Boundary-layer Control
for
Turbulent Drag Reduction

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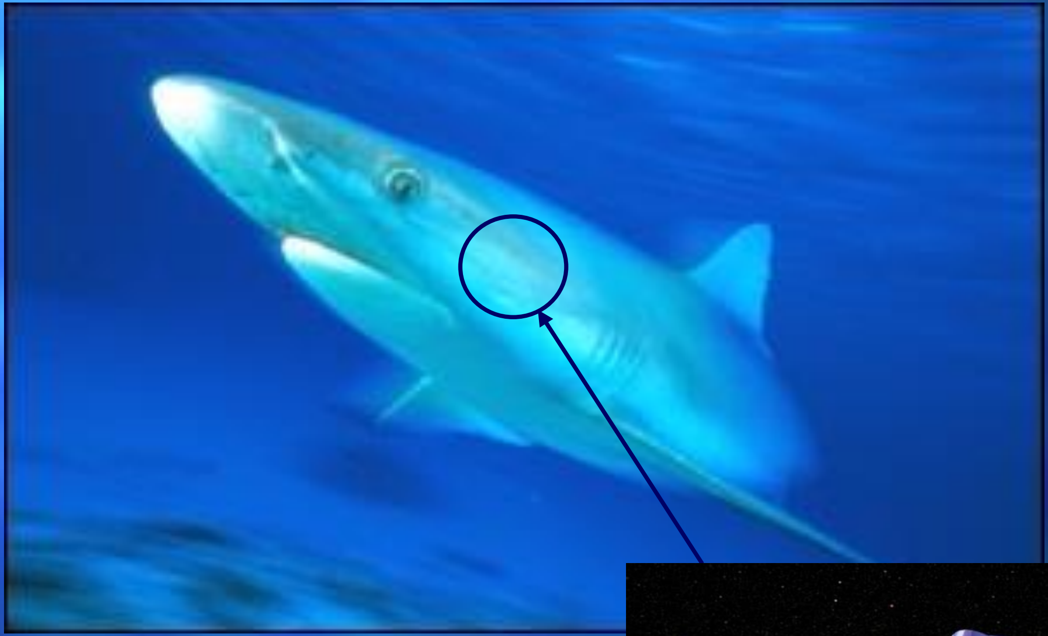
Turbulent Drag Reduction

Near-wall control

- Riblets
- Synthetic jets
- DBD plasma actuators
- Near-wall opposition control
- Spanwise flow & wall oscillations
- Spanwise & streamwise travelling waves

