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Direct Numerical Simulation of Drag Reduction with Uniform Blowing over a Two-dimensional Roughness

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Uniform blowing (UB)

- **Drag contribution in a channel flow with UB(/US)**

$$C_f = \frac{12}{\mathrm{Re}_b} + 12\int_0^2 (1-y)(-\overline{u'v'})dy \; -12V_w \int_0^2 (1-y)\bar{u}dy$$

V_w: Blowing velocity

Viscous Contribution (= laminar drag, **const.**)

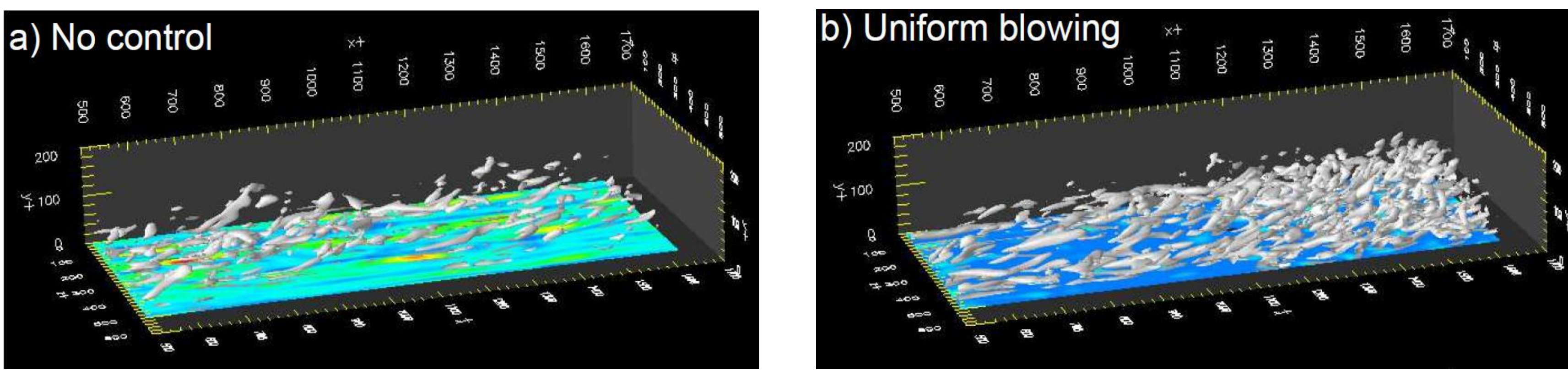
Turbulent contribution

Convective (=UB/US) contribution

(Fukagata et al., *Phys. Fluids*, 2002)

- **Excellent performance** (about **45%** by $V_w = 0.5\% U_\infty$)
- **Unknown over a rough wall**

(Kametani & Fukagata, *J. Fluid Mech.*, 2011)



On a boundary layer, White: vortex core, Colors: wall shear stress

UB over a rough wall

Experimental results so far

- **Similar to the smooth-wall cases**
  - Schetz and Nerney, *AIAA J.*, 1977
  - Voisinet, 1979
- **Opposite behavior (drag increased, turbulent intensity suppressed)**
  - Miller et al., *Exp. Fluids*, 2014

Contradicting remarks exist

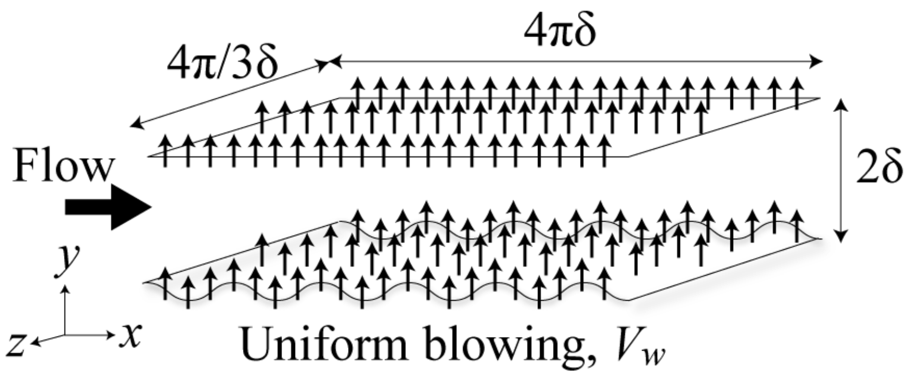
Goal

Investigate the interaction between roughness and UB for drag reduction using numerical simulation

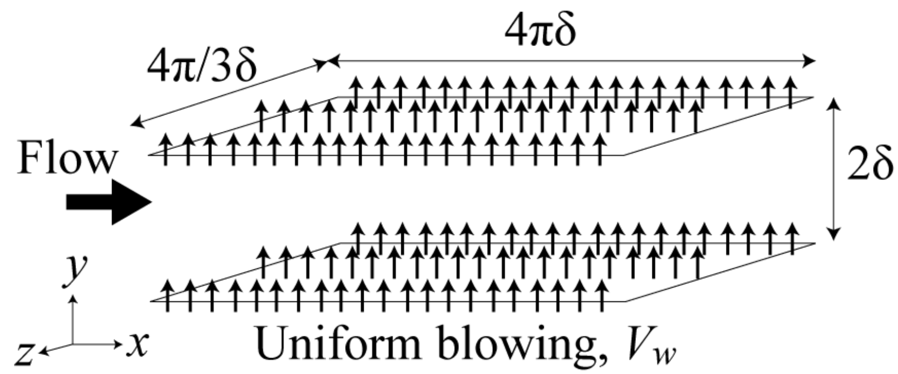
- DNS of turbulent channel flow
- Drag reduction **performance** and **mechanism**
- **Combined effect** of UB and roughness

Numerical procedure

- **Based on FD code** (for wall deformation)
  (Nakanishi et al., *Int. J. Heat Fluid Fl.*, 2012)
- **Constant flow rate,** $\mathbf{Re}_b = 2U_b\delta/\nu = 5600$
  - so that $\mathbf{Re}_\tau \approx 180$ in a plane channel (K.M.M.)
- $\Delta x^+ = 4.4, 0.93 < \Delta y^+ < 6, \Delta z^+ = 5.9$
- **UB magnitude:** $V_w/U_b = 0, 0.1\%, 0.5\%, 1\%$



ROUGH CASE



SMOOTH CASE

Model of rough wall

Roughness displacement

$$d(x) = \delta \sum_{i=1}^{8} A_i \sin\left(\frac{2i\pi x}{L_x/2}\right)$$

(E. Napoli et al., *J. Fluid Mech.*, 2008)

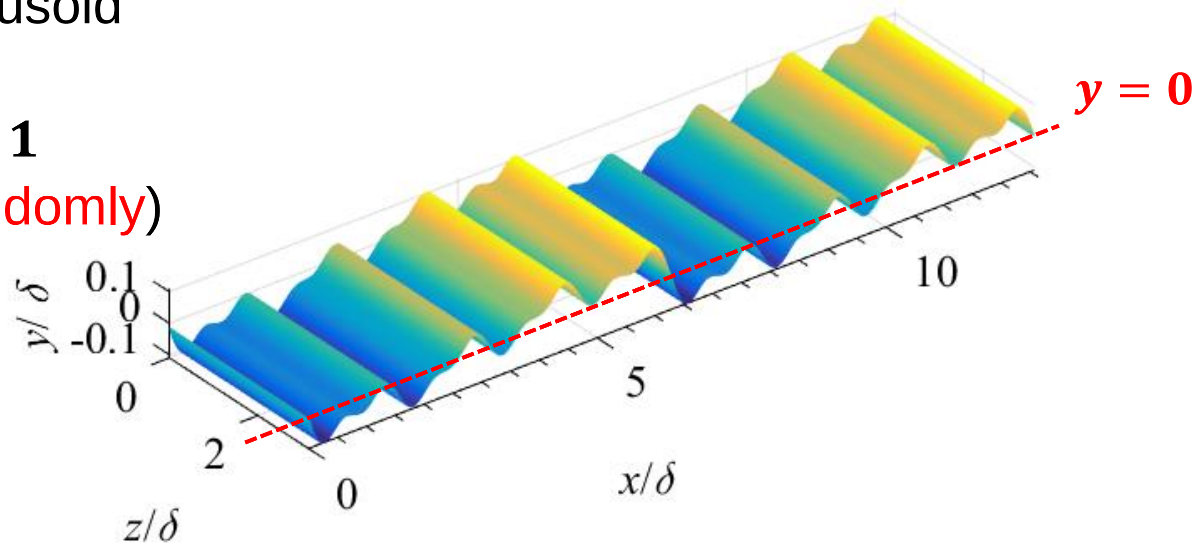
δ: channel half height
L_x: Channel length, $4\pi\delta$
A_i: Amplitude of each sinusoid

$$A_i = \begin{cases} 1, & \text{for } i = 1 \\ [0,1], & \text{for } i \neq 1 \end{cases}$$

