DNS of turbulent channel flow with different types of spanwise forcing

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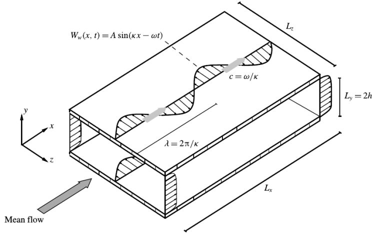
European Drag Reduction and Flow Control Meeting
April 3-6 2017, Rome, Italy

Traveling waves (TW)

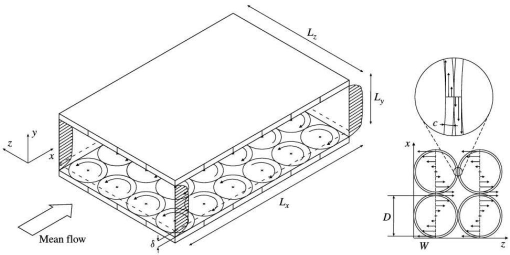


- Spanwise wall oscillation first proposed by Jung et al. PoF 1992
- Streamwise-traveling waves introduced by Quadrio et al. JFM 2009

$$W_w(x,t) = A\sin(kx - \omega t)$$

- Effectiveness supported by experimental data (Auteri et al. 2010, Gouder et al. 2013)
- Up to 58% drag reduction (28% net power saving) at $Re_\tau = 200$
- Drag reduction rate frequently assumed to scale as $\mathcal{R} \sim Re_\tau^{-\gamma}$ ($\gamma \approx 0.2$)
- In fact, Gatti & Quadrio (2013, 2016) have shown milder decrease

Rotating discs (RD)



- First proposed by Keefe (AIAA Paper 97-0547)
- Numerically tested by Ricco & Hahn (JFM 2013), Wise et al. PoF 2013
- Similar intent as streamwise-traveling waves
- Less effective than TW (max drag reduction $\approx 23\%$, max net power saving $\approx 10\%$)
- Oscillating discs have also been considered (Wise & Ricco JFM 2014)

Goals

1. Explore effectiveness of streamwise-traveling wave concept to high Re on sufficiently wide domains
2. Study performance of rotating discs at moderate Re
3. Carry out a comparative evaluation of the two methods
4. Study effect of wall manipulation on heat transfer

Control parameters

Device	λ_x^+	ω^+	A^+	D^+	W^+	gap
TW	1042	0	13.55	NA	NA	NA
RD	NA	NA	NA	1024	13.55	5%

- Suboptimal conditions for TW (zero phase velocity)
- Useful for direct comparison between TW and RD

DNS parameters

Flow case	Control	Line style	Re_b	Re_τ	N_x	N_y	N_z	Δx^+	Δy_w^+	Δz^+
P1000	NA	solid	39600	995	2560	512	1280	7.3	0.09	4.9
TW1000	TW	dashed	39600	815	2560	512	1280	7.3	0.09	4.9
RD1000	RD	dash-dot	39600	898	2560	512	1280	7.3	0.09	4.9
P2000	NA	solid	87067	2017	5120	768	2560	7.4	0.13	5.0
TW2000	TW	dashed	87067	1686	5120	768	2560	7.4	0.13	5.0
RD2000	RD	dash-dot	87067	1846	5120	768	2560	7.4	0.13	5.0

- Computer time from PRACE grant
- Control devices on both walls
- Box size $6\pi h \times 2h \times 2\pi h$
- Four passive scalar fields added

Scalar field	Symbol	*Pr*	Boundary conditions
A	Square	0.2	Uniform forcing
B	Triangle	0.71	Uniform forcing
C	Diamond	1	Uniform forcing
D	Circle	0.71	Assigned difference

The numerical method

Orlandi 2000

- Projection method with direct Poisson solver (Kim & Moin 87)
- Second-order approximation of space derivatives on staggered mesh (Harlow & Welch 65)
- Conservation of total kinetic energy and scalar variance
- Implicit treatment of wall-normal viscous terms
- Third-order low-storage Runge-Kutta time stepping by A. Wray
- Pencil decomposition for efficient parallel implementation

