Developing Wall-Sensing Control for Drag Reduction in Turbulent Channel Flow

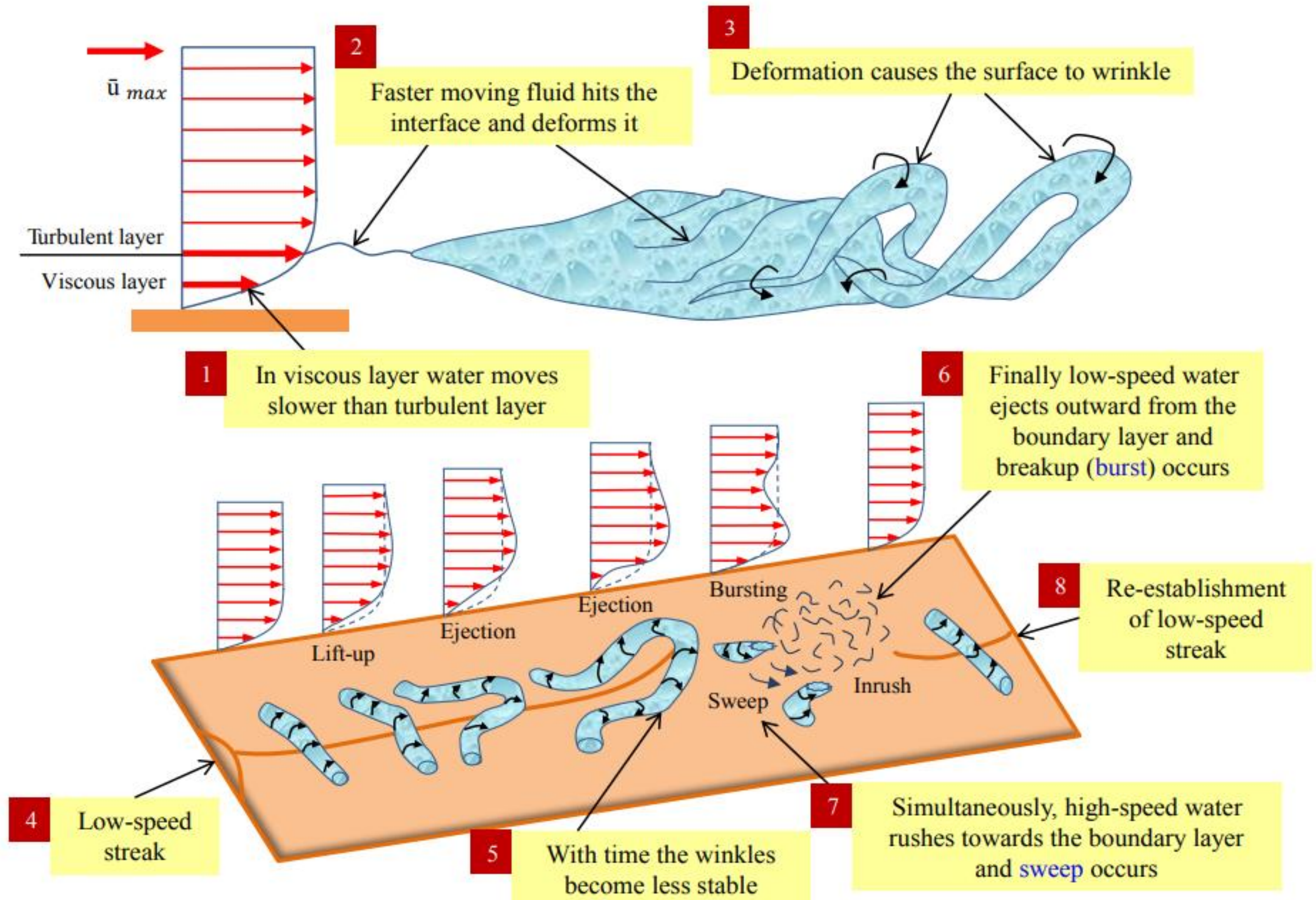
Aryan Prathamesh Kalelkar, B.S.E. Mechanical Engineering
Mentor: Dr. Yulia Peet, Associate Professor
School for Engineering of Matter, Transport and Energy

Research Question

How does incorporating both the streamwise and spanwise components of wall shear stress affect drag reduction in fully developed turbulent channel flow?