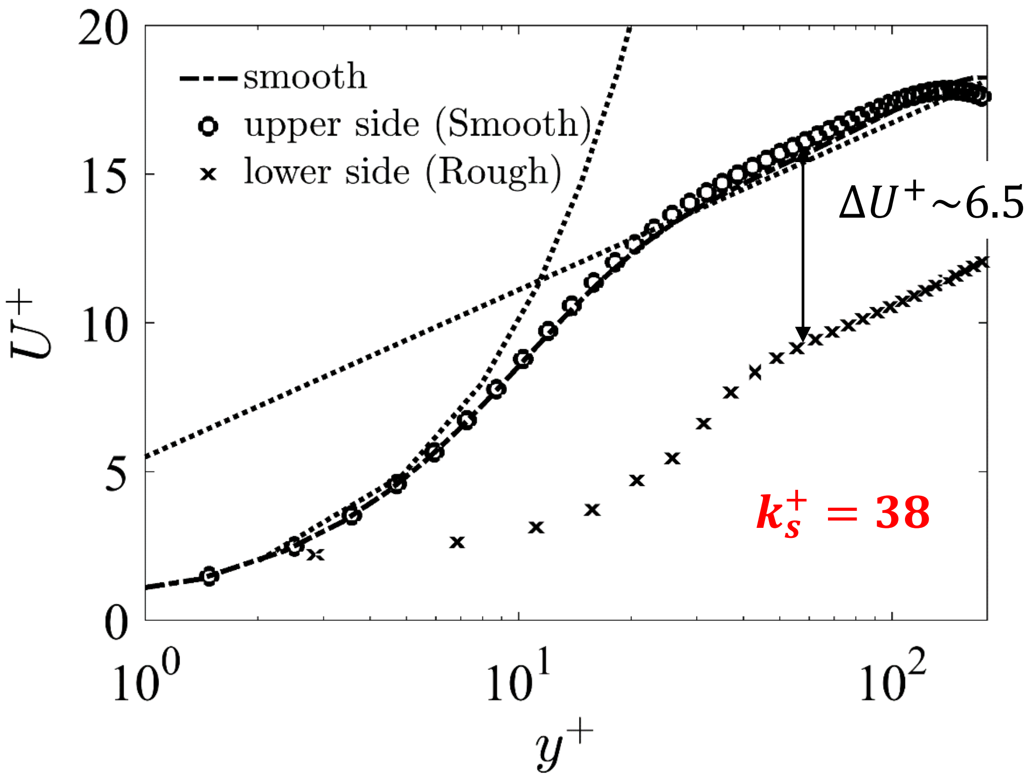
(Defined randomly)

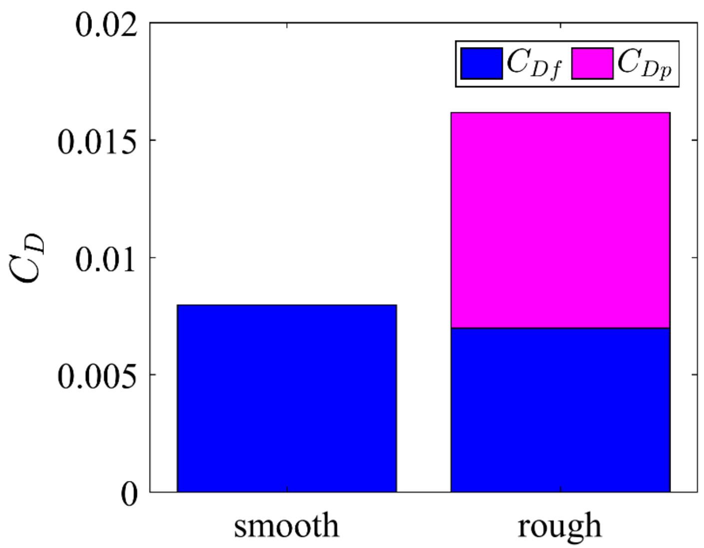
with rescaling so that
$\overline{|d(x)|} = 0.05\delta$

$|d(x)|_{\max} = 0.11\delta$



The result of the base flow





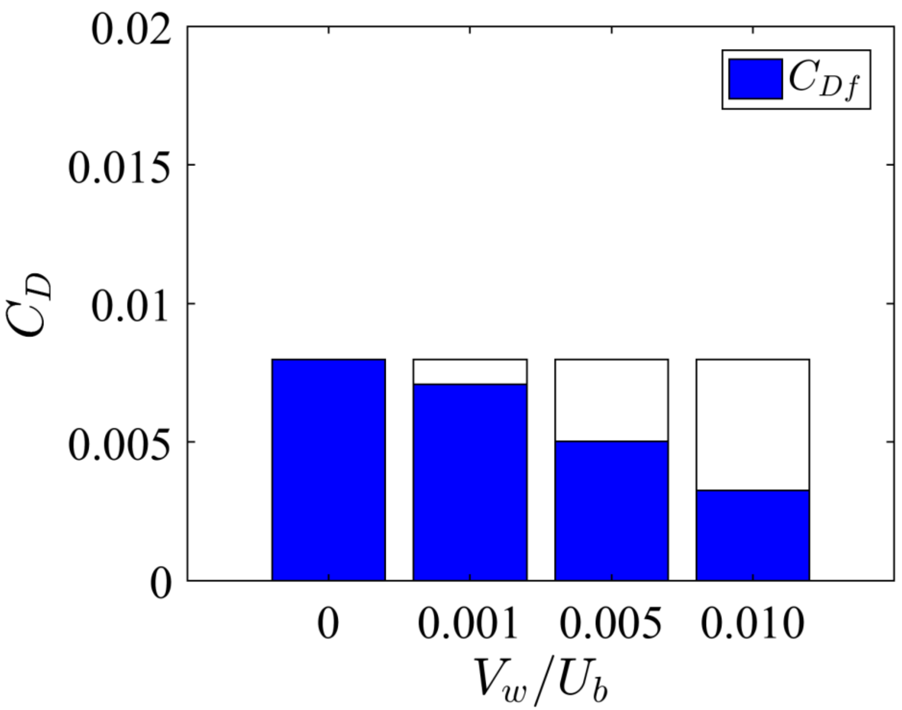
$$C_{Dp} = 2C_{\text{Dave}} - (C_{Df} + C_{Df,u})$$

C_{Dave}: Overall drag coefficient
C_{Df}: C_f of the rough wall side
$C_{Df,u}$: C_f of the smooth wall side

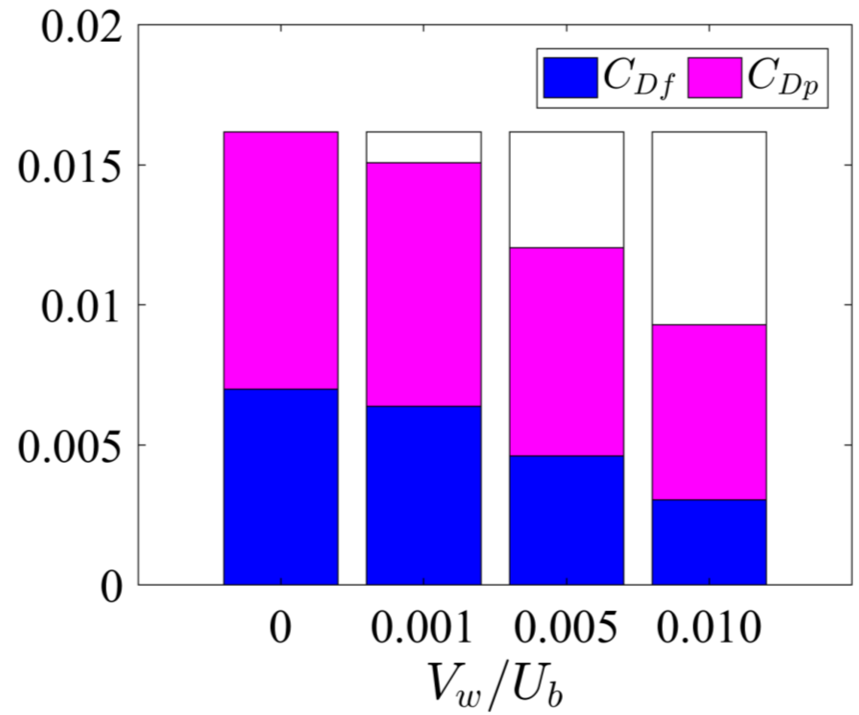
“Transitionally-rough regime”