Global flow parameters

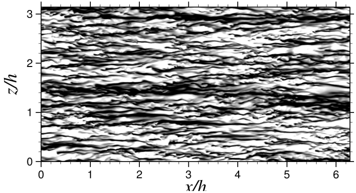
Flow case	C_f	$Nu(A)$	$Nu(B)$	$Nu(C)$	$Nu(D)$	$\Delta Cf\%$	$\Delta Nu(C)\%$
P1000	5.05E-3	38.60	84.09	101.89	73.98	0	0
TW1000	3.39E-3	29.62	58.05	68.61	51.87	-32.9	-32.7
RD1000	4.11E-3	34.77	71.96	86.42	63.87	-18.5	-15.2
P2000	4.27E-3	68.25	157.16	192.86	139.77	0	0
TW2000	2.98E-3	/	112.87	135.58	101.42	-30.2	-29.7
RD2000	3.57E-3	/	137.31	167.33	122.74	-16.2	-13.2

- Mild decrease of drag reducing efficiency with *Re* confirmed for fixed control parameters
- Rotating disks less efficient, but probably also robust to *Re* variation
- Heat transfer suppressed proportionally (Reynolds analogy)

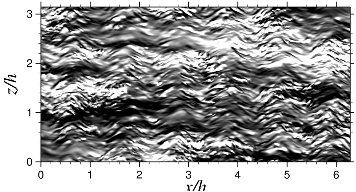
Near-wall streaks

$Re_\tau = 1000$

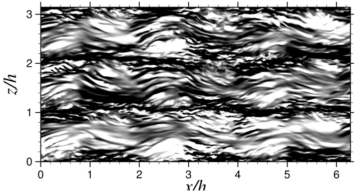
P1000



TW1000



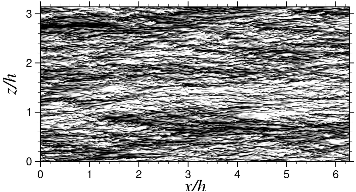
RD1000



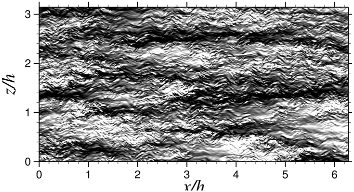
u' contours at $y^+ = 15$, levels from $-3u_\tau$ to $3u_\tau$

$Re_\tau = 2000$

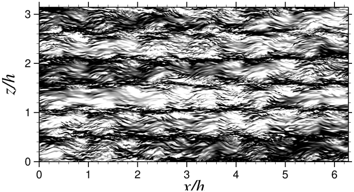
P2000



TW2000



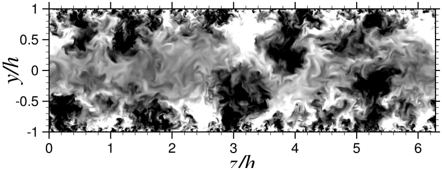
RD2000



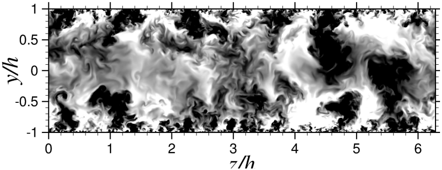
u' contours at $y^+ = 15$, levels from $-3u_\tau$ to $3u_\tau$

$Re_\tau = 2000$

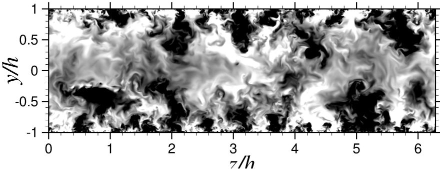
P2000



TW2000



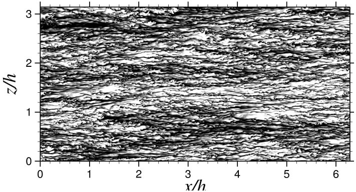
RD2000



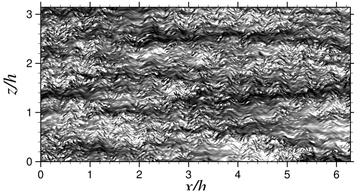
u' contours at $y^+ = 15$, levels from $-2u_\tau$ to $2u_\tau$

