Control of wall turbulence by spinning discs

Pierre Ricco The University of Sheffield
Stanislav Hahn Honeywell Turbo Technologies

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Spanwise wall oscillations

- $W = W_m \cos(\omega t)$
- Spanwise motion - Uniform in x,z
- $\mathcal{R}$=45%, $\mathcal{P}_{net}$=7%

Travelling waves

- $W = W_m \cos(k_x x - \omega t)$
- Spanwise motion - Uniform in z
- $\mathcal{R}$=47%, $\mathcal{P}_{net}$=23%

Rotating discs

- *New drag reduction technique*
- Non-uniform along x, z
- $\mathcal{R}$=23%, $\mathcal{P}_{net}$=10%

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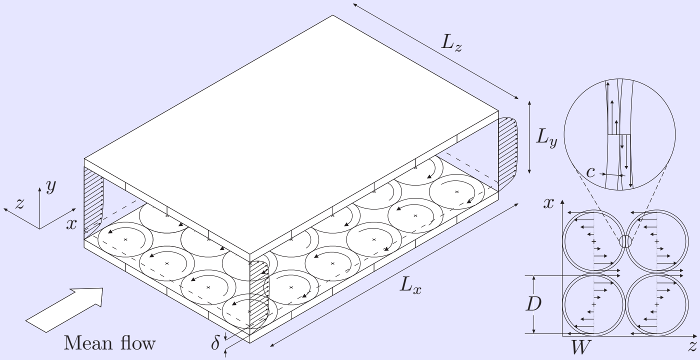
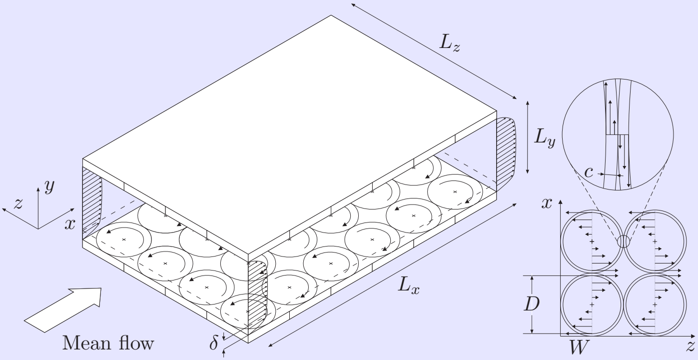


- First proposed by L. Keefe (1998), but no results
- Fully-developed turbulent channel flow $R_\tau = 180$ - DNS: x, z Fourier, y Chebyshev
- Parameters: D diameter, W maximum tip velocity
- Discs neighbouring along z: same sense of rotation
- Discs neighbouring along x: opposite sense of rotation $\rightarrow$ *triangular steady wave*

- Annular gap to avoid Gibbs phenomenon



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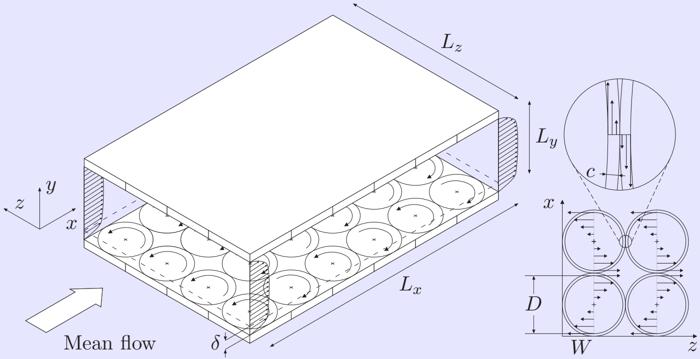

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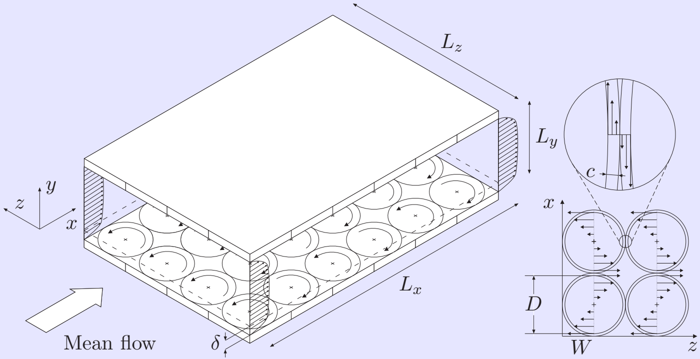

