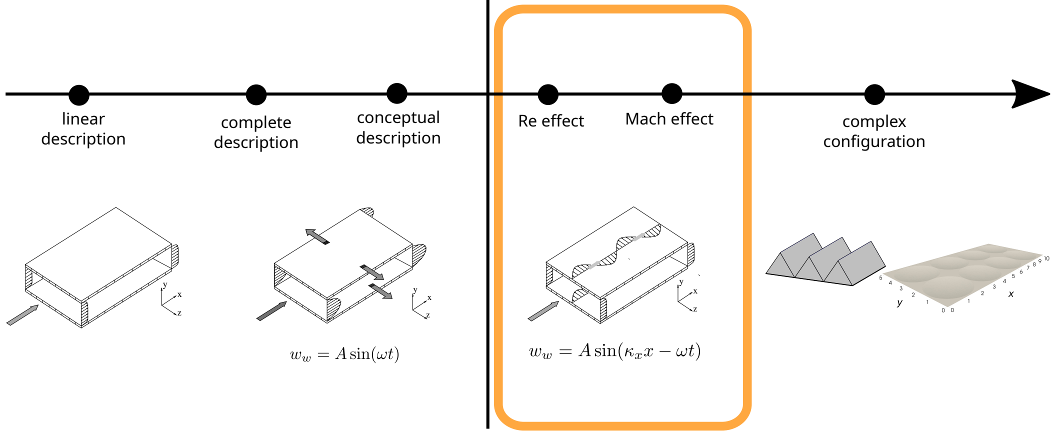
Part II:

Understanding controlled turbulence towards applications

Understanding controlled turbulence towards applications

Understanding wall-bounded turbulence towards its control

Understanding controlled turbulence towards applications



linear description

complete description

conceptual description

Re effect

Mach effect

complex configuration

$w_w = A\sin(\omega t)$

$w_w = A\sin(\kappa_x x - \omega t)$

Motivation

- Gatti & Quadrio 2016, JFM:
  $\mathcal{R}$ marginally decreases with Re

- Marusic et al. 2021, Nat. Commun.:
  $\mathcal{R}$ increases with Re if the control targets large scale structures

Effect of Reynolds number or of the study limitations?

- Gatti & Quadrio 2016, JFM:
  $\mathcal{R}$ marginally decreases with Re

Limitations:

- small domain
- small Re

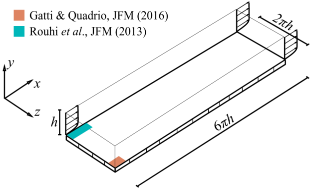
- Marusic et al. 2021, Nat. Commun.:
  $\mathcal{R}$ increases with Re if the control targets large scale structures

Limitations:

- different flows and methods
- LES: small domain
- Experiments: control parameters fixed in outer units

No effect of Reynolds number on drag reduction

- Large-domain DNS
- Open channel flow
- Re_τ: 1000-6000



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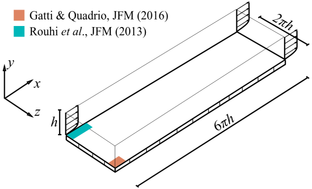
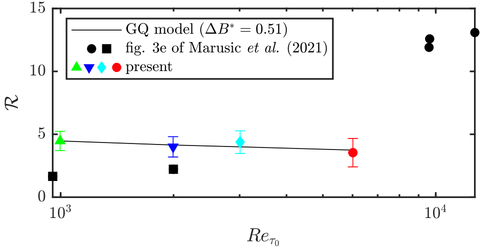


$$A^+ = 5, \kappa_x^+ = 0.00078, \omega^+ = -0.0105$$



$\mathcal{R}$ marginally decreases with Re

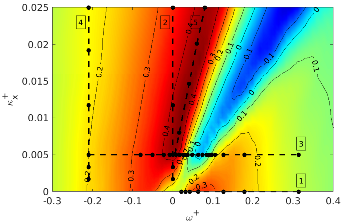
Motivation

- Yao & Hussain 2019, JFM
- Oscillating wall
- $\mathcal{R}$ increases with Mach number

Motivation

- Yao & Hussain 2019, JFM
- Oscillating wall
- $\mathcal{R}$ increases with Mach number