The result of UB

SMOOTH CASE



ROUGH CASE



Total, R **11% 37% 59%** **7% 26% 43%**

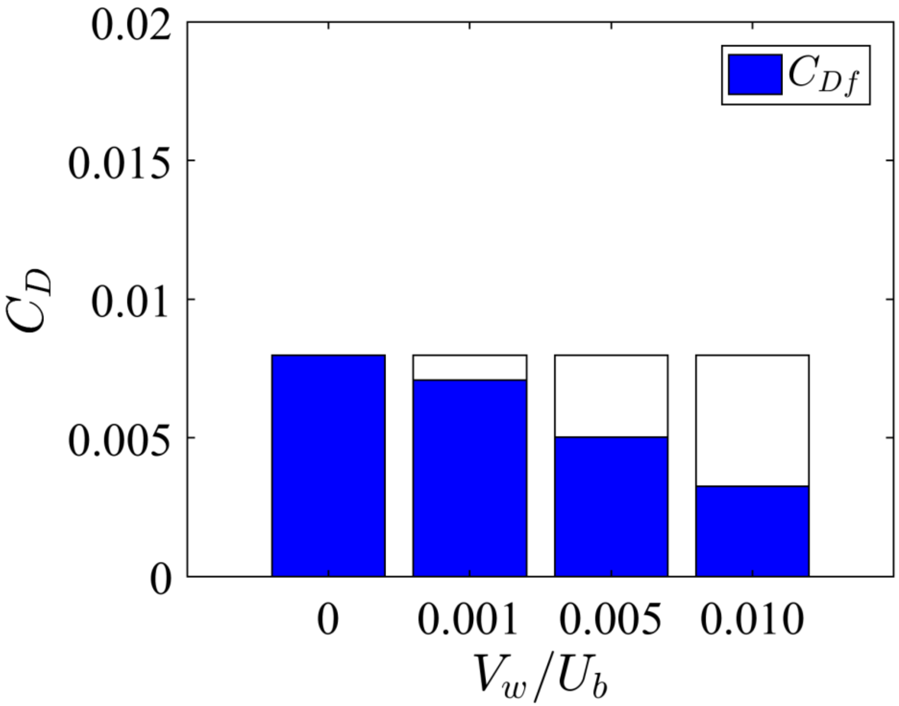
$$R = 1 - \frac{C_{D,\mathrm{ctr}}}{C_{D,\mathrm{nc}}}$$

$C_{D,\mathrm{ctr}}$: controlled

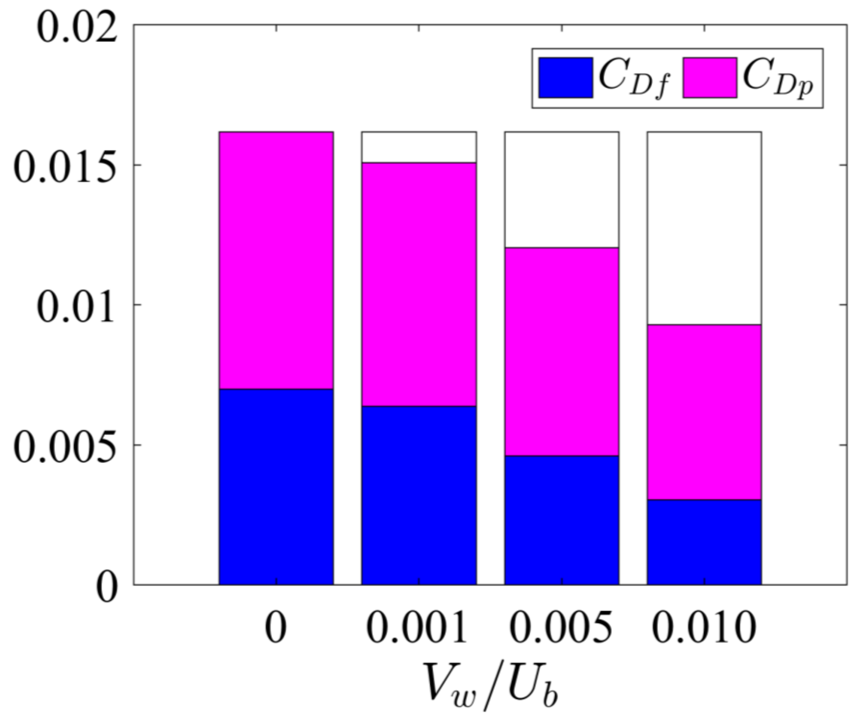
$C_{D,\mathrm{nc}}$: no control

The result of UB

SMOOTH CASE



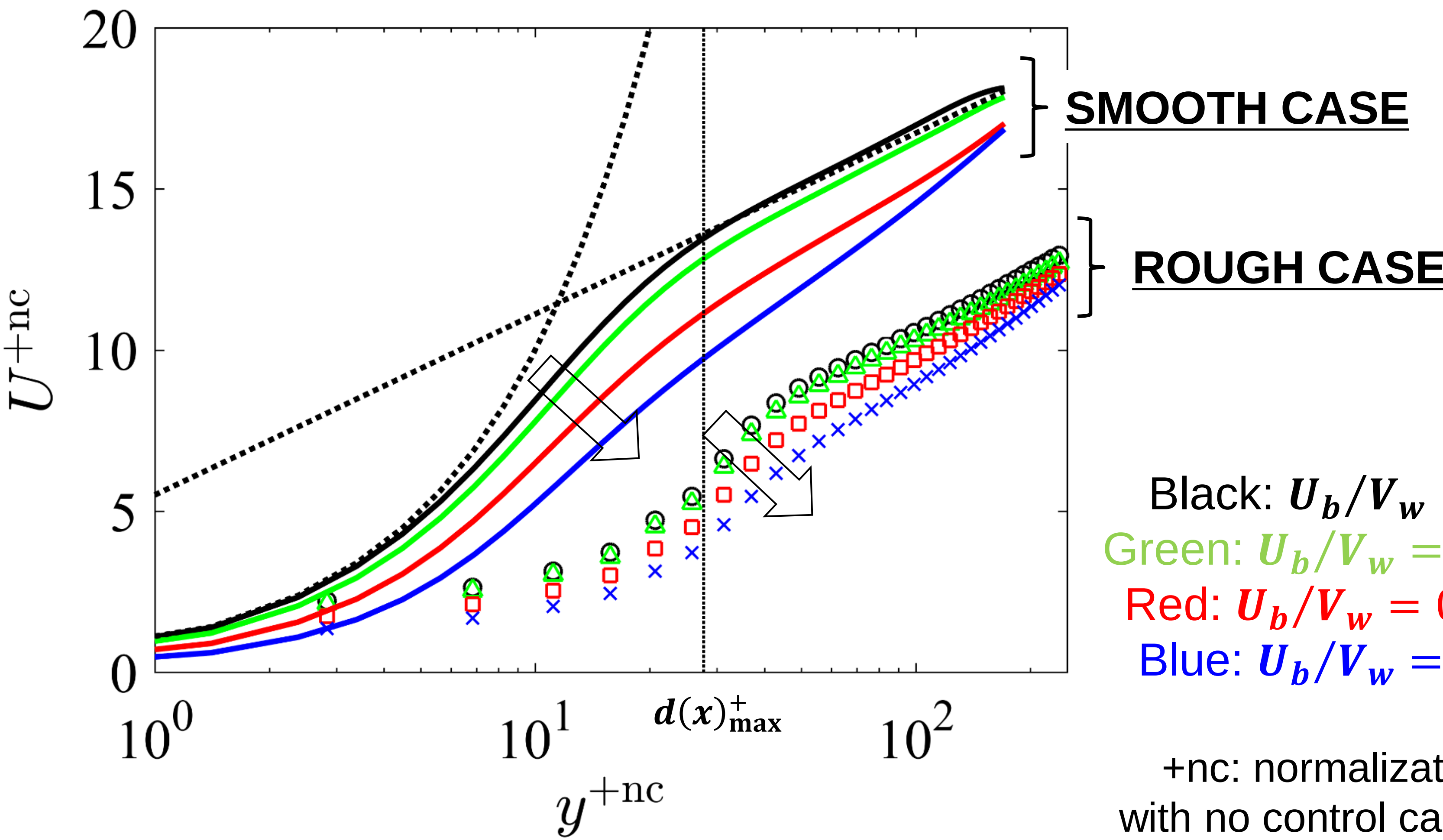
ROUGH CASE



	Smooth case			Rough case		
Total, R	11%	37%	59%	7%	26%	43%
Friction, R_F	11%	37%	59%	9%	34%	57%
Pressure, R_P	-		-	5%	19%	32%

Friction drag reduction mechanism

Bulk mean streamwise velocity



Black: $U_b/V_w = 0$
Green: $U_b/V_w = 0.1\%$
Red: $U_b/V_w = 0.5\%$
Blue: $U_b/V_w = 1\%$