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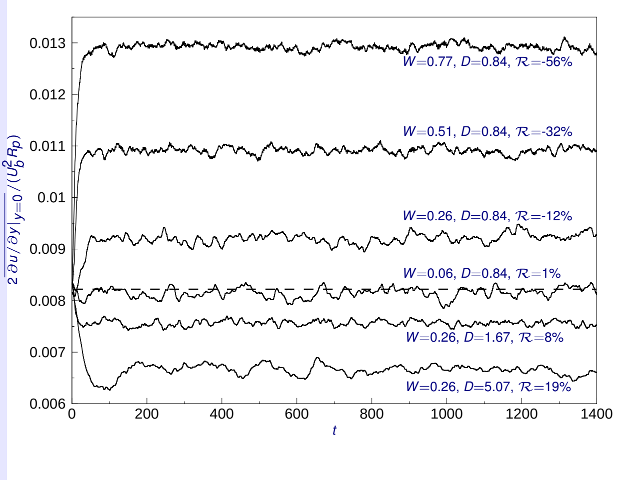
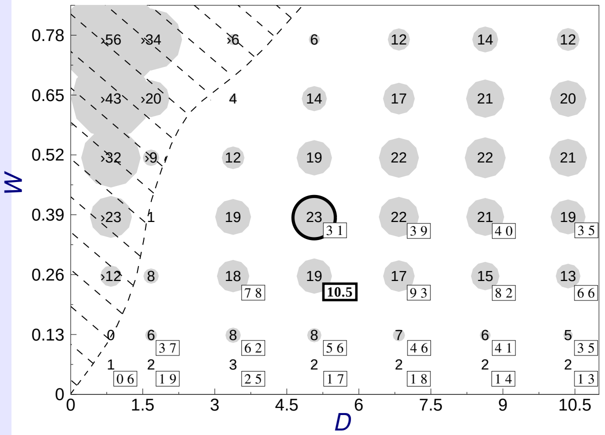


$$\bar{\mathbf{f}} \equiv \frac{1}{L_x L_z}\int_0^{L_z}\int_0^{L_x} \mathbf{f}\,\mathrm{d}x\mathrm{d}z, \quad \langle \mathbf{f} \rangle \equiv \frac{1}{t_f - t_i}\int_{t_i}^{t_f} \mathbf{f}\,\mathrm{d}t$$

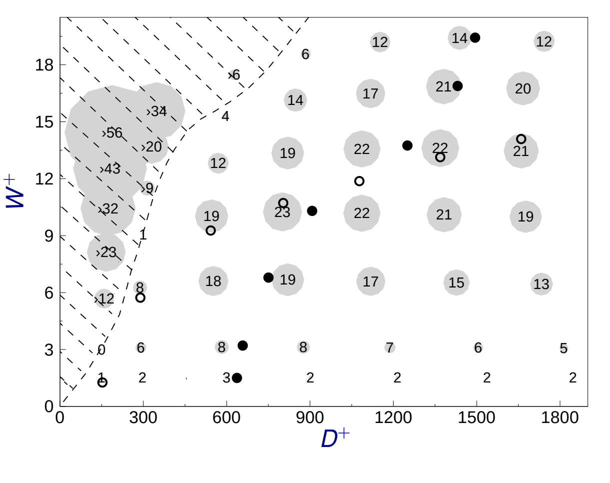
Flow decomposition: $\mathbf{u}(x, y, z, t) = \mathbf{u_m} + \mathbf{u_d} + \mathbf{u_t}$

Mean flow: $\mathbf{u_m}(y) = \langle \bar{\mathbf{u}} \rangle$, Disc flow: $\mathbf{u_d}(x, y, z) = \langle \mathbf{u} \rangle - \mathbf{u_m}$



Drag *increase* may occur at small D, large W

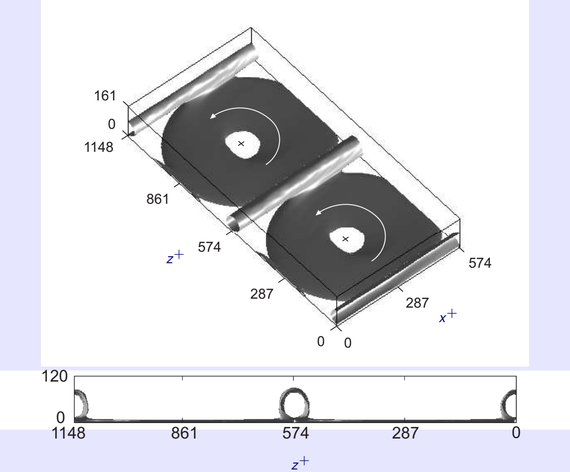
Maximum $\mathcal{R}$=23%, maximum $\mathcal{P}_{net}$=10%