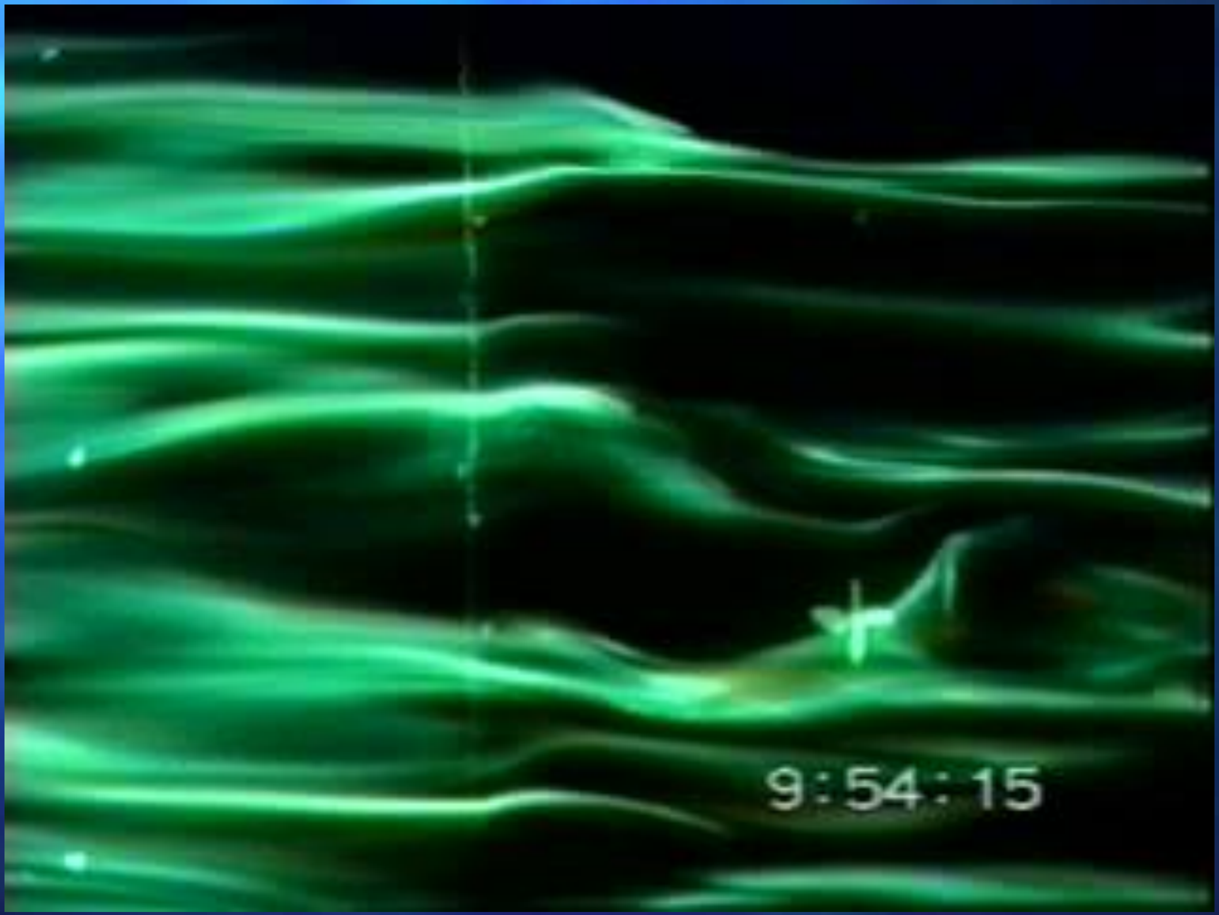
Turbulent Drag Reduction

Riblets



Turbulent Drag Reduction

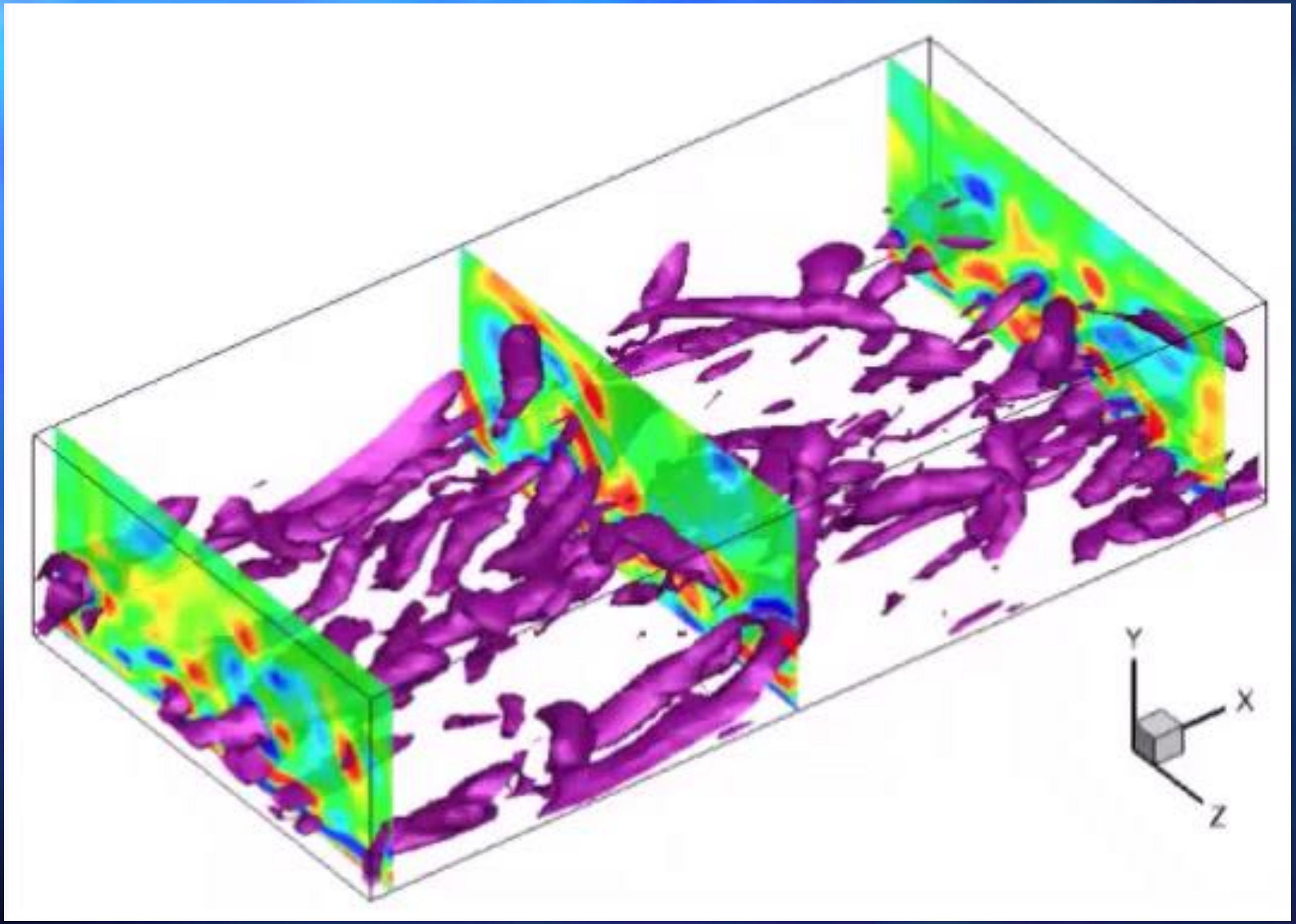
Spanwise-wall oscillation



Leading edge

Turbulent Drag Reduction

Spanwise travelling waves



Turbulent Drag Reduction

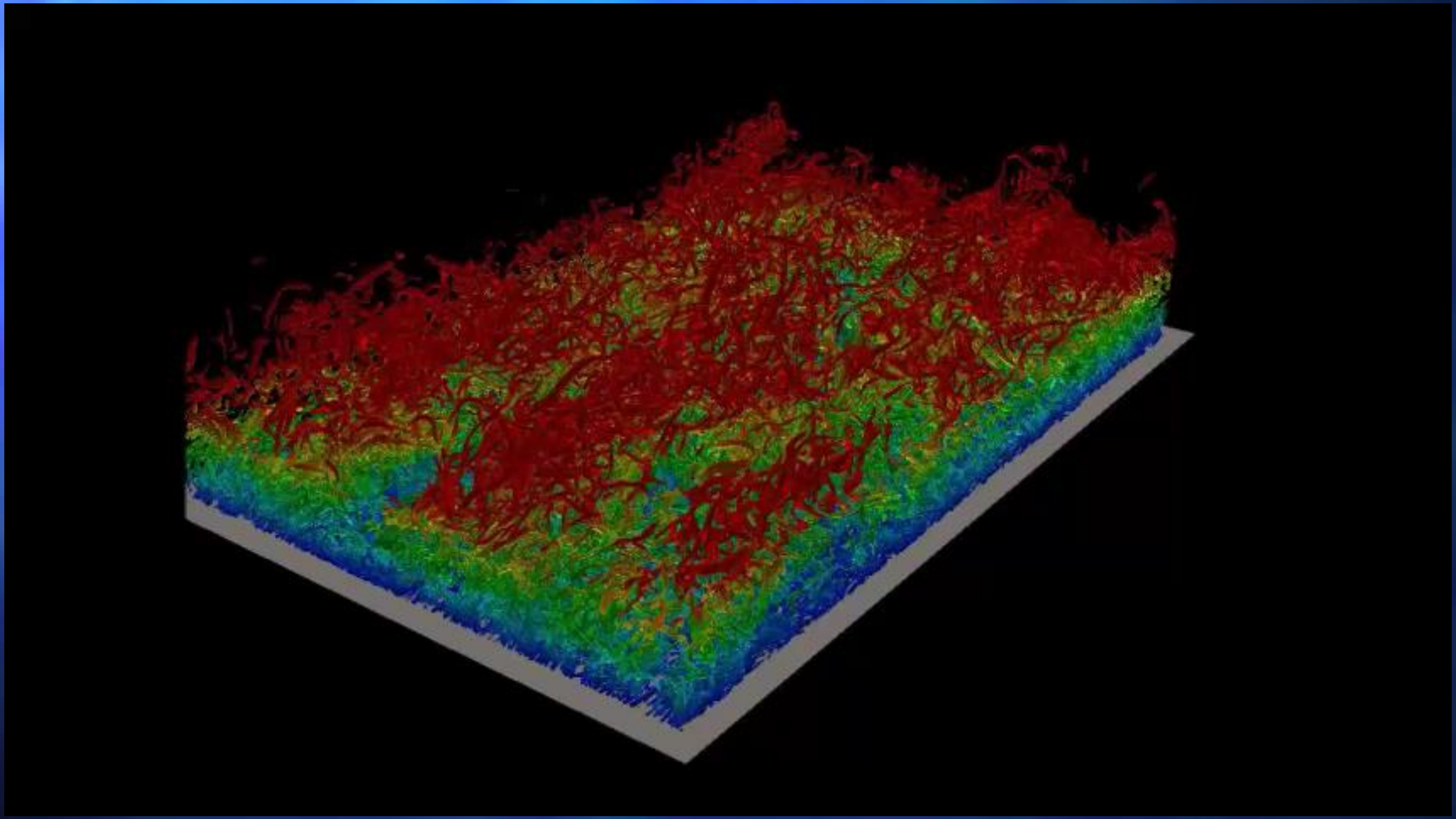
Near-wall control

With an increase in the Reynolds number, the effectiveness of wall-based drag reduction control is reduced together with

- Reduction in sensor/actuator size and