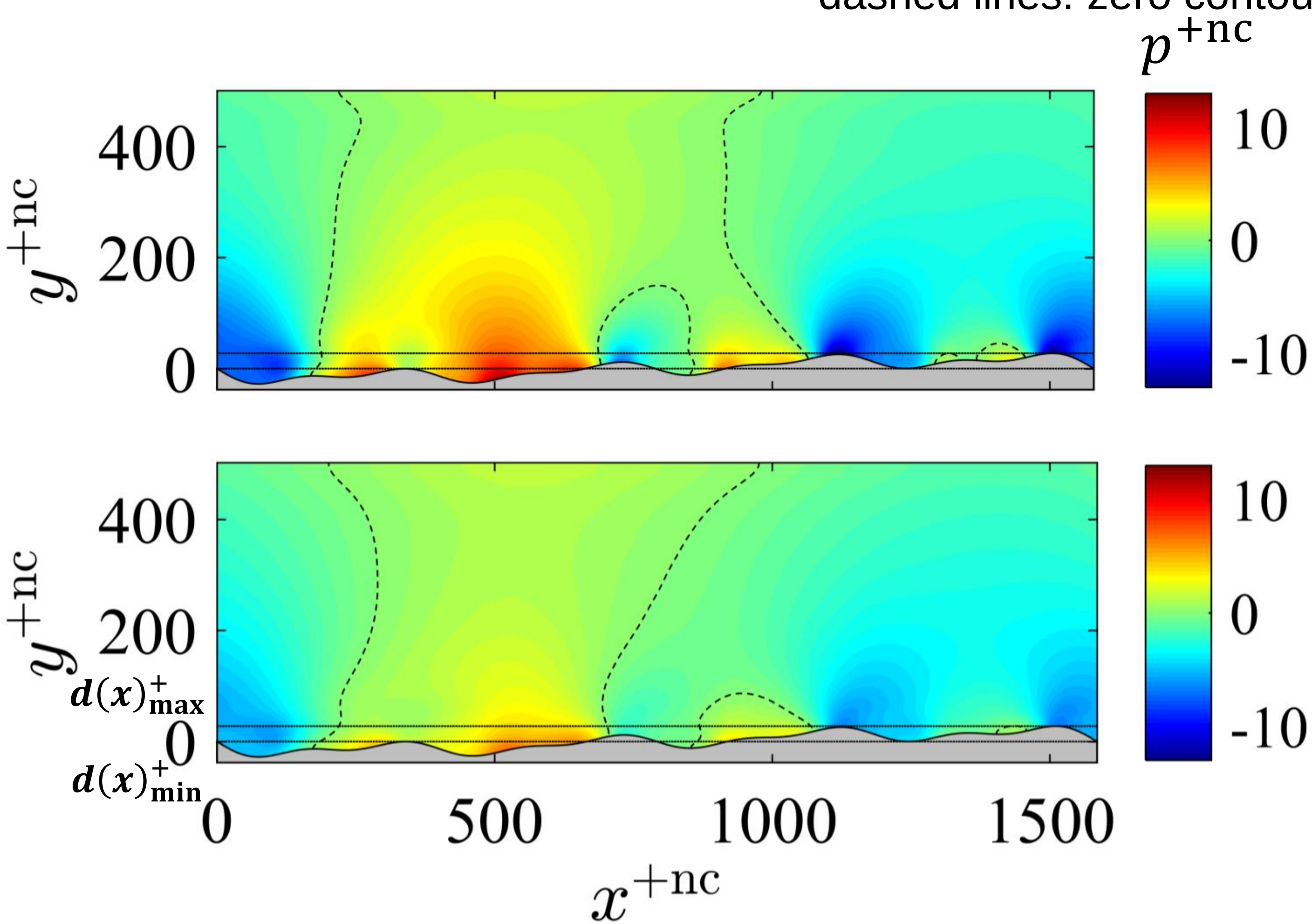
+nc: normalization with no control case u_τ

How does pressure drag decrease?

Pressure contours

averaged in the spanwise and time
dashed lines: zero contour

$\boldsymbol{U_b/V_w}$ $\boldsymbol{= 0}$



$\boldsymbol{U_b/V_w}$ $\boldsymbol{= 1\%}$

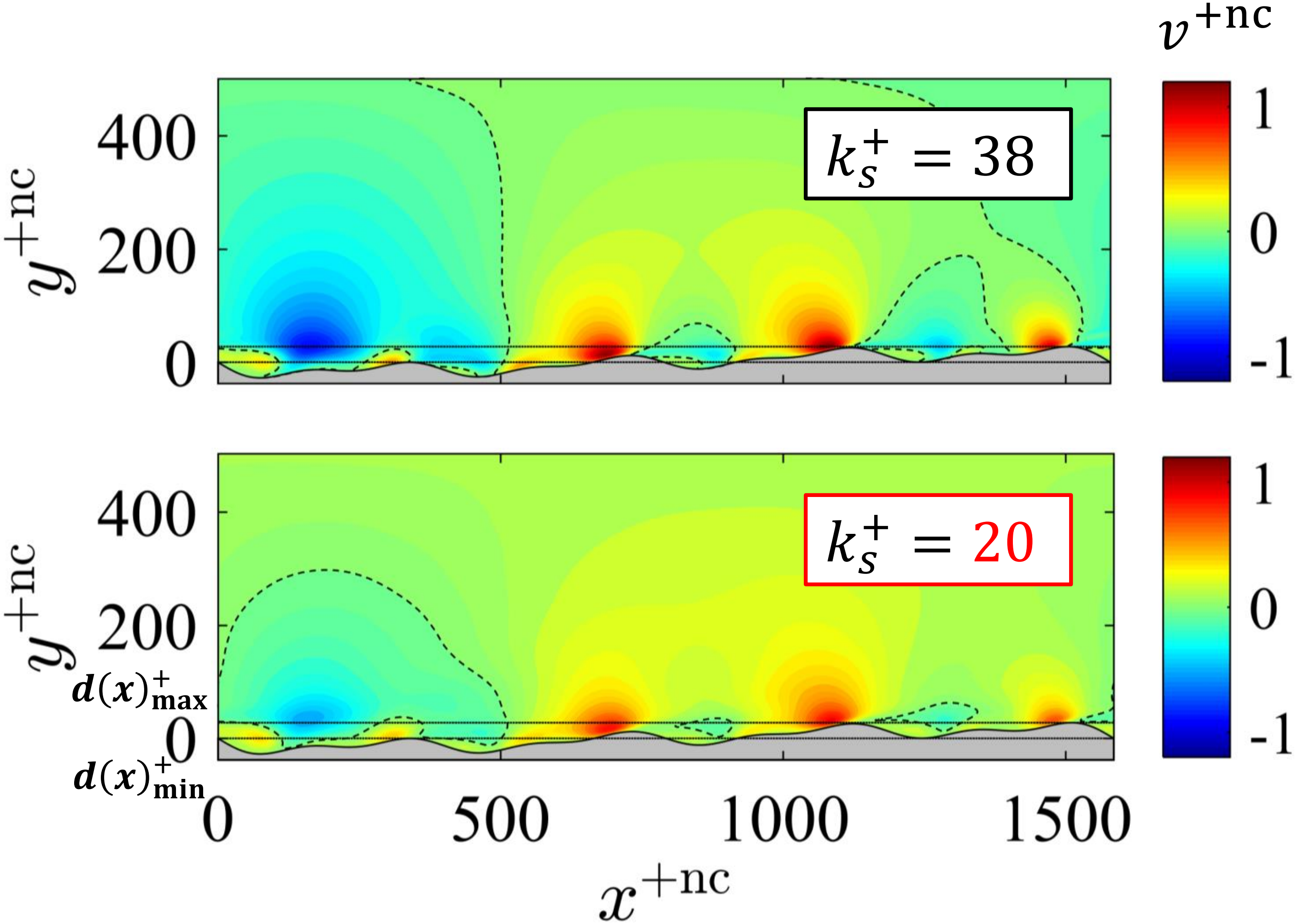
“Smoothing effect”

