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# DNS of a Turbulent Channel Flow with Partial Slip

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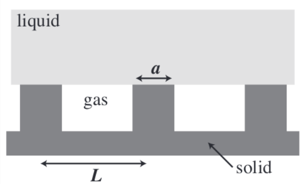
# Motivation

- Friction drag: A major component of total drag in turbulent flows

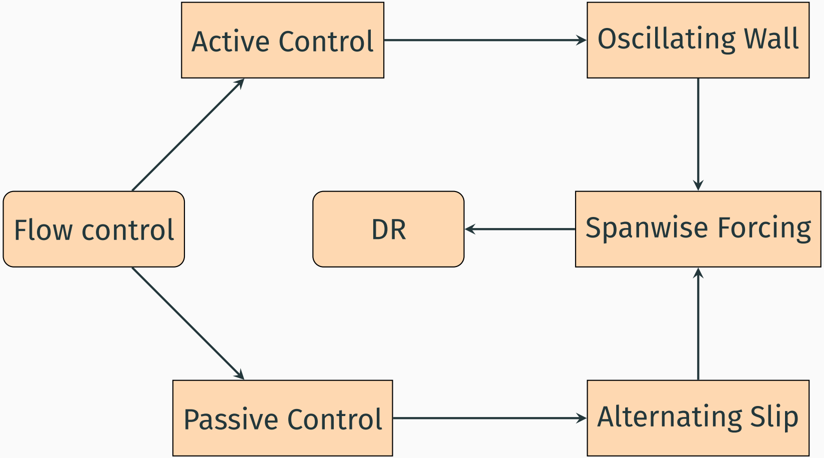
## A Generic Example: Aviation industry

- Friction Drag $\approx$ 50% of Total Drag
- Drag reduction by 10%= 40% increase in profit margins

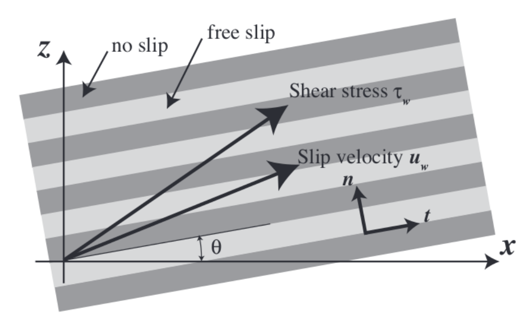
- Drag reduction $\rightarrow$ Flow control: Active and Passive strategies
- Superhydrophobic surfaces $\rightarrow$ entraps air underneath cavities $\rightarrow$ prevents direct contact of fluid and wall $\implies$ Slip




*Source: Hasegawa et.al (2011)*


Active Control
Oscillating Wall
Flow control
DR
Spanwise Forcing
Passive Control
Alternating Slip

# Passive strategy



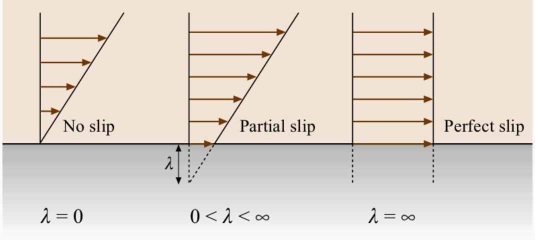

*Source: Hasegawa et.al (2011)* [1]

- Inclined alternating slip and no slip → spanwise forcing
- Involves Slip in streamwise and spanwise direction
- Requires a **fundamental** and **prerequisite** step → **Uniform Streamwise Slip**

[1] Hasegawa, Frohnapfel & Kasagi, J. Phys. Conf. Ser. (2011)

# Partial Slip

- Most employed B.c: No penetration, No slip
- No Penetration: An exact boundary condition
- No Slip: An assumption $\rightarrow$ Is it really valid everywhere?



