Direct numerical simulation of turbulent open channel flow: Streamwise turbulence intensity scaling and its relation to large-scale coherent motions

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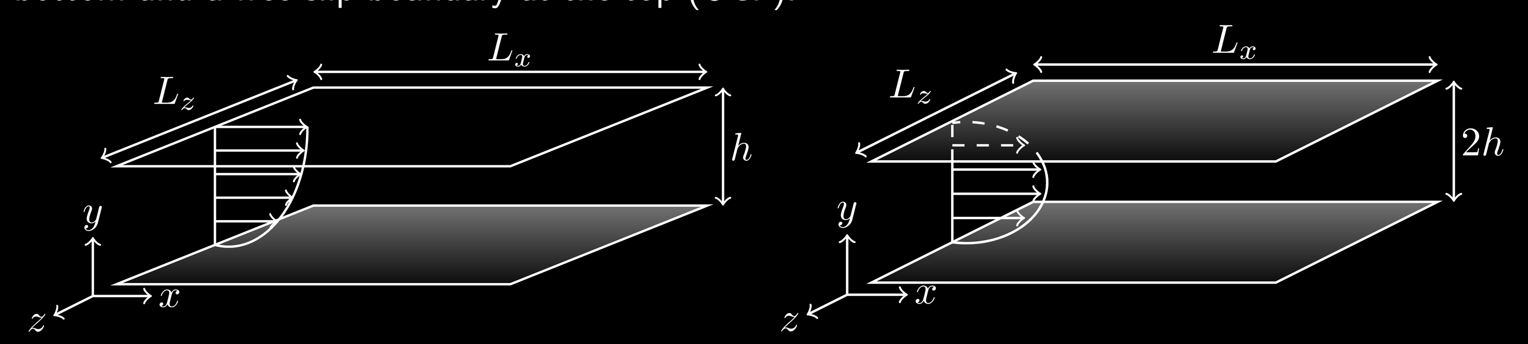
INTRODUCTION & METHODOLOGY

The well-known failure of wall-scaling of the streamwise turbulent intensity in closed channel flows (CCF) is associated with the appearance of very-large-scale motions (VLSMs [2]). In turbulent open channel flow (OCF), VLSMs are larger, more energetic and appear at lower Reynolds number than in CCF [3, 4, 5]. Moreover, VLSMs in OCF are related so so-called super-streamwise vortices (SSV [6]), which are statistically difficult to capture. Thus, to investigate the scaling of turbulence intensities and its relation to underlying coherent structures in OCF, we carried out direct numerical simulations (DNSs) of both OCF and CCF of friction Reynolds numbers up to $\mathrm{Re}_\tau \approx 900$ in large computational domains ($Lx/h \times L_z/h = 12\pi \times 4\pi$). We are solving the incompressible Navier Stokes equations

$$\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u} + \nabla p = \frac{1}{Re}\nabla^2\vec{u},$$
$$\nabla\cdot\vec{u} = 0,$$

in terms of their vertical velocity/vorticity formulation discretised on a Chebyshev-Gauss-Lobatto grid [3]. The method incorporates a direct Poisson solver involving 2D FFTs and a MPI parallelised algorithm. The flow geometry is plane channel with with periodic boundaries in stream- and spanwise direction and either no-slip walls at bottom and top (CCF) or one no-slip boundary at the bottom and a free-slip boundary at the top (OCF).



Both OCF and CCF turbulence statistics data sets are available online [1].

SIMULATION CASES

Case	O200	O400	O600	O900L4	O900L8	O900L12	C200	C400	C600	C900
Re_τ	200	399	596	899	895	894	200	397	593	890
Re_b	3170	6969	11 047	17 512	17 512	17 512	3170	6969	11 047	17 512
L_x/h	12π	12π	12π	4π	8π	12π	12π	12π	12π	12π
L_z/h	4π	4π	4π	2π	4π	4π	4π	4π	4π	4π
N_x	768	1536	1536	1536	2048	3072	768	1536	2048	3072
N_y	129	193	257	385	385	385	129	193	257	385
N_z	512	1024	1536	1024	2048	2048	512	1024	1536	2048
Δx^+	9.8	9.8	14.6	7.4	11.0	11.0	9.8	9.8	14.6	11.0
Δz^+	4.9	4.9	4.8	5.5	5.5	5.5	4.9	4.9	4.8	5.5
Δy^+_{max}	2.5	3.3	3.7	3.7	3.7	3.7	4.9	6.5	7.3	7.3
$\Delta T u_b/h$	8660	1925	1460	417	570	1054	8600	3260	1757	1013
$\Delta T u_\tau^2/\nu$	109 700	43 900	46 980	19 080	26 100	44 700	108 200	73 730	55 960	45 820