Wall-normal velocity contours

averaged in the spanwise and time
dashed lines: zero contour

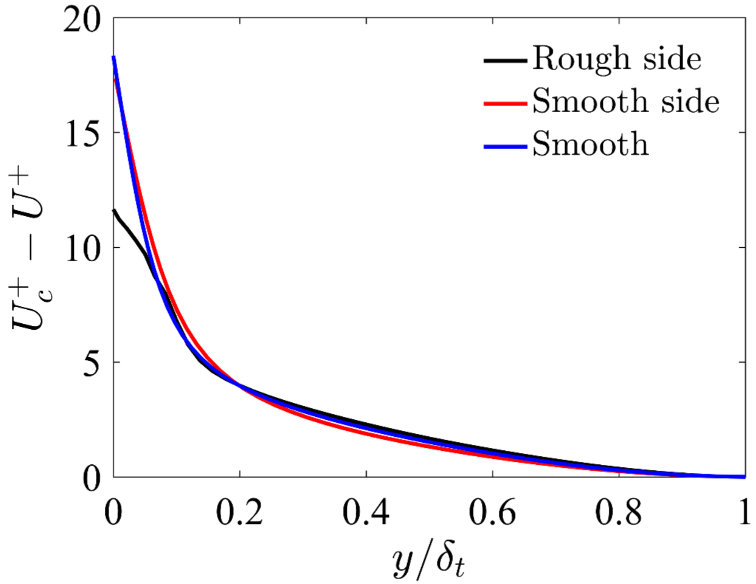
$U_b/V_w = 0$

$U_b/V_w = 1\%$

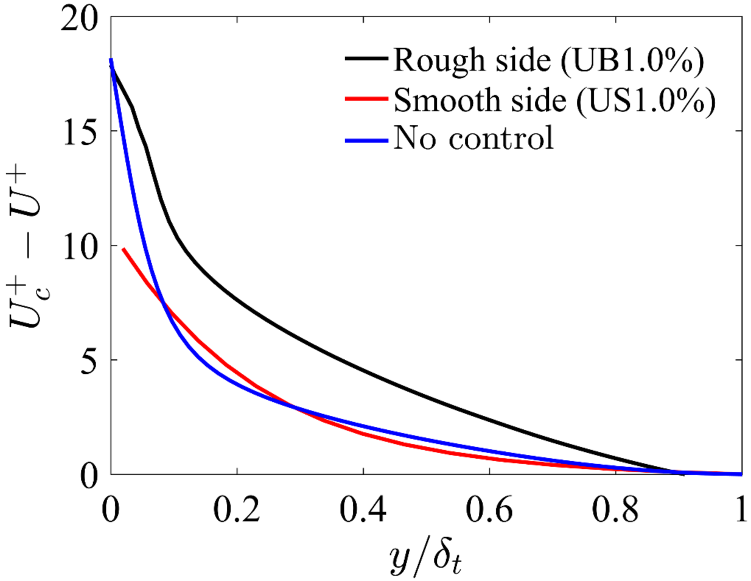


Outer layer similarity with UB

Velocity defect



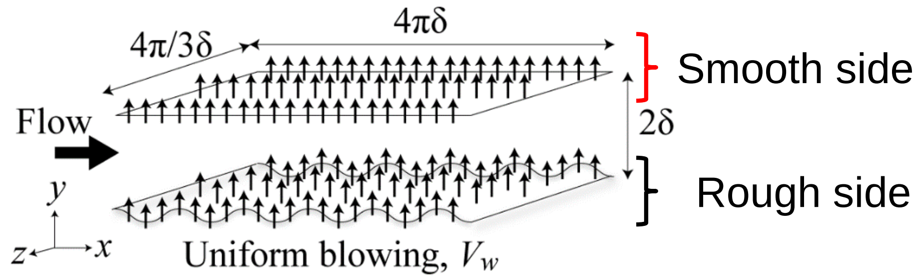
Base flow (No controlled) of
one-side rough wall



1% UB case of
one-side rough wall

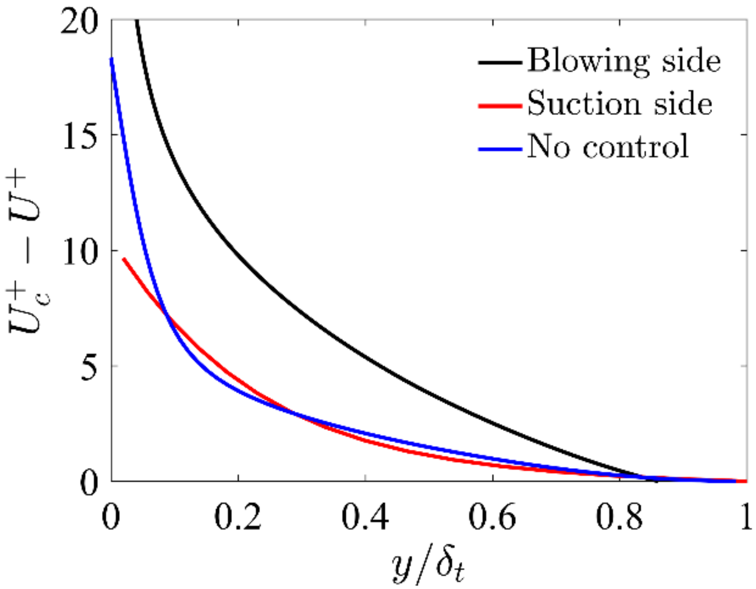
$\boldsymbol{\delta_t}$: distance from a wall to the minimum RMS location

(K. Bhaganagar et al.,
Flow, Turbul. Combust., 2004)