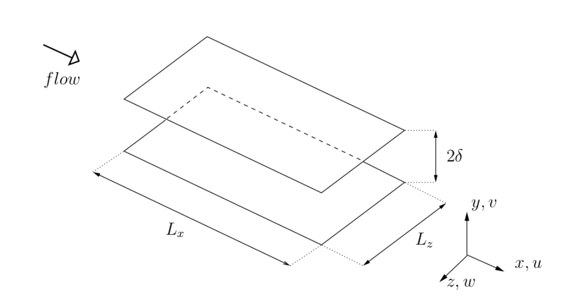

*Source: Lauga et. al, SHB(2005)*

**Navier Slip Model**

$$u_s = \lambda \frac{du}{dy}|_w$$

$\lambda$: Slip Length

# Domain and Approach




*Source: Luchini & Quadrio, JCP(2006)*

- Statistically 1D flow

$$\delta = \frac{y_u - y_l}{2}$$

$$Re = \frac{u\delta}{\nu}$$

- Unsteady, viscous, incompressible flow $\rightarrow$ Non-dimensional Navier-Stokes
- Pseudo-spectral approach
- Mesh Resolution: 128×100×128

$x$, $y$, $z$ : Streamwise, wall-normal, spanwise

$L_x$, $L_y$, $L_z$ : Domain size in respective directions

# Reference Case: Comparison

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho u_b^2}$$

$$c_f = \frac{\tau_w}{\frac{1}{2}\rho u_c^2}$$

$u_b$ : Bulk velocity

$u_c$ : Centerline velocity

$u_{\tau 0}$ : Reference friction velocity

| Parameter | Kim et. al [2] | DNS Study |
|---|---|---|
| $C_f$ | $8.18 \times 10^{-3}$ | $7.96 \times 10^{-3}$ |
| $c_f$ | $6.04 \times 10^{-3}$ | $5.98 \times 10^{-3}$ |
| $u_b/u_{\tau 0}$ | 15.63 | 15.85 |
| $u_c/u_{\tau 0}$ | 18.2 | 18.29 |

[2] Kim, Moin & Moser, JFM (1987)

# Drag Reduction

**Reference literature: Min-Kim (2004)** [3] $\rightarrow$ Study with uniform slip for various slip lengths $\rightarrow$ chosen case for comparison: Uniform streamwise slip at $Re_\tau$=180

$$DR = \frac{\frac{d\overline{u}}{dy} - \frac{d\overline{u}}{dy}|_0}{\frac{d\overline{u}}{dy}|_0} \times 100$$

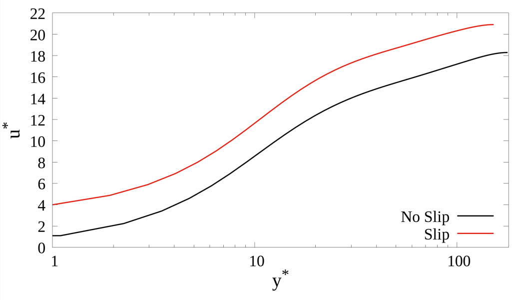
$(.)^+$ = Reference friction scaling

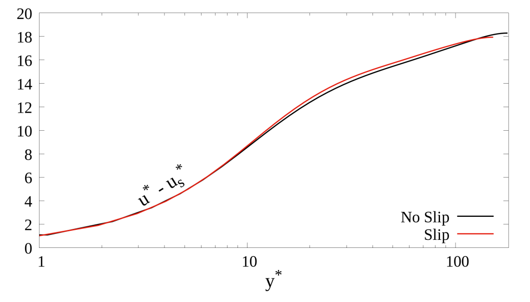
$(.)^*$ = Actual friction scaling

| Parameter | Min-Kim | DNS Study |
|---|---|---|
| $\lambda$ | 0.02 | 0.02 |
| $\lambda^+$ | 3.566 | 3.558 |
| $u_s^*$ | 3.006 | 2.974 |
| DR(%) | -29 | -27.5 |

$\lambda$ : Slip length $\qquad u_s$ : Mean slip velocity

[3] Min & Kim, Phys. Fluids (2004)