Scalar field C, $Re_\tau = 2000$

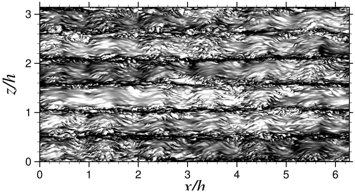
P2000



TW2000



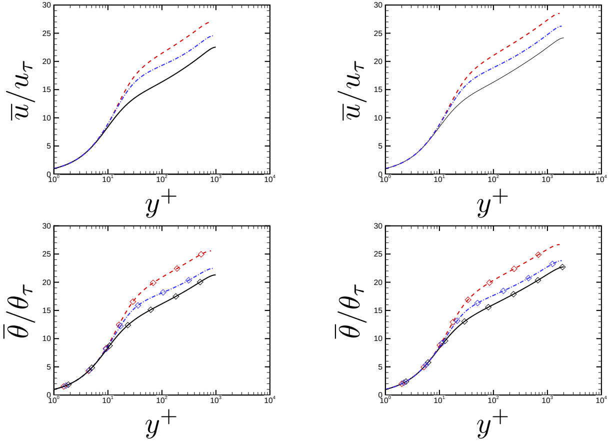
RD2000



θ' contours at $y^+ = 15$, levels from $-3\theta_\tau$ to $3\theta_\tau$

Mean profiles - inner representation

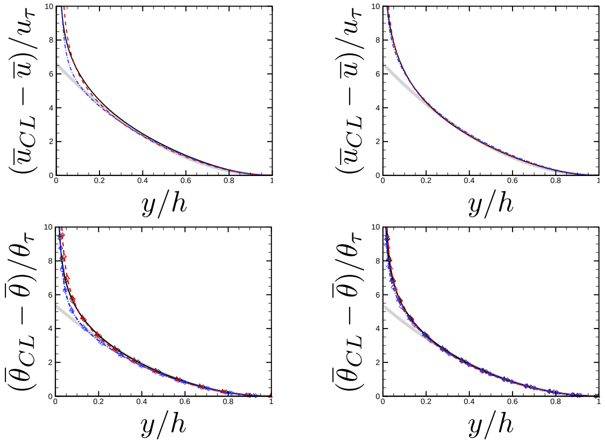
$Re_\tau = 1000$ $\qquad$ $Re_\tau = 2000$



- Near log layer for all flow cases

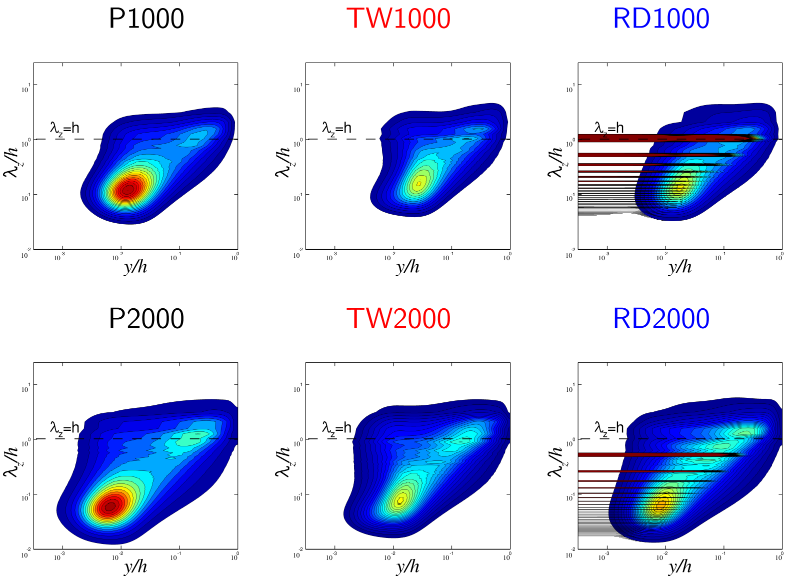
Mean profiles - defect representation

$Re_\tau = 1000$ $\qquad$ $Re_\tau = 2000$



- Parabolic profiles (thick grey lines) in channel core

Spectral maps of u'



Summary

- Effectiveness of TW confirmed at higher Re, on wider domains
- Slight reduction of efficiency with Re
- RD seem to follow similar trends
- RD yield stronger modification of the core flow
- Friction reduction accompanied by proportionate reduction of heat transfer