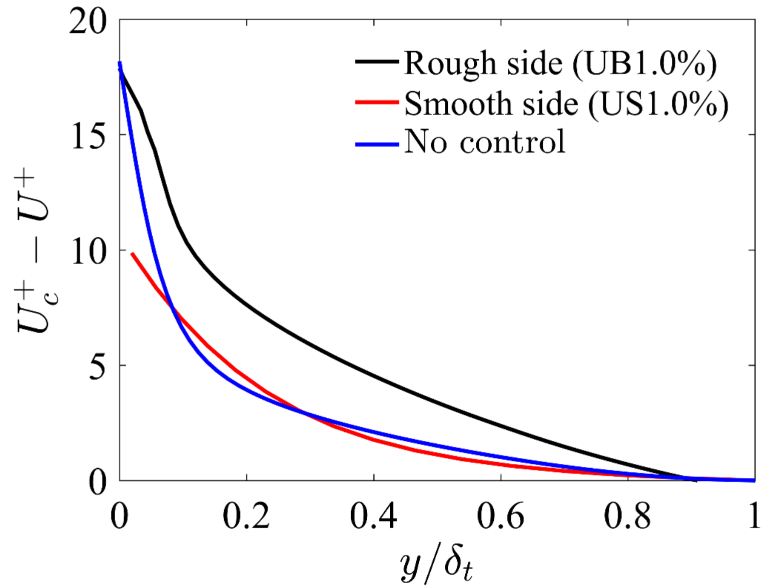


Comparison with smooth case

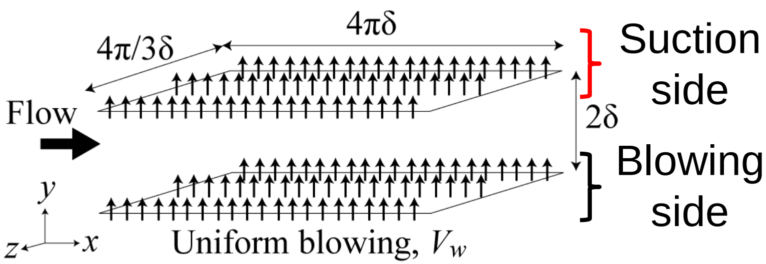
Velocity defect

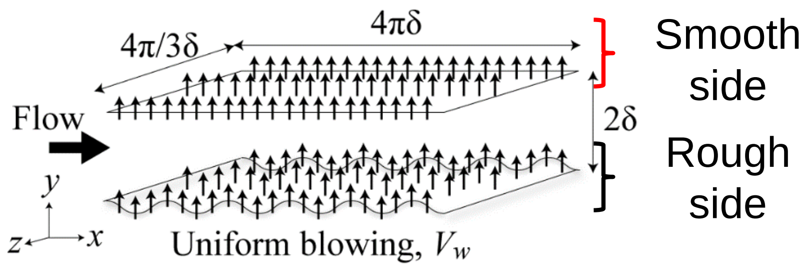


1% UB case of
both-side smooth wall



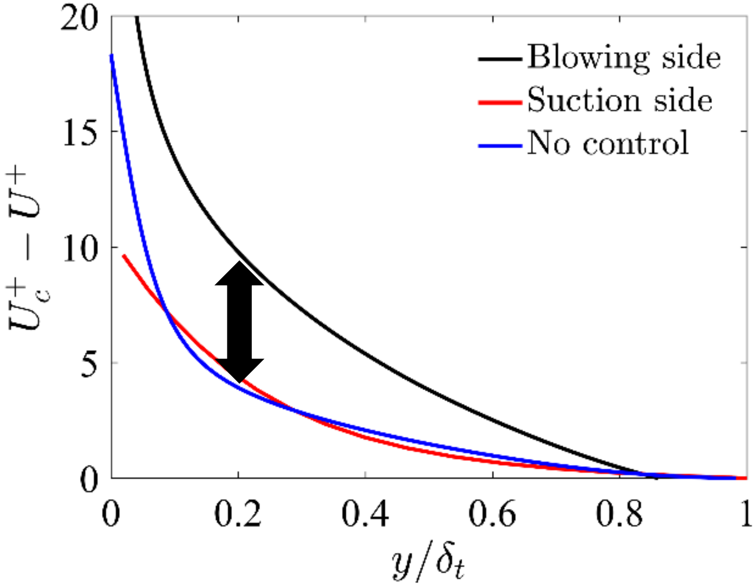
1% UB case of
one-side rough wall



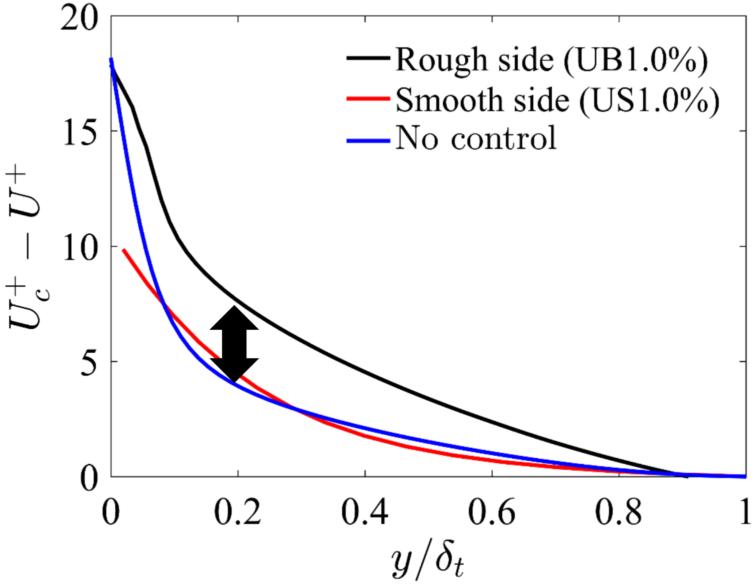


Comparison with smooth case

Velocity defect



1% UB case of
both-side smooth wall



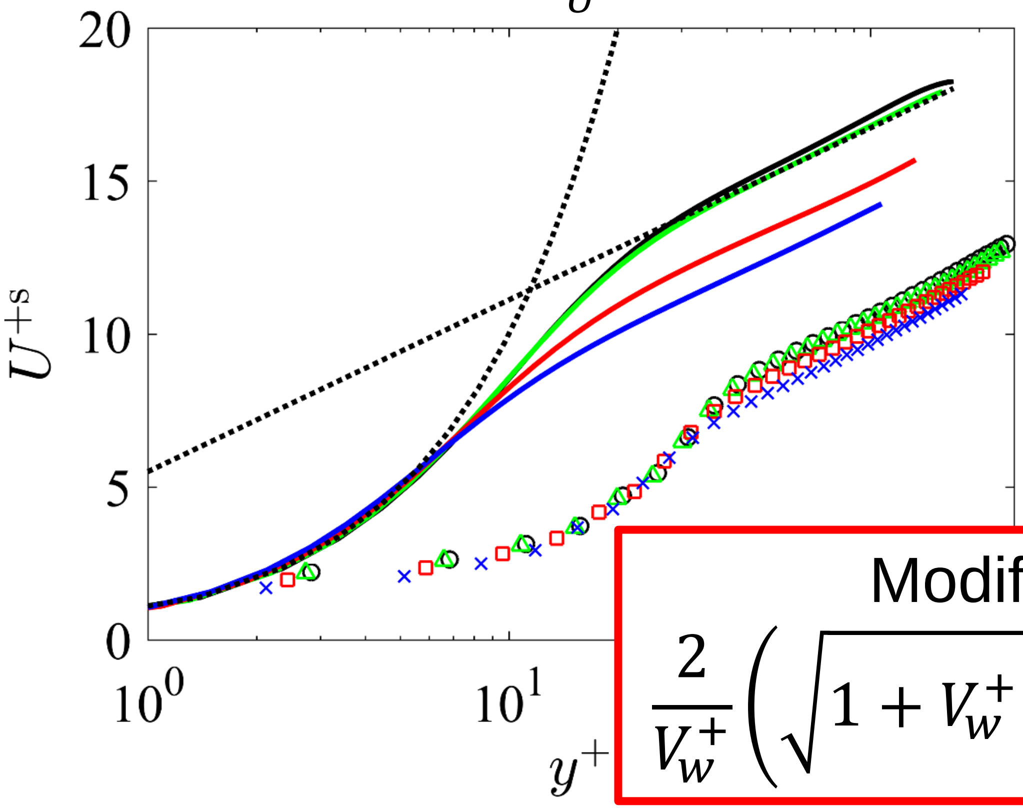
1% UB case of
one-side rough wall

Same tendency, but quantitatively weakened

Stevenson's law of the wall

Plots using Stevenson's law of the wall (Stevenson, 1963)

$$\underbrace{\frac{2}{V_w^+}\left(\sqrt{1+V_w^+U^+}-1\right)}_{U^{+S}} = \frac{1}{\kappa}\ln y^+ + B$$



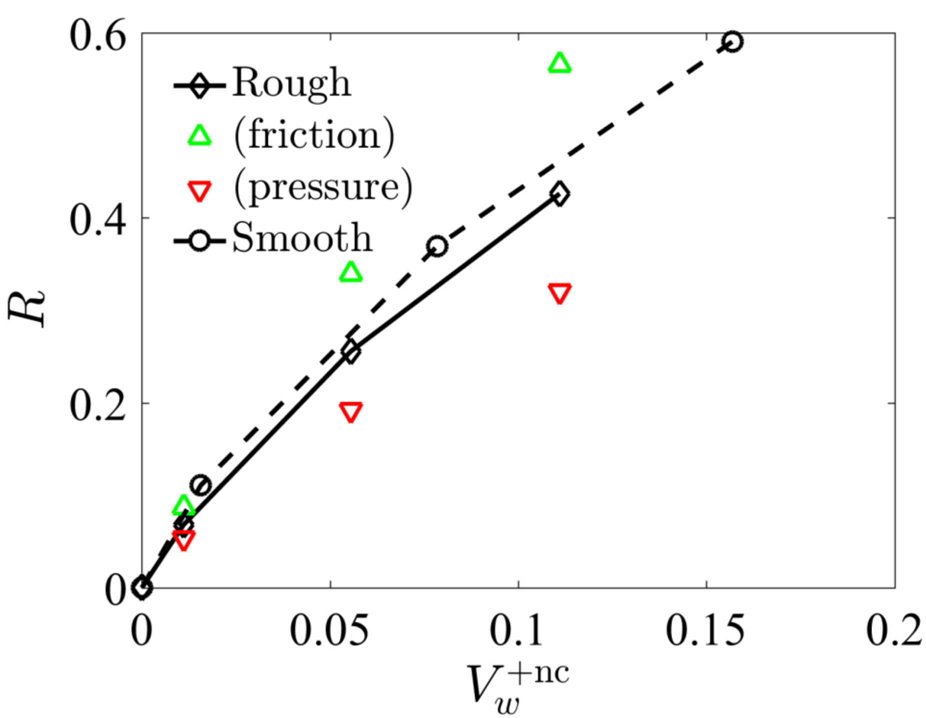
Roughness function ΔU^+

Modified law is suggested:

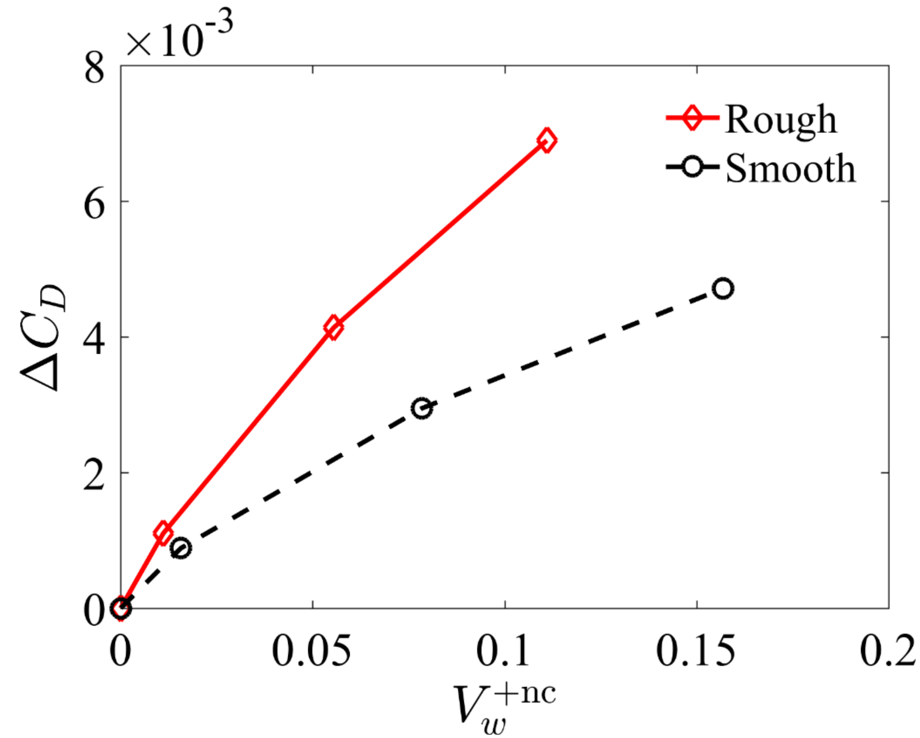
$$\frac{2}{V_w^+}\left(\sqrt{1+V_w^+U^+}-1\right) = \frac{1}{\kappa}\ln y^+ + B - \Delta U^+$$