Maximum $\mathcal{R}$=23% $\rightarrow$ $D^+\approx 900$, $W^+\approx 11$

Maximum $\mathcal{P}_{net}$=10% $\rightarrow$ $D^+\approx 900$, $W^+\approx 7$

Flow visualization
Near-wall disc flow

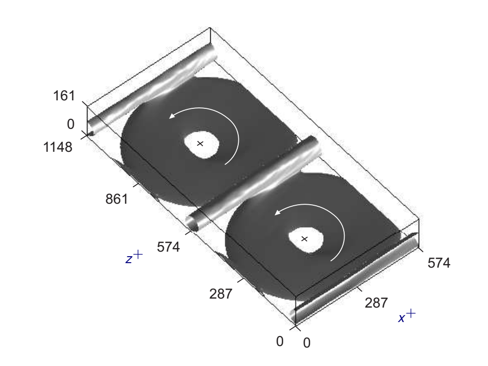


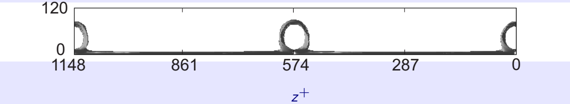
Time-averaged disc flow: $\mathbf{u_d}(x, y, z) = \langle \mathbf{u} \rangle - \mathbf{u_m}$

$q^+(u_d^+, w_d^+) \equiv \sqrt{u_d^{+2} + w_d^{+2}} = 2.3$

Doughnuts: thin circular patterns shielding wall from turbulence

Tubes: x-stretched tubular structures between discs





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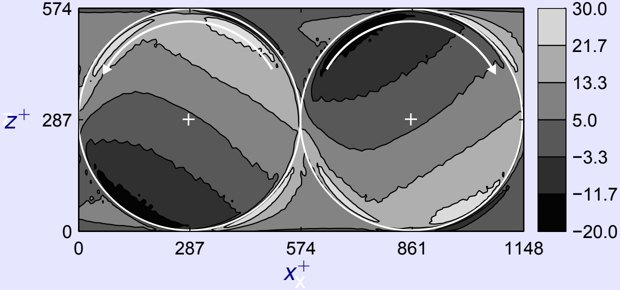
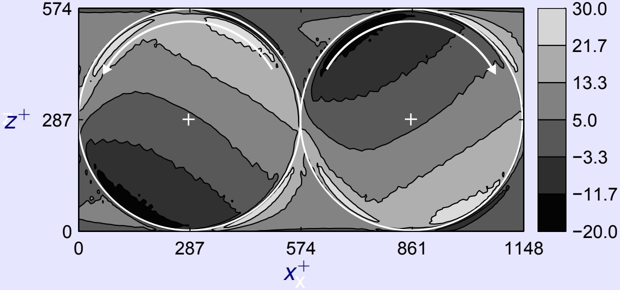
WALL-SHEAR STRESS



Large regions of *negative* wall-shear stress

Maximum wall-shear stress can be *five times* the mean one



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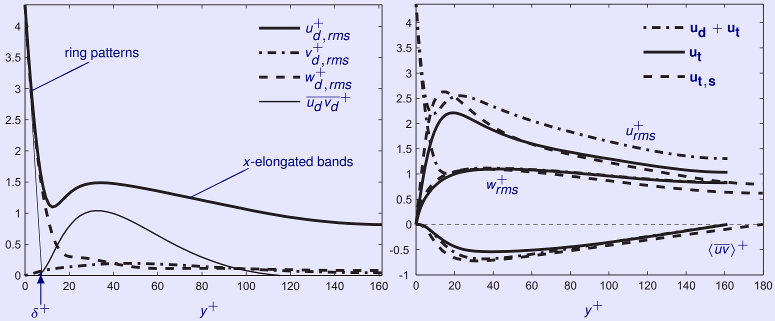
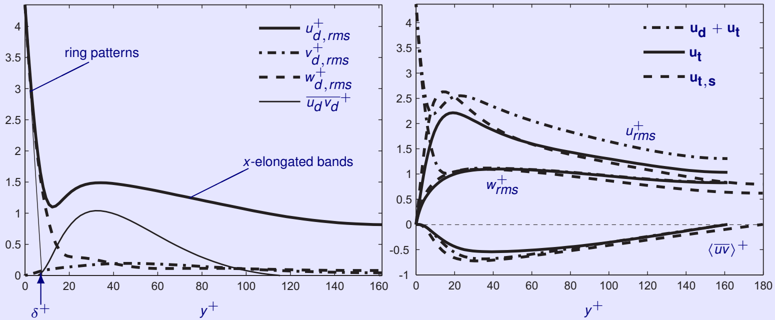
Flow statistics