- Increase in required sensor speed, as well as
- Increase in the number of sensors/actuators

Control effects can last about $x^+ \sim 1000$

Turbulent Drag Reduction
Outer-layer control



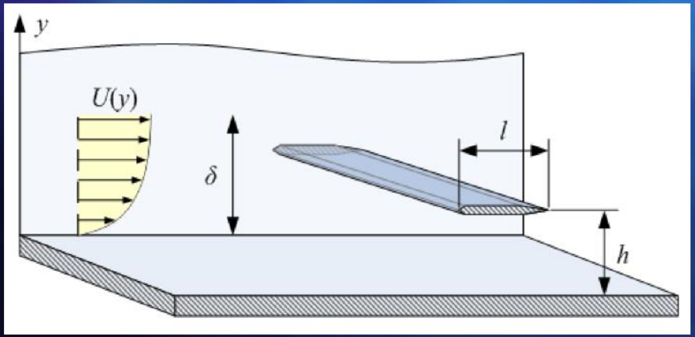
Schlatter (2009)

Turbulent Drag Reduction
Outer-layer control

- LEBU (Large-Eddy Break-up) devices
- Vertical Blade devices
- Large-scale turbulence control
- Outer-layer opposition control

Turbulent Drag Reduction
LEBU devices

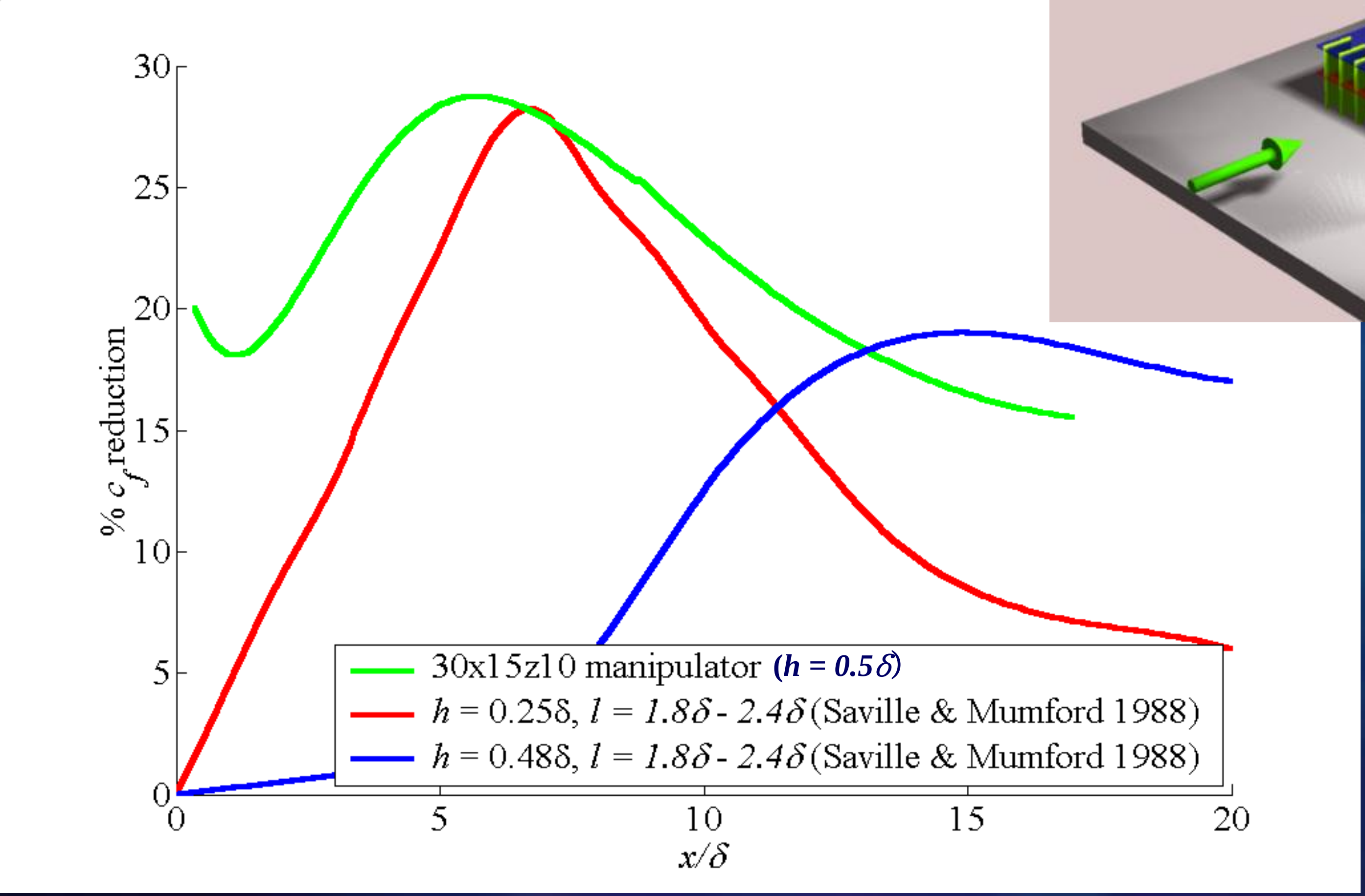
Govindaraju & Chambers (1987)