- Reduction in $Re_\tau$
- Higher shift $\rightarrow$ Due to slip velocity?
- Collapse of Profiles
- $u^+ = \kappa^{-1} ln(y^+) + B$
- $\Delta B > 0 \implies$ DR

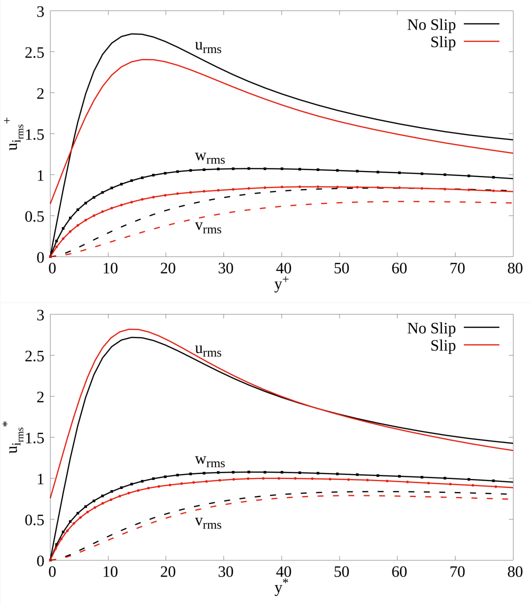
Estimating[a] $\Delta B$ from Drag reduction:

$$\Delta B = \sqrt{\frac{2}{C_{f_0}}}[(1 - DR)^{-\frac{1}{2}} - 1] - \frac{1}{2\kappa} ln(1 - DR)$$

| | Expression Output | DNS Output |
|---|---|---|
| $\Delta B$ | 2.99 | 3.02 |

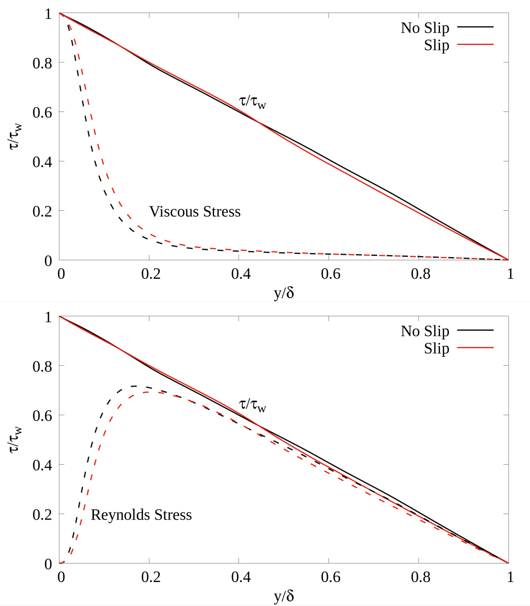
[a] Gatti & Quadrio, JFM (2016)

# Turbulent Intensities




- Anisotropy across the channel
- Near wall contains peak turbulent activity
- Reduction of intensities with slip velocity
- Increase of $u_{rms}$ near wall due to $u_s$ fluctuations
- Peak shifted farther away from wall

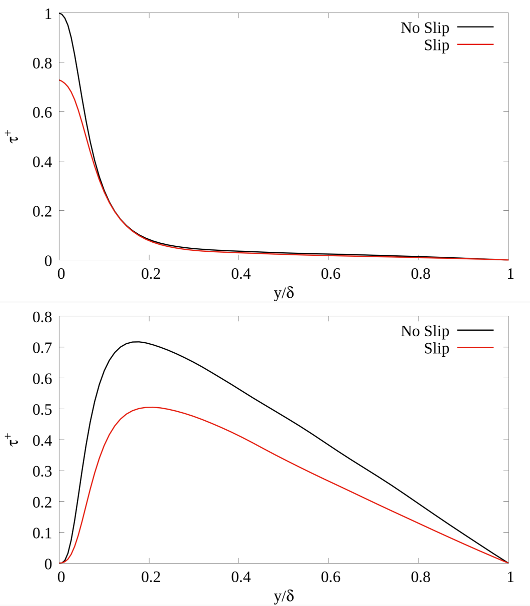
# Shear Stresses




$$\tau = \mu \frac{d\overline{u}}{dy} - \rho \overline{u'v'} = \tau_w \left(1 - \frac{y}{\delta}\right)$$