- *Bands*: outer *x*-elongated regions of high and slow velocity
- $u^+_{d,rms}(0)=w^+_{d,rms}(0)=W^+\sqrt{(\pi/3)[1+2D^+/(2c^+ + D^+)]}/4$=4.37
- TKE of fluctuating velocity decreases
- *Tubes* contribute to change of Reynolds stresses $\rightarrow \mathcal{R}$ via FIK identity Fukagata *et al.* 2002

$$\mathcal{R}(\%) = 100 \frac{R_p \int_0^1 (1-y)\left[\langle \overline{u_t v_t} \rangle + \overline{u_d v_d} - \langle \overline{u_{t,s} v_{t,s}} \rangle\right] \mathrm{d}y}{U_b - R_p \int_0^1 (1-y) \langle \overline{u_{t,s} v_{t,s}} \rangle \, \mathrm{d}y}$$



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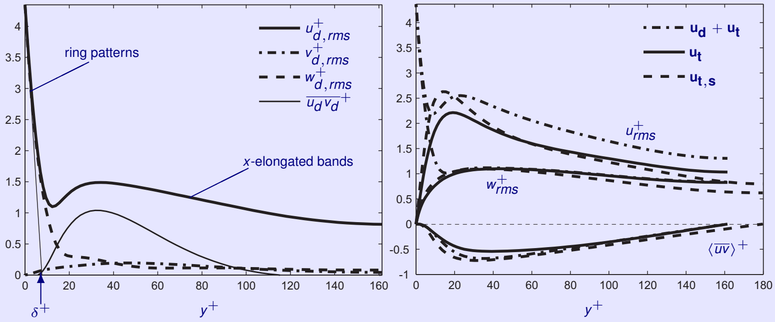

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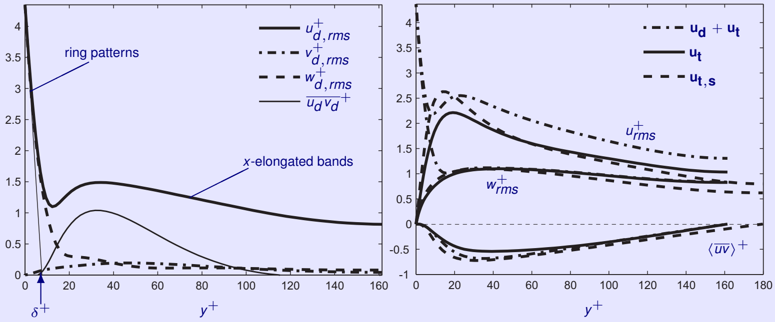

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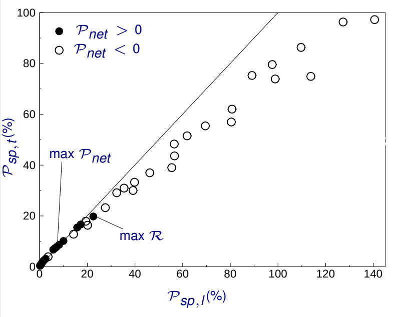
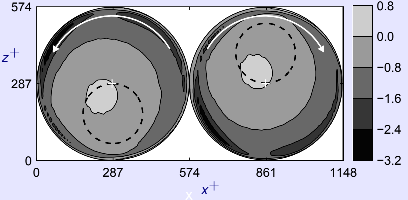




$$\mathcal{P}_{sp,t}(\%) = -\frac{100R_p}{R^2_{\tau,s}U_b}\overline{u_d(x,0,z)\frac{\partial u_d}{\partial y}\Big|_{y=0}} + \overline{w_d(x,0,z)\frac{\partial w_d}{\partial y}\Big|_{y=0}} \approx 25\pi W^2 R_p/(2\delta U_b R^2_{\tau,s})$$

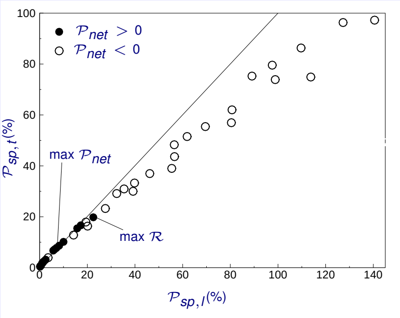
Power spent predicted well by von Kármán pump laminar solution