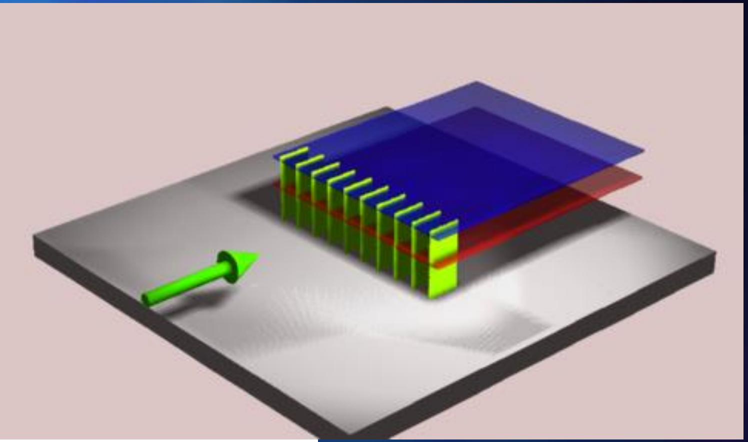


Smith & Gordeyev (2014)

Turbulent Drag Reduction

Vertical Blade devices



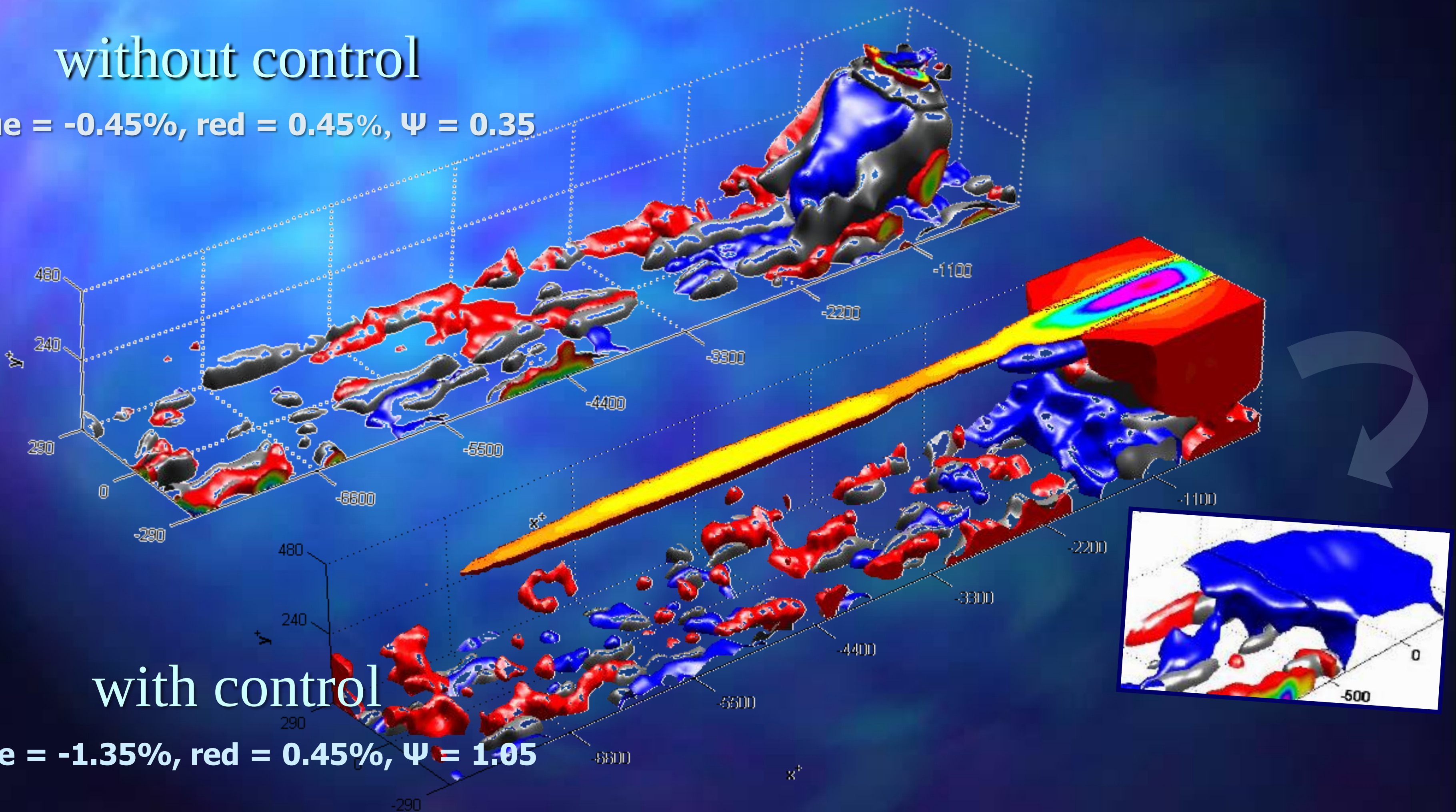


Outer-layer opposition control

Turbulent boundary layers

without control

blue = -0.45%, red = 0.45%, Ψ = 0.35



with control

blue = -1.35%, red = 0.45%, Ψ = 1.05

Turbulent Drag Reduction
Outer-layer control

Outer-layer based control only requires

- Very few sensors and actuators, which are of
- Conventional *size* and *response time*