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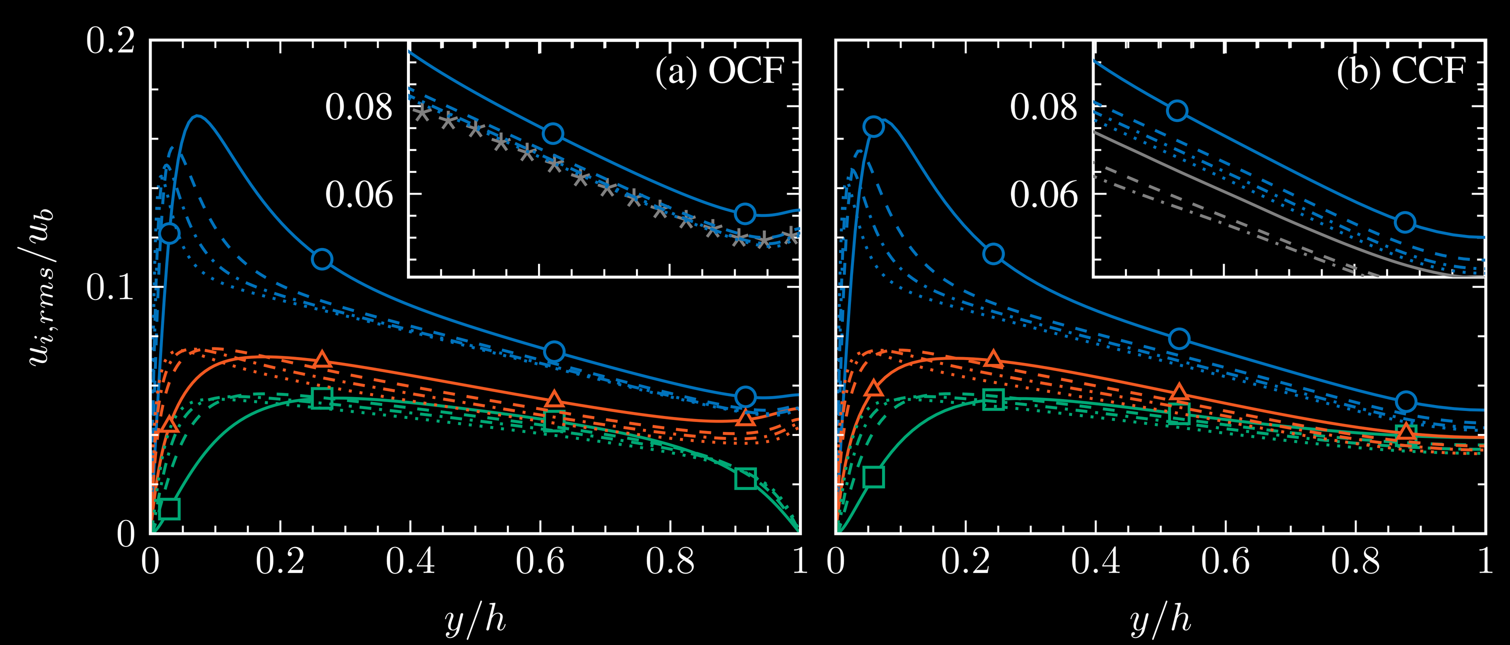
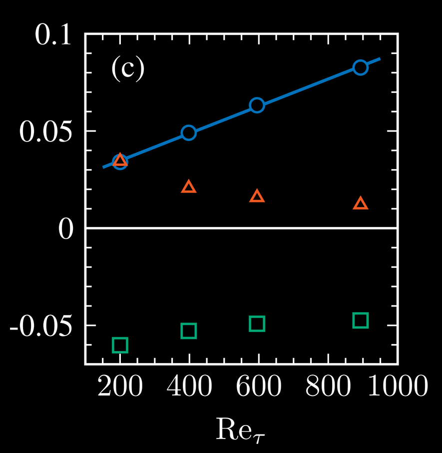
TURBULENCE INTENSITY SCALING

Streamwise turbulence intensity in OCF appears to scale with the bulk velocity u_b