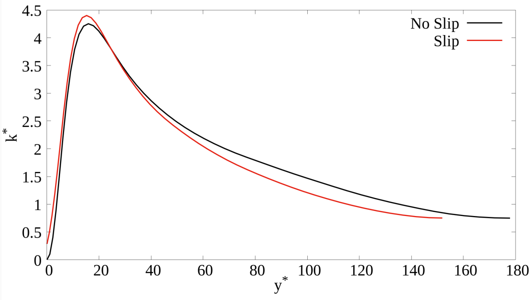
- Total stress linear
- Viscous stress near wall phenomenon
- Reynolds stress relevant across channel
- Low Reynolds number effects visible
- Complementary behaviour near wall

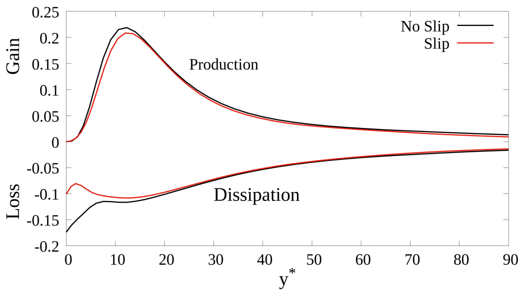
# Shear Stresses in + scaling




- $\tau^+ = \tau/\tau_{w0}$; $\tau_{w0}$: Wall shear stress of no slip wall
- Reduction in stresses when compared with no slip wall
- Reynolds stress irrelevant at the wall
- $\tau/\tau_w$ = 0.73 for slip case $\implies$ $\tau|_{slip}$ = 73 $\%$ $\tau_{w_0}$ $\implies$ 27$\%$ DR

# Turbulent Kinetic Energy




$$k = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

$$P = -\overline{u_i' u_j'} \frac{\partial \overline{u_i}}{\partial x_j} \qquad \epsilon = 2\nu \overline{s_{ij}' s_{ij}'}$$

- Increase of $k^*$ at wall by 0.3 as $u^*_{rms}$ increases by 0.7
- Peak of production at $y^*$ when stresses equate
- No peak of $\epsilon$ at the wall in slip.
- Decrease of $\epsilon$ in viscous sublayer and peak at $y^* \approx 20 \rightarrow$ stable structures, turbulence away from wall

# Conclusions

- Study coherent with data of Min-Kim(2004)
- Drag significantly reduced by partial slip specifically by 27$\%$ in accordance with Min-Kim(2004)
- Higher shift in mean profile $\implies \Delta B > 0 \rightarrow$ Reduction in Drag
- Turbulent intensities exhibit controlled behaviour
- Low Re effects and peak dissipation away from wall $\rightarrow$ Turbulence away from wall
- Validation successful and a green light to address spanwise forcing

# THANK YOU!

# Drag Reduction: A theoretical prediction

Can Drag be computed directly from $\lambda$ ? [4]

$$\lambda^+ = \frac{1 - u_\tau^+}{{u_\tau^+}^2}(\kappa^{-1} ln(Re_{\tau_0}) + F) - \frac{1}{\kappa u_\tau^+} ln(u_\tau^+)$$

$$R_d = \frac{C_{f0} - C_f}{C_{f0}} = 1 - \left(\frac{u_\tau}{u_{\tau 0}}\right)^2 \implies u_\tau^+ = \sqrt{1 - R_d}$$

$R_d$ : Drag Reduction Rate

- $\lambda^+ = 3.56 \implies u_\tau^+ = 0.86 \implies R_d = 0.267$

| Parameter | Theory | DNS Study |
|---|---|---|
| $u_\tau$ | 0.03 | 0.03 |
| $R_d(\%)$ | 26.7 | 27.4 |

[4] Fukagata, Kasagi & Koumoutsakos, Phys. Fluids (2006)