Control effect lasts much longer ~ 50δ

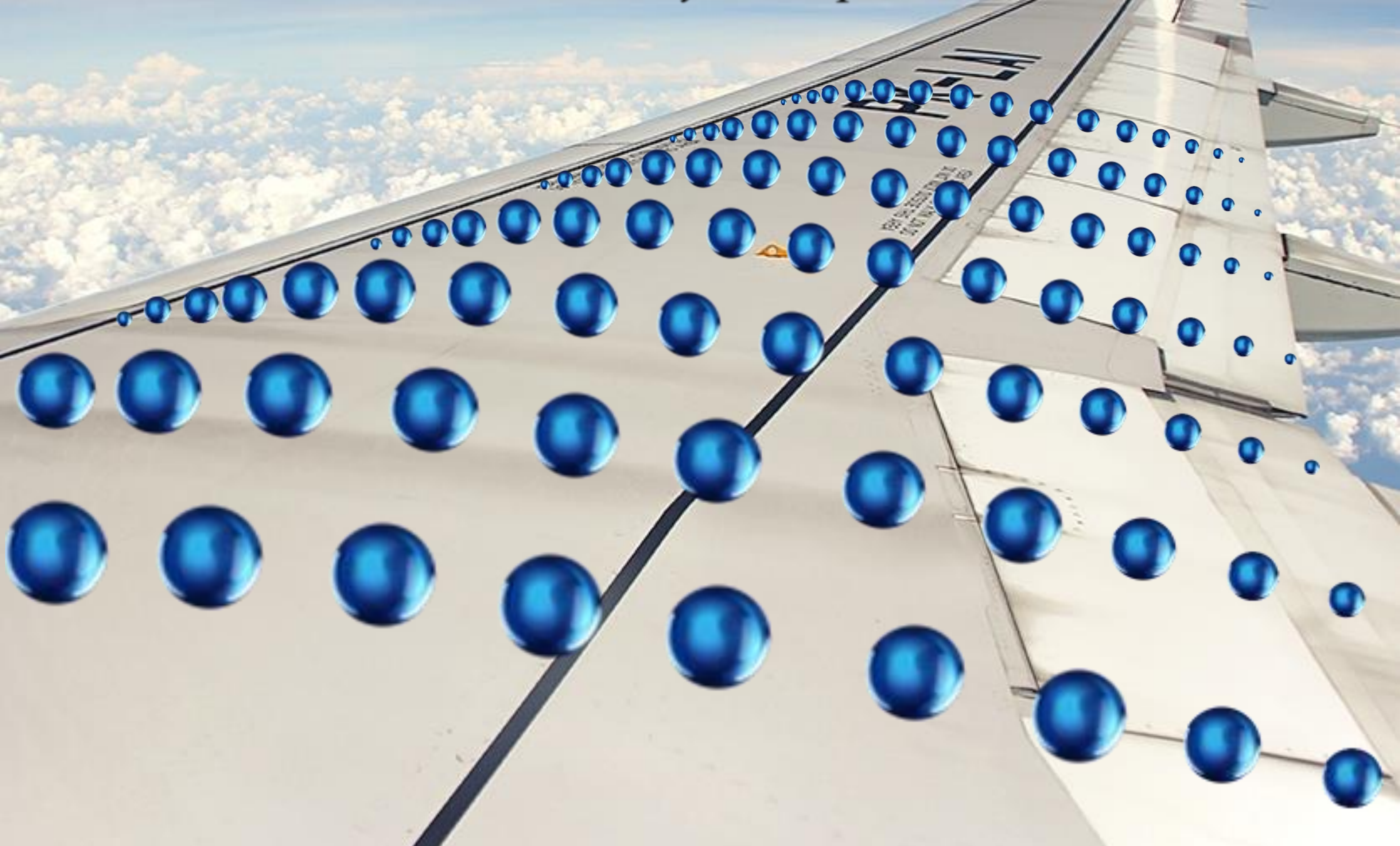
Turbulent Drag Reduction

Emerging techniques

- Uniform blowing
- Laser energy deposition
- Turbulence modulation by solid particles

Turbulent Drag Reduction

Turbulence modulation by solid particles



Turbulent Drag Reduction

Turbulence modulation by solid particles

Relevant parameters for turbulent drag reduction

- Non-dimensional particle size: d^+ and d^+/η^+
- Particle-to-fluid density ratio: $R = \rho_p/\rho_f$
- Stokes number (time-scale ratio): $St = \tau_p/\tau_f$
- Galileo number (gravity/viscosity): $Ga = [(R\text{-}1)\cdot d^{\,3}\cdot g]^{1/2}/\nu$
- Froude number (inertia/gravity): $Fr = d^+/Ga$

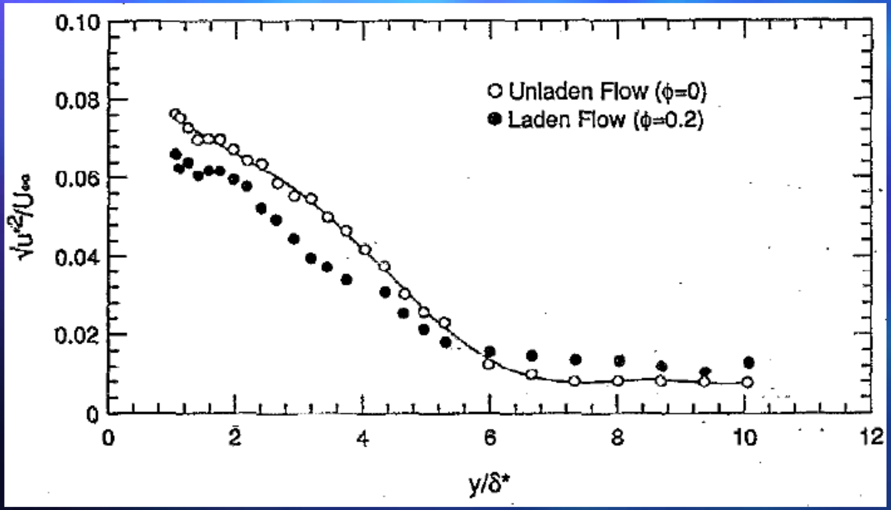
Turbulent Drag Reduction

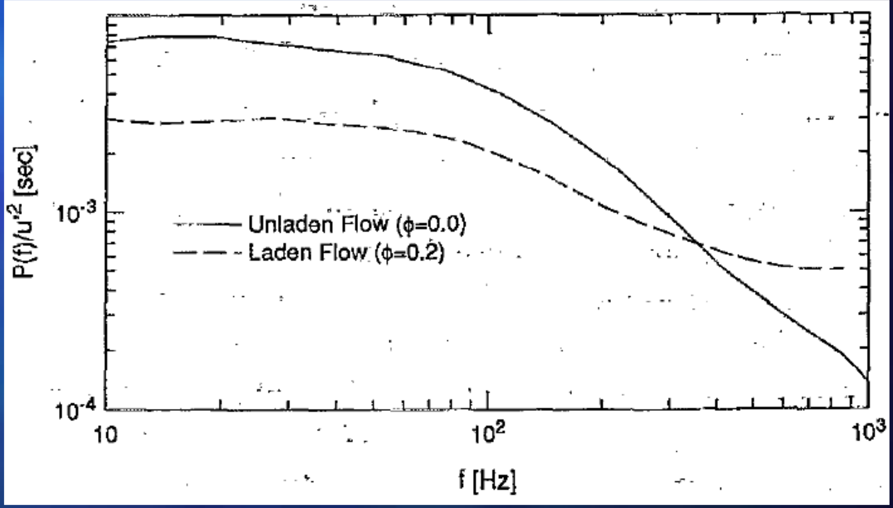
Turbulence modulation by solid particles