Normalization by $u_\tau^{\mathrm{nc}+}$

Drag reduction rate,
R



Drag reduction,
$\Delta C_D = C_{D,\mathrm{nc}} - C_{D,\mathrm{ctr}}$



R becomes similar when plotted with V_w^+

nc: no control
ctr: controlled

Concluding remarks

DNS of turbulent channel flow is performed over a rough wall with UB

- **UB is effective over a rough wall**
  - Almost same in drag reduction rate, but larger in drag reduction amount (when normalized by $u_\tau^{+\mathrm{nc}}$)
- **Drag reduction mechanisms are considered**
  - Friction drag is reduced by wall-normal convection
  - Pressure drag is reduced by “smoothing effect”
- **Combined effect (UB + roughness) slightly exists**
- **Modified Stevenson’s law of the wall is suggested**

Thank you for your kind attention

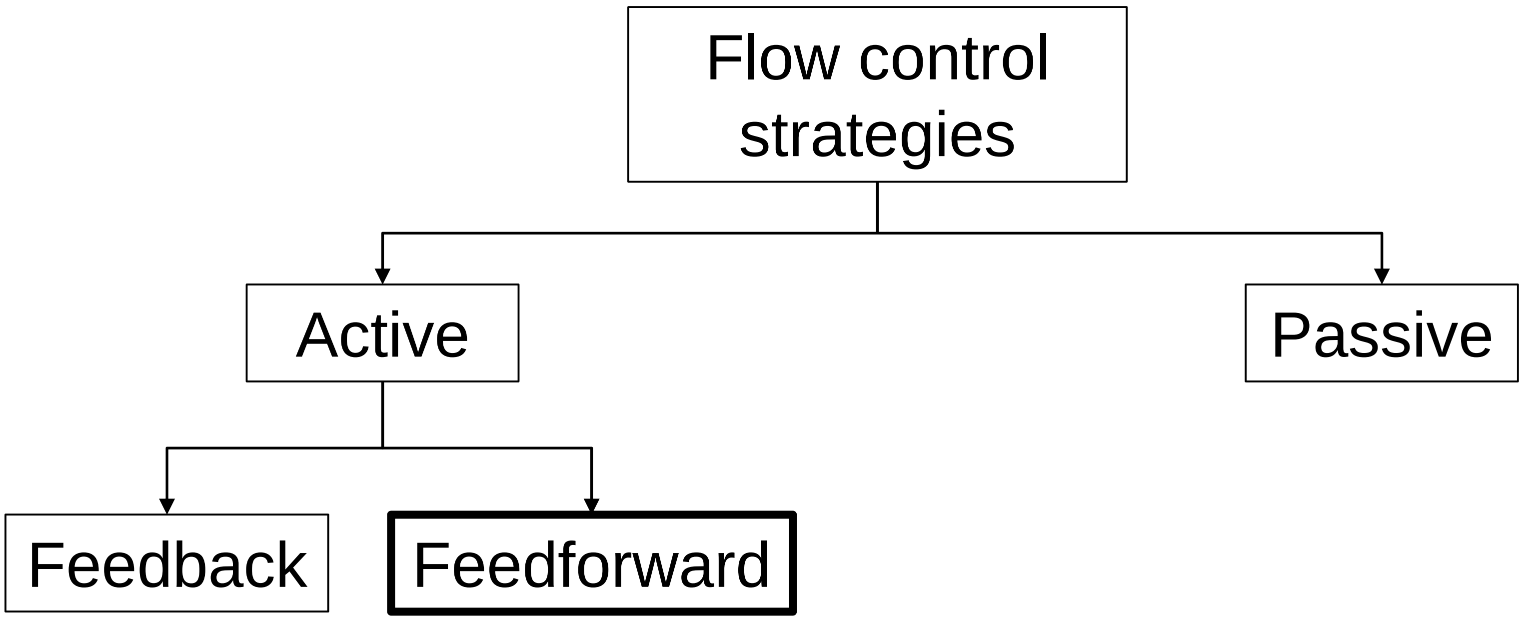
Background

Turbulence

- **Huge drag**
- **Environmental** problems
- High operation **cost**
- **How to control**?

Flow control classification

(M. Gad-el-Hak, *J. Aircraft*, 2001)



- Uniform blowing

Governing equations

(S. Kang & H. Choi, *Phys. Fluids*, 2000)

Incompressible Continuity and Navier-Stokes in ξ_i coordinate

$$
\begin{cases}
\dfrac{\partial u_i}{\partial \xi_i} = -S \\
\dfrac{\partial u_i}{\partial t} = -\dfrac{\partial (u_i u_j)}{\partial \xi_j} - \dfrac{\partial p}{\partial \xi_i} + \dfrac{1}{\mathrm{Re}_b}\dfrac{\partial^2 u_i}{\partial \xi_j \xi_j} - \dfrac{dP}{d\xi_1}\delta_{i1} + S_i
\end{cases}
$$

where

$$
S_i = -\varphi_t \frac{\partial u_i}{\partial \xi_2} - \phi_j \frac{\partial (u_i u_j)}{\partial \xi_2} - \phi_j \frac{dp}{d\xi_2}\delta_{ij} + \frac{1}{Re}\left(2\phi_j \frac{\partial^2 u_i}{\partial \xi_j \xi_2} + \phi_j \phi_j \frac{\partial^2 u_i}{\partial \xi_2^2} + \frac{1}{2}\frac{\partial (\phi_j \phi_j)}{\partial \xi_2}\frac{\partial u_i}{\partial \xi_2}\right)
$$

$$
S = \phi_j \frac{\partial u_i}{\partial \xi_2} \qquad \phi_j = \varphi_j - \delta_{j2} \qquad \varphi_j = \begin{cases} -\dfrac{1}{1+\eta}\left(\xi_2 \dfrac{\partial \eta}{\partial \xi_i} + \dfrac{\partial \eta_0}{\partial \xi_i}\right), \text{for j} = 1,3 \\ \dfrac{1}{1+\eta}, \qquad \text{for j} = 2 \end{cases}
$$

Coordinate transformation

(S. Kang & H. Choi, *Phys. Fluids*, 2000)

Calculation grids: ξ_i (Cartesian with extra force)

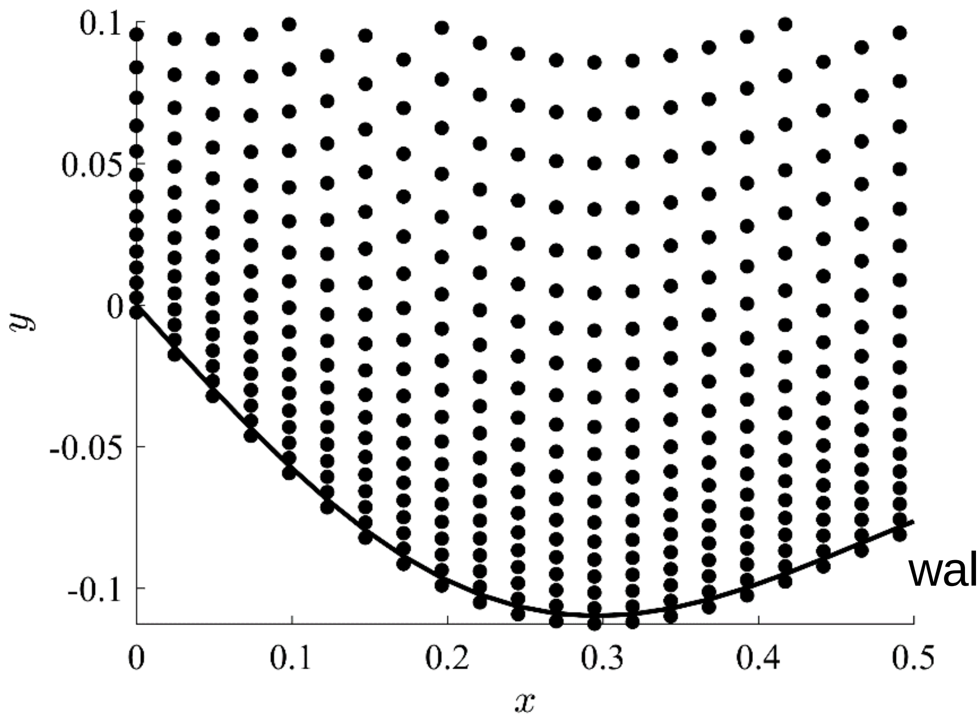
$$\begin{cases} x = \xi_1 \\ y = \xi_2(1+\eta) + \eta_d \\ z = \xi_3 \end{cases}$$