Background & Motivation

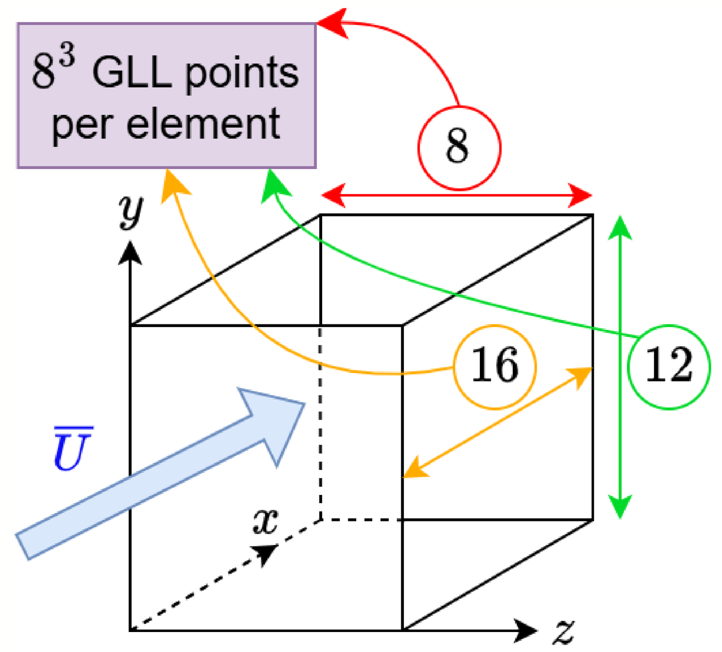
- Drag reduction (DR) is a critical engineering goal for maximizing efficiency and reducing fuel consumption.
- Streamwise vortices (aligned with the flow) result in sweep and ejection events at the wall[1][3].
- Spanwise vortices (normal to the flow) generate alternating high and low speed streaks near the wall[2].



- Active control methods like opposition control show significant DR but are limited by high energy demand and complex system requirements.
- Passive control methods are feasible, but their modest DR demands significant work to enhance efficiency.

Methodology

- Direct Numerical Simulations (DNS) were performed using the spectral element code Nek5000.



Dimensions: $2\pi h \times 2h \times \pi h$
h is Channel Half-width
$16 \times 12 \times 8$ Elements

Courant-Friedrichs-Lewy Stability Criterion

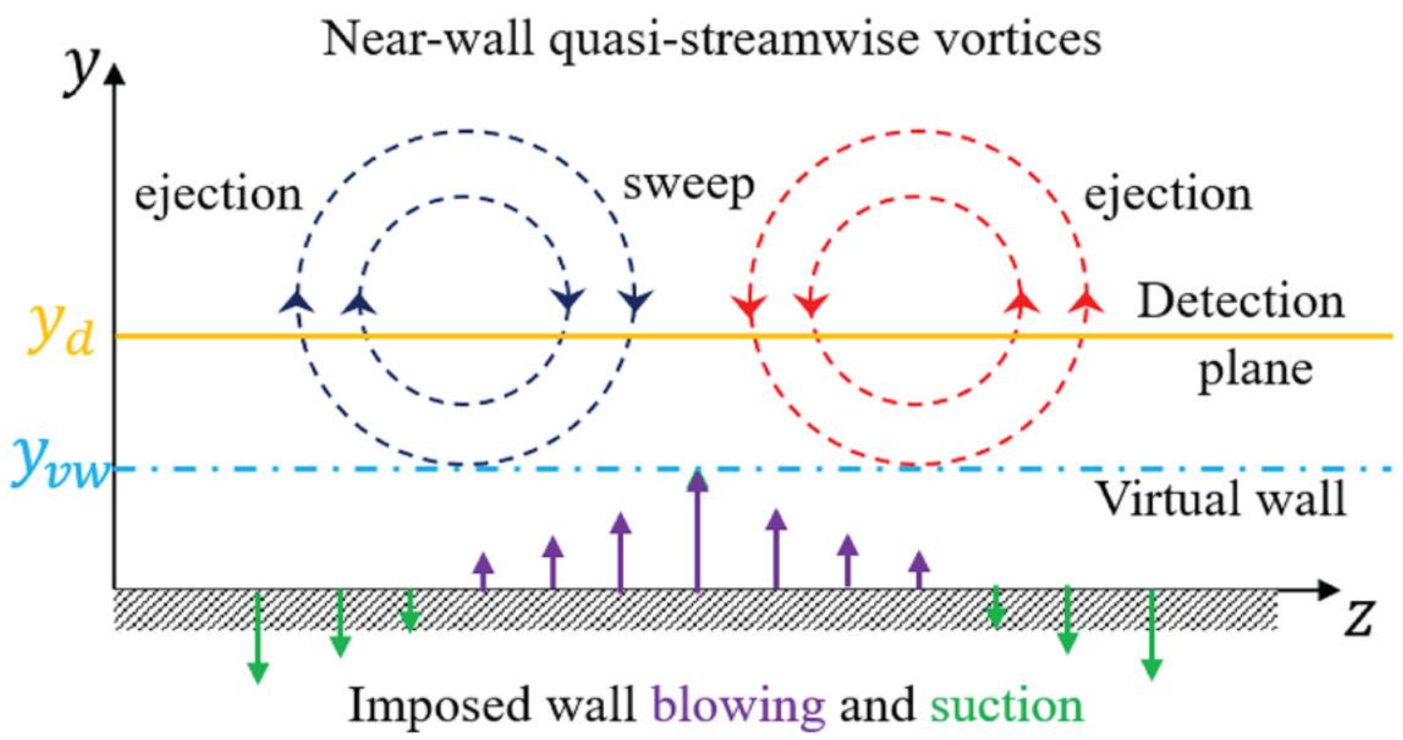
$$CFL = u\frac{\Delta t}{\Delta x} = 0.5$$