$d^+ = 1.7$

$R = 8{,}800$

$St = 53$





Rogers & *Eaton* (1991)

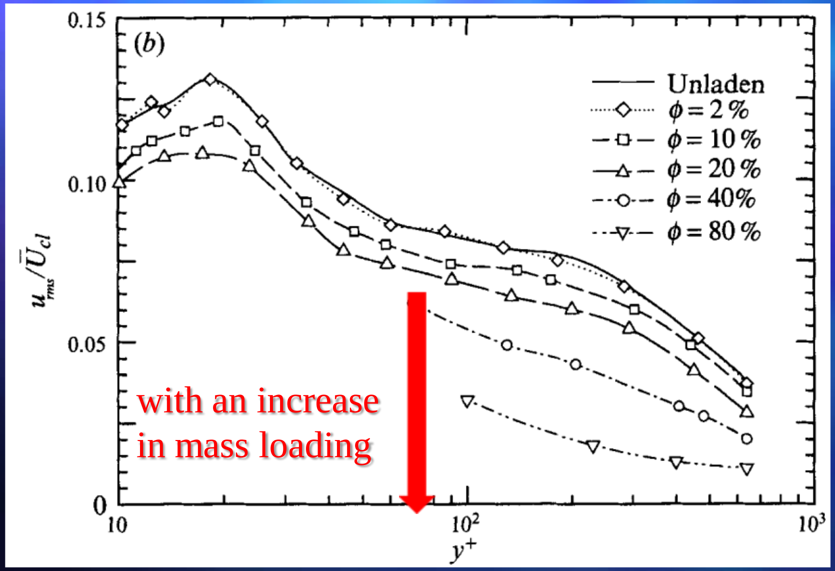
Turbulent Drag Reduction

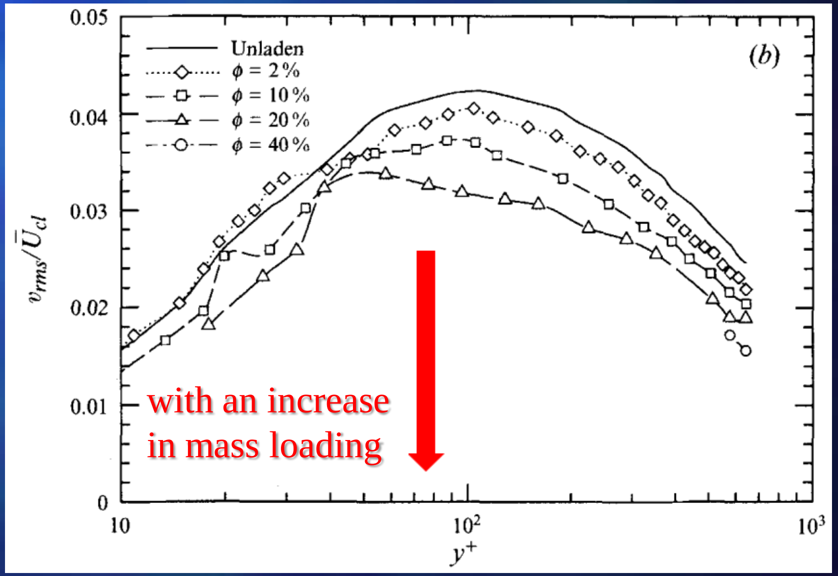
Turbulence modulation by solid particles

$d^+ = 2.3$

$R = 8{,}800$

$St = 3$

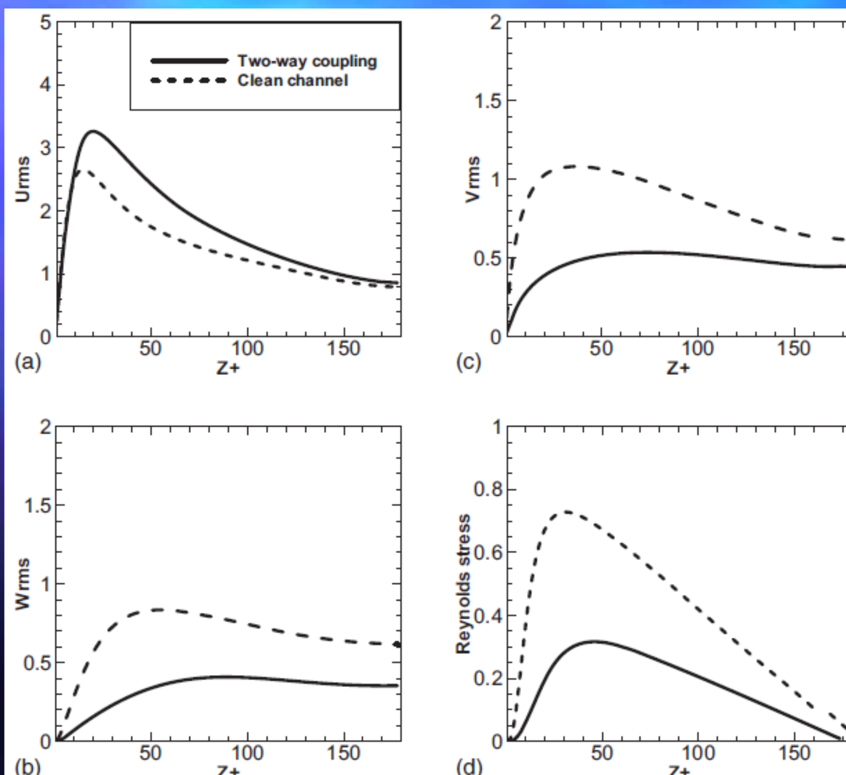




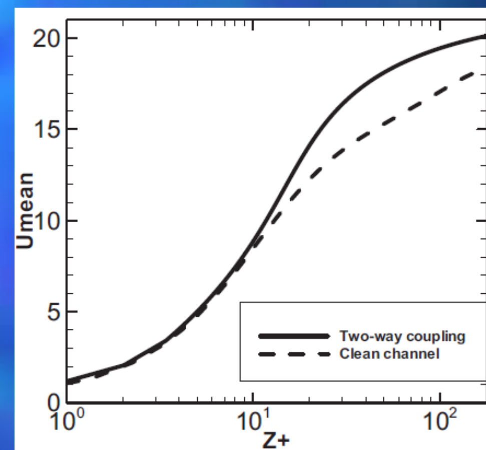
Kulick *et al.* (1994)