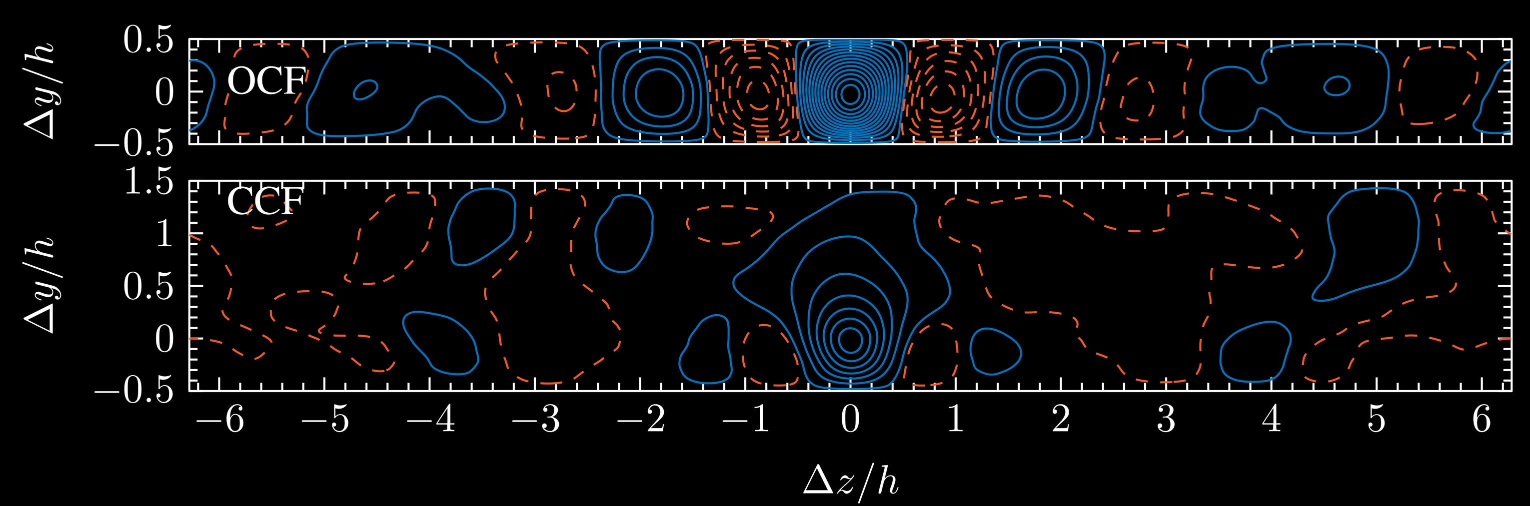
(a,b) Turbulence intensities normalized by u_b as function of the distance from the wall y/h for OCF (a) and CCF (b): —○—, u_{rms}; —□—, v_{rms}; —△—, w_{rms}. Solid lines, $\mathrm{Re}_\tau \approx 200$; dashed lines, $\mathrm{Re}_\tau \approx 400$; dashed-dotted lines, $\mathrm{Re}_\tau \approx 600$; dotted lines, $\mathrm{Re}_\tau \approx 900$. The insets show a zoom for the streamwise turbulence intensity component. The symbols (*) in (b) indicate a profile from OCF measurements by [5] at $\mathrm{Re}_\tau = 2407$. The gray lines in (d) indicate CCF DNS data at $\mathrm{Re}_\tau = 2003$ (—, [2]), $\mathrm{Re}_\tau = 5186$ (- - -, [7]), $\mathrm{Re}_\tau = 10049$ (- - -, [8]).

(c) Areas between OCF and CCF turbulence intensities normalized with the friction velocity,

$$a_i = \int_{y=0}^{h} u^O_{i,rms}\,\mathrm{d}y/(u^O_\tau h^O) - \int_{y=0}^{h} u^C_{i,rms}\,\mathrm{d}y/(u^C_\tau h^C),$$

where $u^O_{i,rms}$ and $u^C_{i,rms}$ denote the i-component of the OCF and CCF turbulence intensity, respectively. •, a_x; ▪, a_y; ▴, a_z. The blue line indicates the linear scaling law $a_x = 0.0208 + 7\cdot 10^{-5}\mathrm{Re}_\tau$. The data presented here suggests that a_y and a_z settle at a constant value for higher Reynolds numbers, while a_x increases linearly.

SUPER-STREAMWISE VORTICES



SSV extracted from two-point correlations of the streamfunction of the streamwise averaged cross-sectional velocity components, $R_{\psi\psi}(\Delta y, \Delta z, y_0) = \langle \psi_{\langle v\rangle_x\langle w\rangle_x}(y_0, z)\psi_{\langle v\rangle_x\langle w\rangle_x}(y_0+\Delta y, z+\Delta z)\rangle_{zN}$ where $\langle\cdot\rangle_{zN}$ represents averaging in z-direction as well as over $N = 50$ snapshots and $\psi_{\langle v\rangle_x\langle w\rangle_x}(y,z) = \int_{\hat{y}=0}^{y}\langle w\rangle_x(\hat{y}, z)\,\mathrm{d}\hat{y} - \int_{\hat{z}=0}^{z}\langle v\rangle_x(0,\hat{z})\,\mathrm{d}\hat{z}$.

VERY-LARGE-SCALE MOTIONS

⟵ OCF / CCF ⟶