- Transpiration Velocity[3]

$$u_y\Big|_{wall}(x,z,t) = G \cdot \left[\left(\nu\frac{\partial u_i}{\partial y}\right)_{wall}(x,z,t) - \overline{\left(\nu\frac{\partial u_i}{\partial y}\right)_{wall}}(t)\right]$$

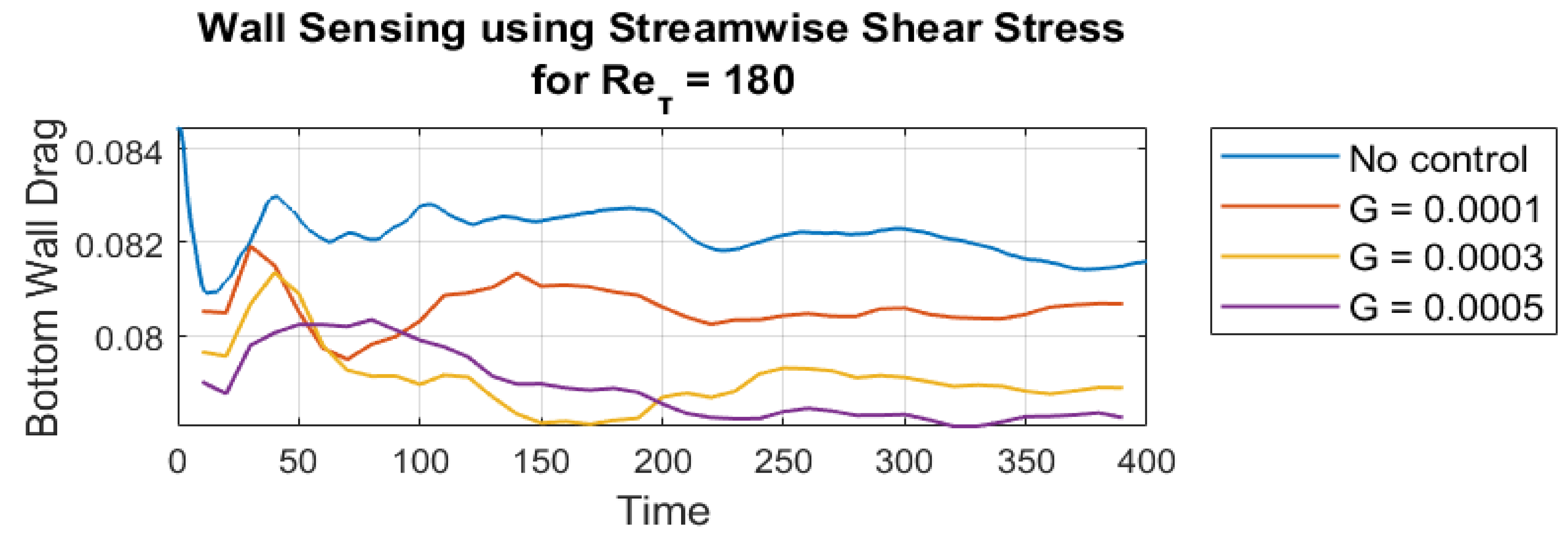
- Wall Shear Stress[3]