(x, y, z: physical coordinate)

$$\eta \equiv (\eta_u - \eta_d)/2$$
$$= -d(x)/2$$
$$\eta_d = r(x), \eta_u = 0$$

η_d, η_u: displacement of lower/upper wall

Actual grid points allocation



Post processing

- **Drag coefficient decomposition for rough case**

$$C_{Duf} = \frac{8}{\mathrm{Re}_b}\frac{d\bar{u}}{dy}\bigg|_{\xi_2=2}$$

$$C_{Dlf} = \frac{8}{\mathrm{Re}_b}\overline{\left(\frac{du}{dy}\bigg|_{\xi_2=0} + \frac{dv}{dx}\bigg|_{\xi_2=0}\right)}$$

(Friction component)

$$C_{Dlp} = -16\frac{dP}{d\xi_1} - \left(C_{Dlf} + C_{Duf}\right)$$

(Pressure component)

- **Drag reduction rate**

$$R_{Dl} = \frac{\Delta C_D}{C_{D,M=0}} \times 100\ [\%]$$

Only focusing on lower side,
subscript "l" omitted hereafter

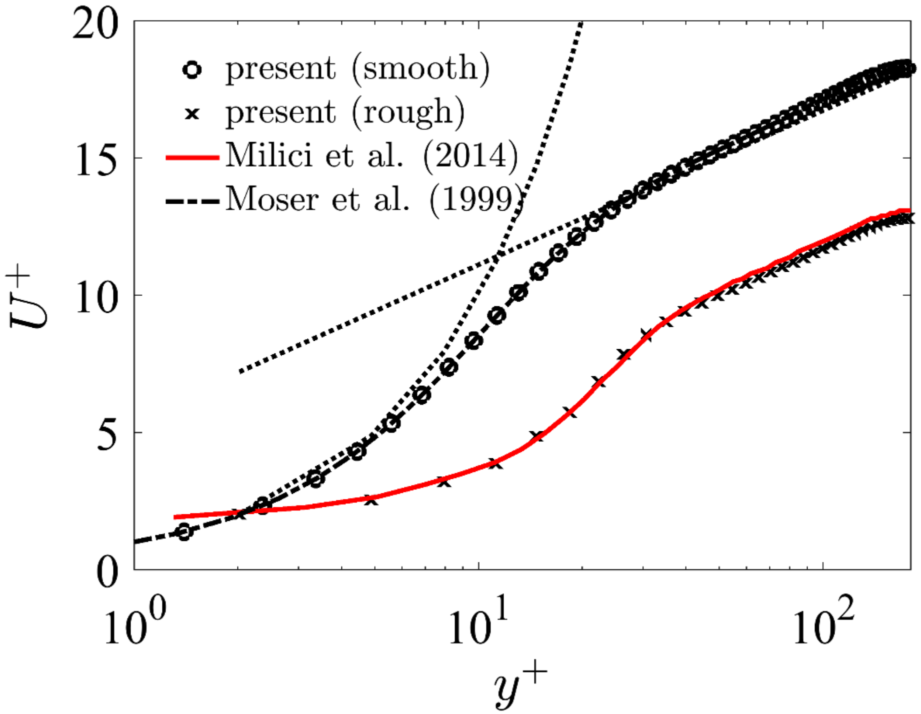
Discretization methods

- **Energy-conservative second-order finite difference schemes (In space)**
- **Low-storage third-order Runge-Kutta / Crank-Nicolson scheme (In time)**

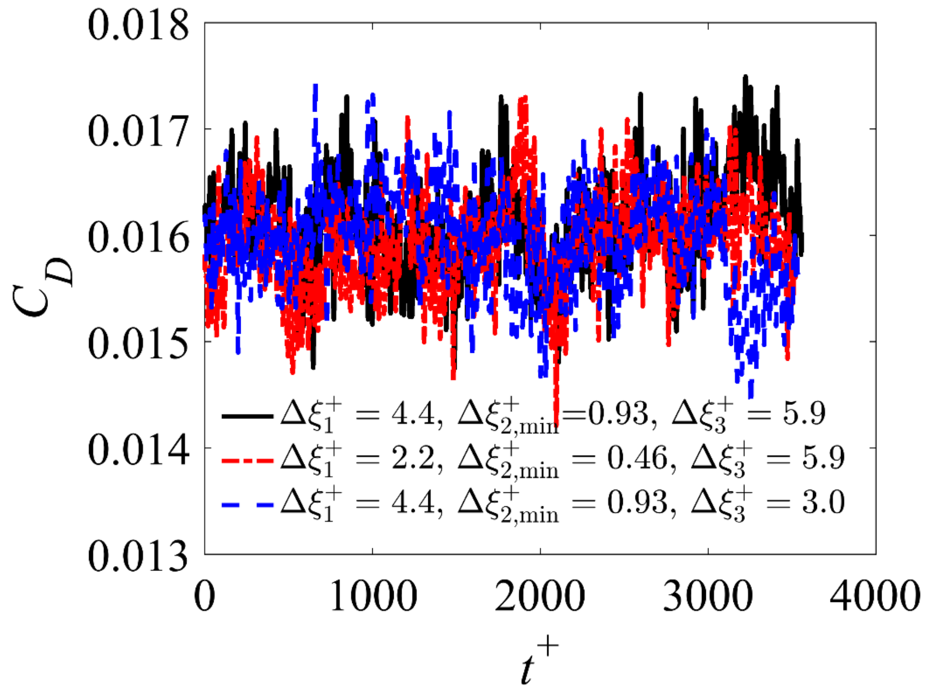
  + SMAC method for pressure correction

Discretized in the staggered grid system

Validation & Verification



Bulk mean streamwise velocity



Time trace of instantaneous C_D

Less than 2% of difference from the most resolved case

Stevenson's law of the wall

Plots using Stevenson's law of the wall (Stevenson, 1963)

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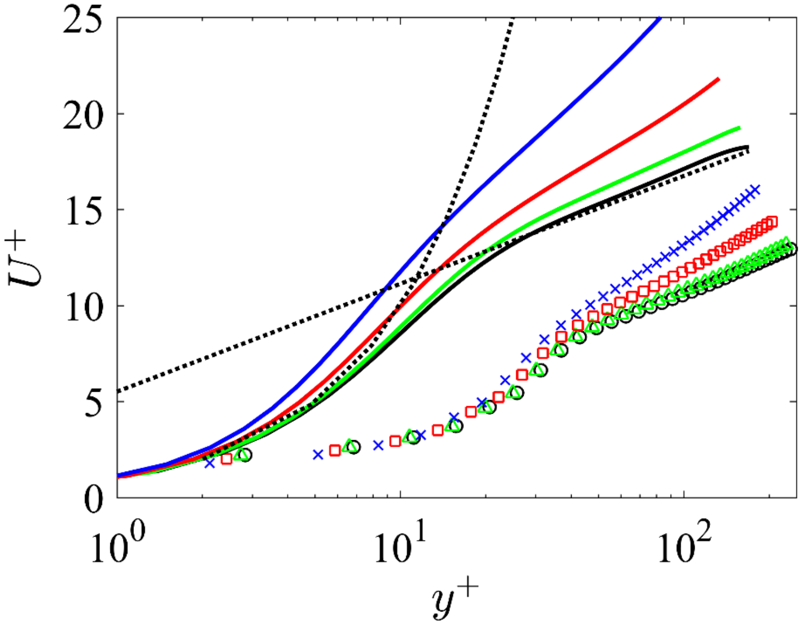
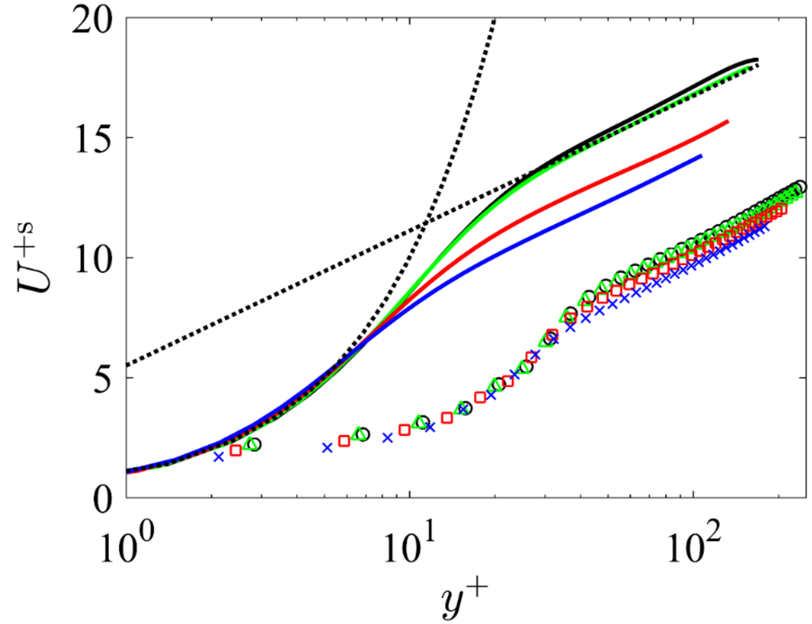


Normalized by local u_τ



Normalized by Stevenson's law