Direct Numerical Simulation of Drag Reduction with Uniform Blowing over a Rough Wall

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Background

Turbulence
- Huge drag
- Environmental problems
- High operation cost
- How to control?
Flow control classification
(M. Gad-el-Hak, J. Aircraft, 2001)

Flow control strategies

- Active
  - Feedback
  - Feedforward
    - Uniform blowing

- Passive
Uniform blowing (UB)
(Sumitani & Kasagi, AIAA J., 1995)
Kametani & Fukagata, J. Fluid Mech., 2011)

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

\[ C_f = \frac{12}{Re_b} + 12 \int_0^2 (1-y)(-\bar{u}'\bar{v}')dy -12V_w \int_0^2 (1-y)\bar{u}dy \]

Viscous
Contribution
=Turbulent
= Convective (=UB/US)
(= laminar drag, const.)
contribution

- Excellent performance (about 45% by \( V_w = 0.5\% U_\infty \))

- Unknown over a rough wall

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

Investigate the interaction between roughness and UB for drag reduction

- DNS of turbulent channel flow
- Focus on drag reduction performance and mechanism
**Numerical procedure**

- **Based on FD code** (for wall deformation)  
  (Nakanishi et al., *Int. J. Heat Fluid Fl.*, 2012)
- **Constant flow rate**, $Re_b = 2U_b \delta/\nu = 5600$
  - so that $Re_\tau \approx 180$ in a plane channel (K.M.M.)
- $\Delta x^+ = 4.4, 0.93 < \Delta y^+ < 6, \Delta z^+ = 5.9$
- **UB magnitude**: $M = 0, 0.001, 0.005$

![Diagram of flow patterns](Image)
Model of rough wall
(E. Napoli et al., *J. Fluid Mech.*, 2008)

Roughness displacement

\[ d(x) = \delta \sum_{i=1}^{4} A_i \sin \left( \frac{2^i \pi x}{L_x/2} \right) \]

\( \delta \): 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

\[ |d(x)|_{\text{max}} = 0.11\delta \]

\[ |d(x)| = 0.05\delta \]
Coordinate transformation

Calculation grids: $\xi_i$ (Cartesian with extra force)

\[
\begin{align*}
    x &= \xi_1 \\
    y &= \xi_2(1 + \eta) + \eta_d \\
    z &= \xi_3
\end{align*}
\]

($x, y, z$: physical coordinate)

Actual grid points allocation

\[
\eta \equiv (\eta_u - \eta_d)/2
= -\frac{d(x)}{2}
\]

$\eta_d = r(x), \eta_u = 0$

$\eta_d, \eta_u$: displacement of lower/upper wall
Post processing

- Drag coefficient decomposition for rough case

\[ C_{Du_f} = \frac{8}{Re_b} \frac{d\bar{u}}{dy} \bigg|_{\xi_2=2} \]

\[ C_{Dlf} = \frac{8}{Re_b} \left( \frac{d\bar{u}}{dy} \bigg|_{\xi_2=0} + \frac{dv}{dx} \bigg|_{\xi_2=0} \right) \]

\[ C_{Dlp} = -16 \frac{dP}{d\xi_1} - (C_{Dlf} + C_{Du_f}) \]

(Friction component)

(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.
Drag reduction rate, $R_D$

**SMOOTH CASE**

<table>
<thead>
<tr>
<th>$C_D$</th>
<th>0</th>
<th>0.1</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>0</td>
<td>0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- **Total** $R_D$: $\downarrow 11\%$ $\downarrow 37\%$
- **Friction** $R_{D,F}$: $\downarrow 11\%$ $\downarrow 37\%$
- **Pressure** $R_{D,P}$: - -

**ROUGH CASE**

<table>
<thead>
<tr>
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</table>

- Total $R_D$: $\downarrow 7\%$ $\downarrow 26\%$
- Friction $R_{D,F}$: $\downarrow 9\%$ $\downarrow 34\%$
- Pressure $R_{D,P}$: $\downarrow 5\%$ $\downarrow 19\%$
How does friction drag decrease?

Bulk mean streamwise velocity

Black: $M = 0$
Green: $M = 0.001$
Red: $M = 0.005$

Normalization based on $M = 0$
How does pressure drag decrease?