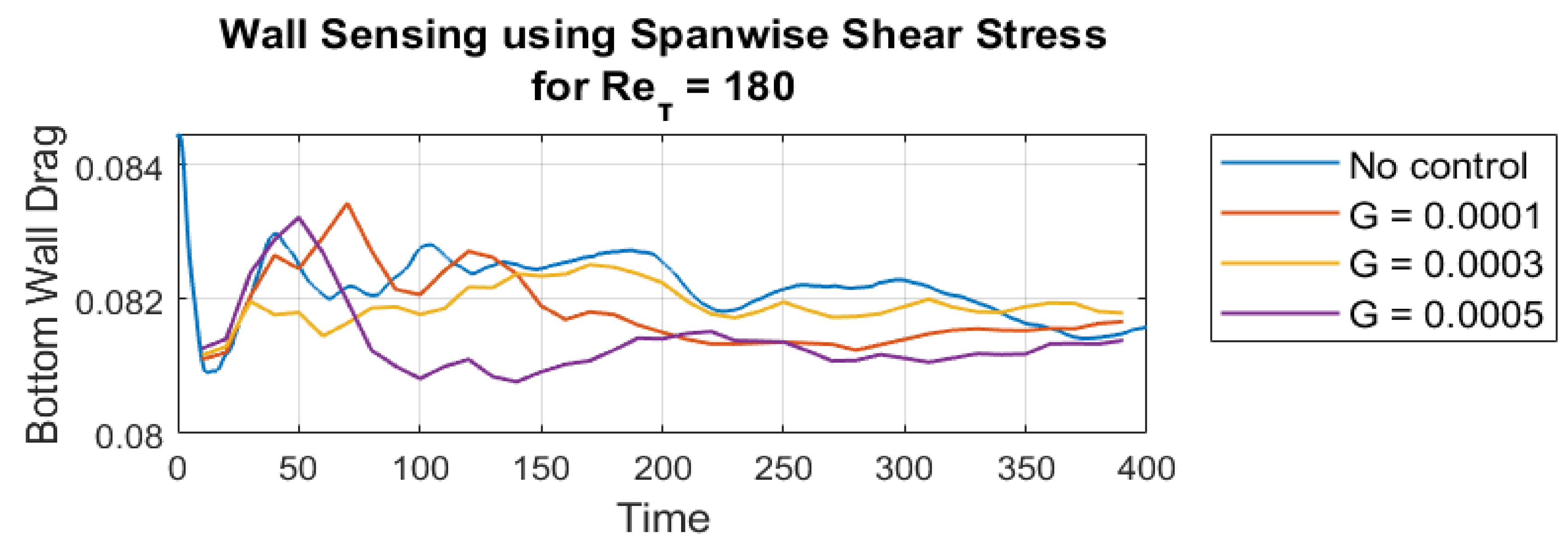
$$\tau_{wall}(t) = \overline{\left(\nu\frac{\partial u_i}{\partial y}\right)_{wall}} \; ; \; i = \begin{cases} x, & \textit{Streamwise shear} \\ w, & \textit{Spanwise shear} \end{cases}$$



Discussion & Results

- Spanwise shear stress generates far less drag than streamwise shear stress.
- Combining spanwise and streamwise shear stress results in limited drag reduction.





Gain $(\times 10^{-4})$	%DR (Streamwise)	%DR (Spanwise)
1	1.12 %	-0.0938 %
3	3.38 %	-0.249 %
5	4.20 %	0.253 %

Future Scope

- Examining the effects of higher control gains and varying time-averaging intervals on drag reduction.
- Investigating drag reduction when transpiration velocity is applied at an angle to the wall normal.

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Acknowledgments

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References

[1] S. Salim et al., "The influence of turbulent bursting on sediment resuspension under unidirectional currents," DOI: 10.5194/esurf-5-399-2017.
[2] M. F. Baig et al., "The mechanism of streak formation in near-wall turbulence: Journal of Fluid Mechanics," DOI: 10.1017/S0022112005006506.
[3] A. Subedi et al., "Turbulent Flow Control Using Wall Sensing," DOI: 10.2514/6.2024-3868.

ASU Ira A. Fulton Schools of Engineering
Arizona State University