Turbulent Drag Reduction

Turbulence modulation by solid particles



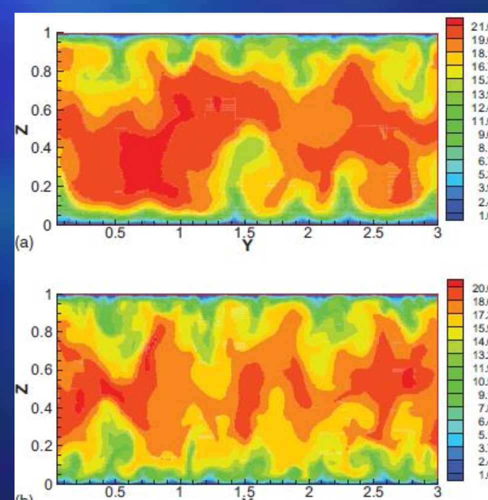
Zhao *et al.* (2010)



$d^+ = 0.36$

$R = 1{,}042$

$St = 3.33$



with micro-particles

without particles

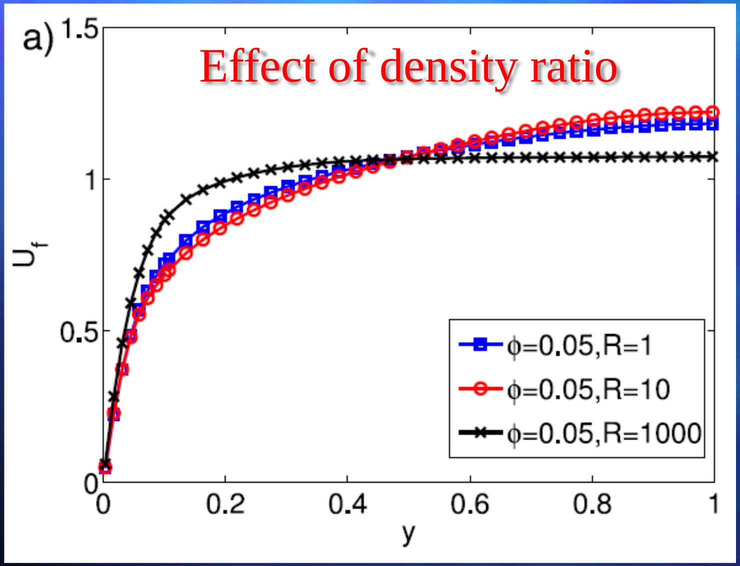
Turbulent Drag Reduction

Turbulence modulation by solid particles

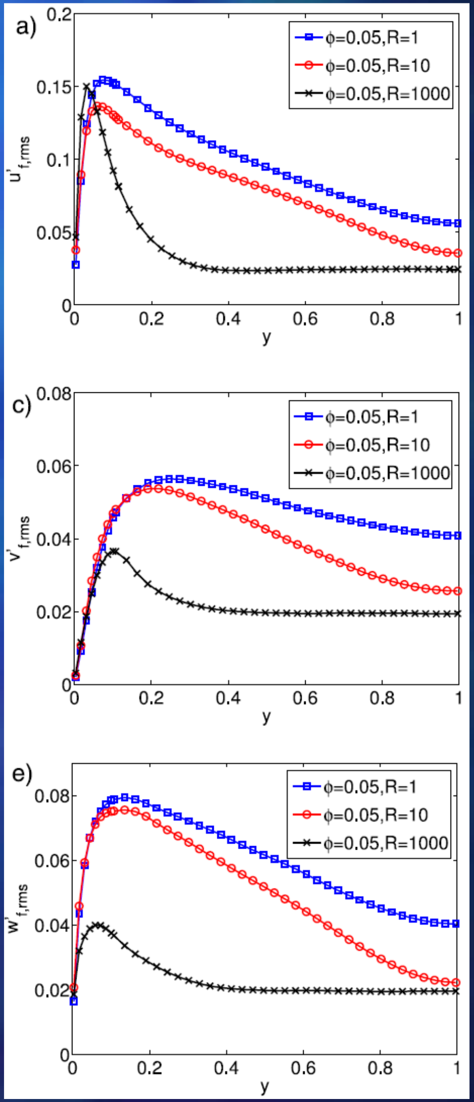
$d^+ = 20$

$R = 1{,}000$

$St = 2{,}470$

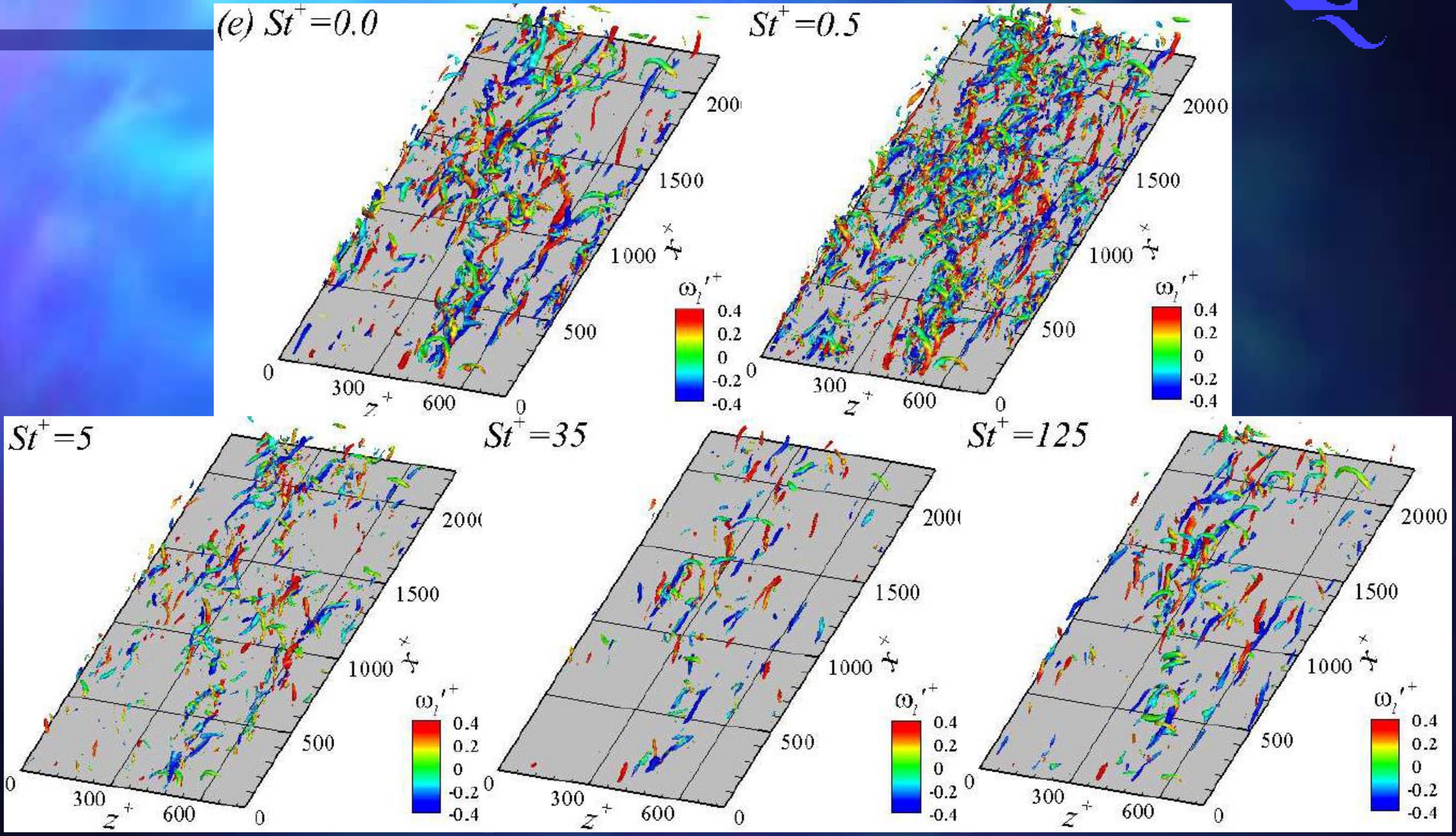


Fornari *et al.* (2016)



Turbulent Drag Reduction

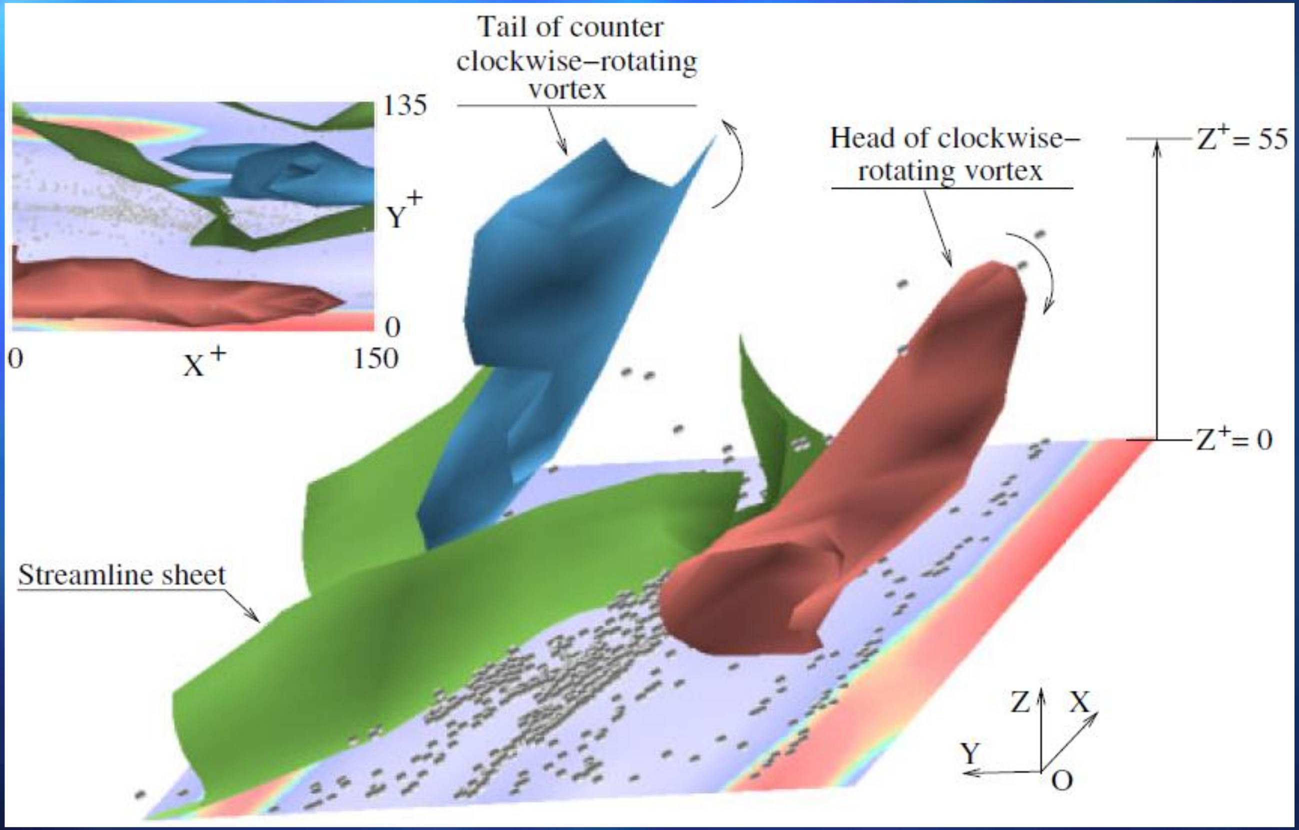
Turbulence modulation by solid particles



Lee & Lee (2015)

Turbulent Drag Reduction

Turbulence modulation by solid particles



Soldati (2005)

Turbulent Drag Reduction

Conclusions

- Near-wall control techniques are not appropriate for aircraft application unless they are passive. The control effect lasts only for a short distance downstream ($x^+ \sim 1000$), which requires a prohibitive number of actuators to cover the entire flow surface.
- Our focus should therefore be directed towards Outer-layer control, whose downstream effect lasts much longer ($x/\delta \sim 50$). Also, the number of required actuators are less, to be placed only at strategic positions over the aircraft surface.
- *Solid Particles Injection* must be fully investigated for its drag reduction capabilities.