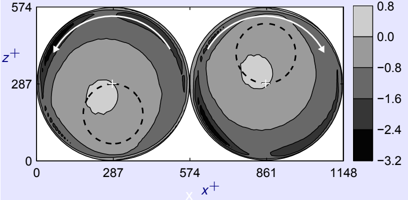
$\mathcal{P}_{sp,t}(\%) = -100 G W^{5/2} R_p^{3/2} / (\sqrt{2D} U_b R^2_{\tau,s})$ where $G = -0.61592$

Agreement is good for small $\mathcal{P}_{sp,t}$ and positive $\mathcal{P}_{net}$

Local power spent may be positive - dashed lines are laminar-flow prediction

Regenerative breaking effect: **fluid does work on discs**





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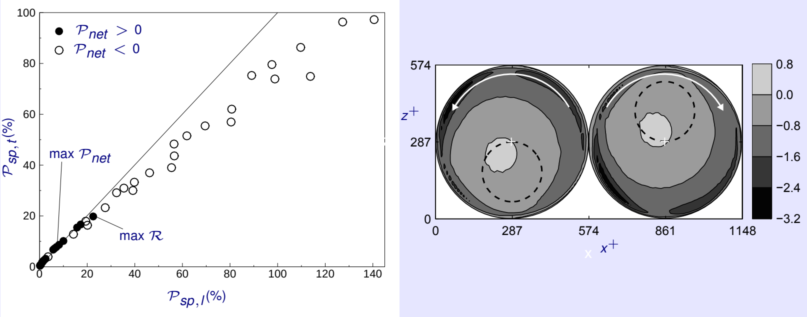

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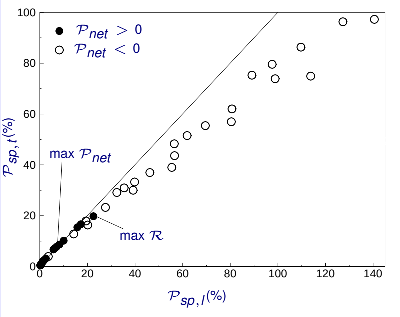

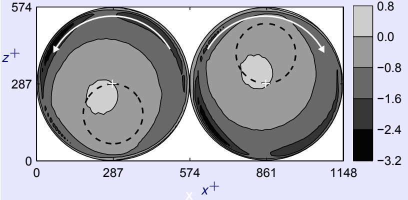

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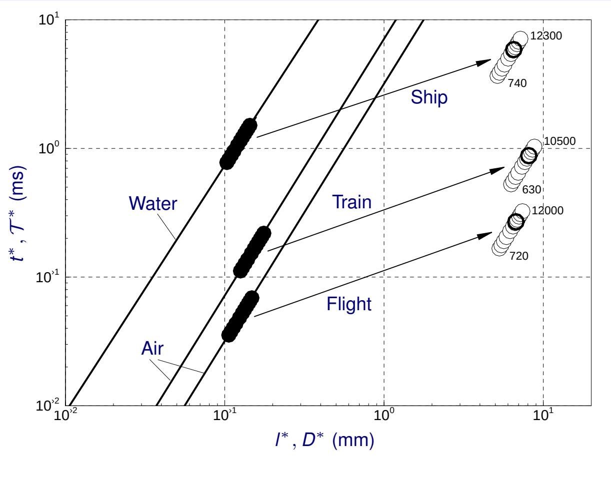

Modified graph from Kasagi *et al.* 2009

Temporal scale of disc forcing is **one** orders of magnitude larger than turbulence scales

Spatial scale of disc forcing is **two** orders of magnitude larger than turbulence scales

W^+=**10**, D^+=**1500** $\rightarrow \mathcal{R} \approx$ **20%**

Reynolds number effect :-($\mathcal{R} \sim R_\tau^{-0.2}$, $\mathcal{P}_{net} \sim R_\tau^{-\alpha}$, $\alpha < 0.2$?

Ship hull

- x=1.5 m, U=10 m/s $\rightarrow R_\tau = 5000$
- D = 6.5 mm
- f = 170 Hz

High-speed train

- x=1.8 m, U=80 m/s $\rightarrow R_\tau = 5000$
- D = 8 mm
- f = 1130 Hz

Commercial aircraft

- x=1.5 m, U=225 m/s $\rightarrow R_\tau = 5000$
- D = 7 mm
- f = 3700 Hz

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GRAZIE!

REFERENCES

Ricco, P. Hahn, S.
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