- Present work
- Travelling waves



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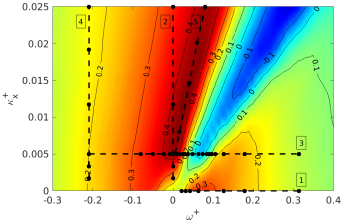
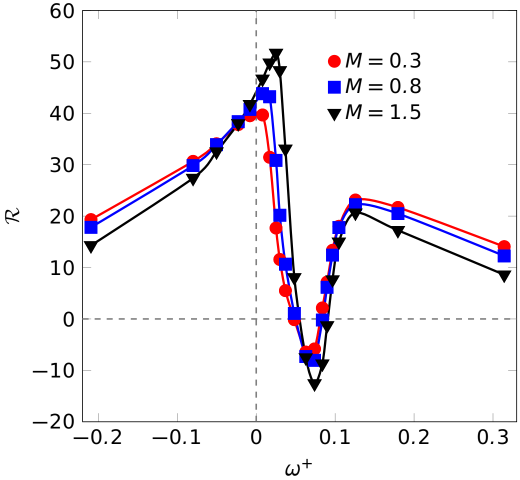


$Re_\tau = 400, A^+ = 12, \kappa_x^+ = 0.005$

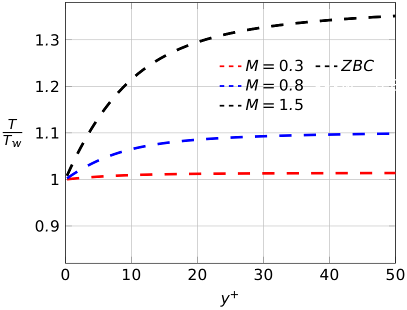


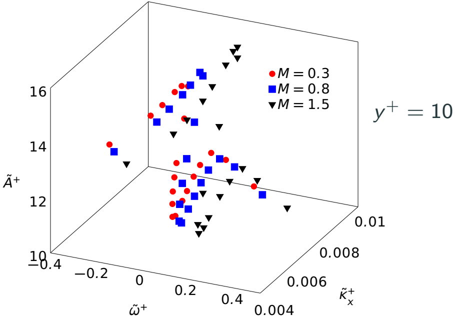
Effect of Mach number or thermodynamics?

Zero Bulk Cooling (ZBC)

Bulk temperature is free to evolve in time

- Different thermodynamic state
- T/T_w of an internal flow





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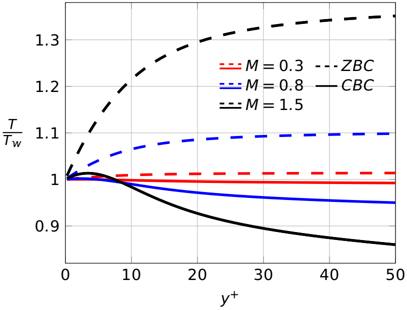
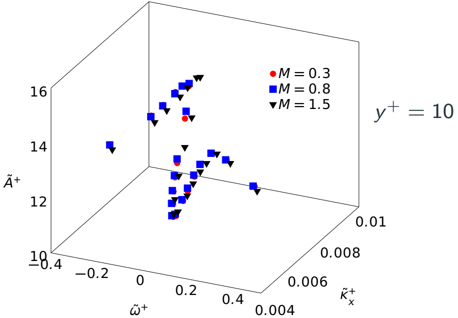


Constrained Bulk Cooling (CBC)

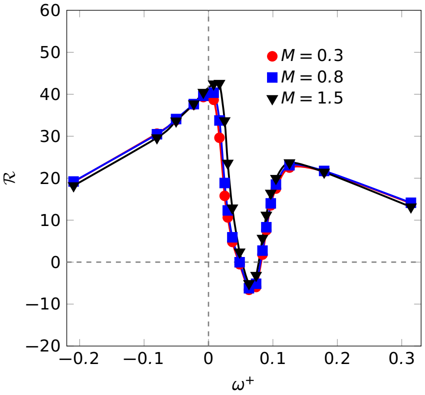
Bulk temperature is fixed in time

Fixed portion of kinetic energy converted into thermal energy at the wall (Cogo et al. 2023, JFM)