Pressure contours

\[ M = 0 \]

averaged in the spanwise and time dashed lines: zero contour

\[ M = 0.005 \]
Stream function

Solid lines: $M = 0$
Dashed lines: $M = 0.005$

Uniform Blowing
In practical applications

Drag reduction amount, $\Delta C_D = C_{D,M=0} - C_{D,M=0.1,0.5}$

![Diagram showing drag reduction comparison between smooth and rough walls with $\Delta C_D$ plotted against $M$.]
Concluding remarks

DNS of turbulent channel flow over a rough wall with UB

- **UB is effective over rough walls**
  - Lower drag reduction rate (7%, 26% / 11%, 37% in rough / smooth case, with $M = 0.001, 0.005$)

- **Drag reduction mechanism**
  - Friction drag by wall-normal convection (=conventional)
  - Pressure drag by prevention of stagnant flow

- **Outlook toward practical applications**
  - More saving opportunity over rough walls
Future plans

- Another drag reduction technique on rough surface
  - Spanwise oscillation (ongoing)
- Assessment of net energy? (should be external flow)
- Calculation at higher Reynolds number?
- Other types of rough surfaces (e.g., 3D structure)?
Uniform blowing (UB)
(Sumitani & Kasagi, AIAA J., 1995
Kametani & Fukagata, J. Fluid Mech., 2011)

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

\[ C_f = \frac{12}{Re_b} + 12 \int_0^2 (1 - y)(-u'v')dy - 12V_w \int_0^2 (1 - y)\bar{u}dy \]

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

White: vortex core, Colors: wall shear stress
Governing equations

Incompressible Continuity and Navier-Stokes in $\xi_i$ coordinate

\[
\begin{align*}
\frac{\partial u_i}{\partial t} &= -\frac{\partial (u_i u_j)}{\partial \xi_j} - \frac{\partial p}{\partial \xi_i} + \frac{1}{Re} \frac{\partial^2 u_i}{\partial \xi_j \partial \xi_j} - \frac{dP}{d\xi_1} \delta_{i1} + S_i \\
\frac{\partial u_i}{\partial \xi_i} &= -S
\end{align*}
\]

where

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

\[
S = \phi_j \frac{\partial u_i}{\partial \xi_2}
\]

$\phi_j = \varphi_j - \delta_{j2}$

$\varphi_j = \begin{cases} 
- \frac{1}{1 + \eta} \left( \xi_2 \frac{\partial \eta}{\partial \xi_2} + \frac{\partial \eta_0}{\partial \xi_2} \right), & \text{for } j = 1,3 \\
\frac{1}{1 + \eta}, & \text{for } j = 2 
\end{cases}$
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  
(B. Milici et al., *J. Fluid Mech.*, 2014)

Bulk mean streamwise velocity

Time trace of instantaneous $C_{D,r}$

*Less than 2% of difference with most resolved one*
How does friction drag decreases?

Reynolds shear stress contour

\[ M = 0 \]

\[ M = 0.005 \]

*averaged in the spanwise and time dashed lines: zero contour
ś distribution (2D contour)

Based on $u_\tau$ in w/o control case

No control case

UB 0.5% case
$\bar{u}$ distribution (2D contour)

No control case

UB 0.5% case

Based on $u_\tau$ in w/o control case
Stream function (detailed)
$u_{\text{rms}}$ distribution

- **Black**: w/o control
- **Green**: UB 0.1%
- **Red**: UB 0.5%

Normalized by $u_\tau$ in w/o control case
\( \nu_{\text{rms}} \) distribution

Black: w/o control  
Green: UB 0.1%  
Red: UB 0.5%

Normalized by \( u_\tau \)  
in w/o control case
$w_{\text{rms}}$ distribution

Black: w/o control  
Green: UB 0.1%  
Red: UB 0.5%

Normalized by $u_\tau$ in w/o control case
$u'^+v'^+$ distribution

Black: w/o control
Green: UB 0.1%
Red: UB 0.5%

Normalized by $u_\tau$
in w/o control case
• Effective slope = about 0.2
• $k_{\text{rms}}$
• Sand grain roughness
• 3D?
• How to calculate skin-friction drag
• The history of UB
• Pressure component legend (purple) of smooth case should be removed
• More time for drag reduction rate slide