- Same control in the buffer layer
- T/T_w of an aeronautical boundary layer



No effect of Mach number on drag reduction

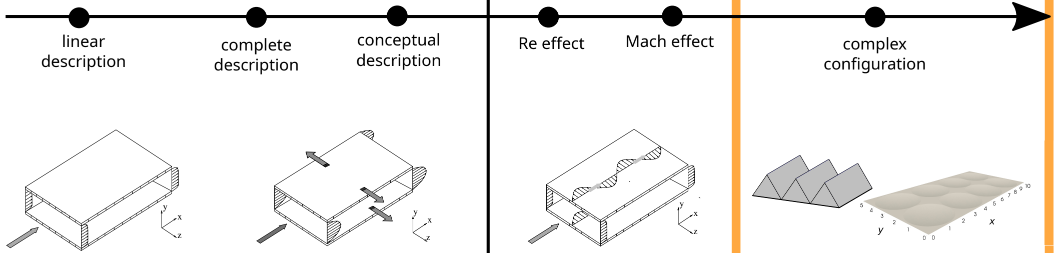


$\mathcal{R}$ almost constant with M

Understanding controlled turbulence towards applications

Understanding wall-bounded turbulence towards its control

Understanding controlled turbulence towards applications



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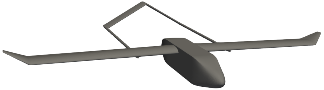
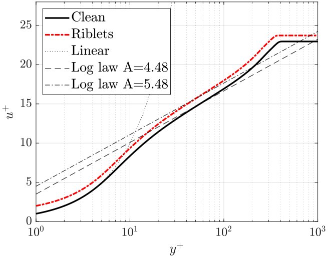
Large-scale modifications of the flat geometry

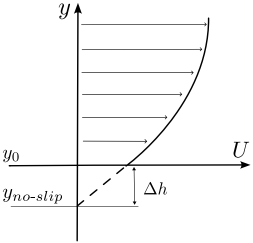
From flat wall to multi-body geometries



- UAV at $Re = \frac{\rho U_\infty c}{\mu} = 5 \times 10^5$
- RANS simulations
- homogenized bc

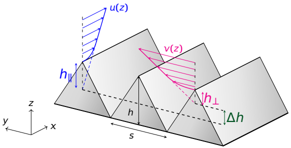


How to test riblets on complex geometries



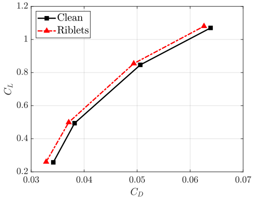
Partial slip BC:

- $u^+(y_0) = u^+(y_{no\text{-}slip}) + \Delta h^+ \frac{\partial U^+}{\partial y^+}|_{y_0}$
- optimal riblets size: $\Delta h^+ = 1$

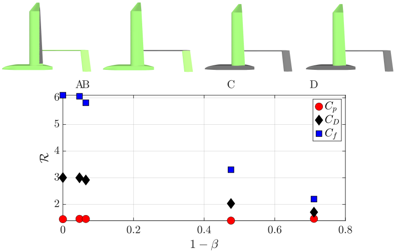


Exploitation of secondary effects

- Increment of aerodynamic efficiency
  - riblets → change P distribution → L
  - $L = const \rightarrow \alpha \downarrow \rightarrow E = C_L/C_D \uparrow$
    - $C_L = const$
    - $C_D \downarrow (C_D = C_f \downarrow + C_p \downarrow)$



- Reduced cost-benefit ratio
  - $1 - \beta = 1 \rightarrow \mathcal{R} = 3\%$
  - $1 - \beta = 0.28 \rightarrow \mathcal{R} = 1.7\%$
  - less than 1/3 of the coverage → more than 1/2 of the efficacy



Conclusions

- The information provided by the presented tools can be aggregated to design a more efficient control law
- The search for an actuator should be postponed until finding the optimum control law

- Spanwise forcing retains its utility under realistic flow conditions and its underlying physics ramains unchanged
- Riblets still work on complex configuration but their production and maintanance costs open up the need of designing more efficient passive techniques

Thank you for your attention!