On-off pumping for drag reduction in a turbulent channel flow

G. Foggi Rota[1,2], A. Monti[1], M. E. Rosti[1] and M. Quadrio[2]

[1]Complex Fluids and Flows Unit, OIST, Japan
[2]Dipartimento di Scienze e Tecnologie Aerospaziali, PoliMi, Italy

Question

Can we exploit an unsteady injection of pumping energy for drag reduction?

Flow control: where are we?

Passive

No control energy

Active

Control energy

Hybrid

(more) Pumping energy

Making an existing idea practical

J. Fluid Mech. (2012), vol. 700, pp. 246–282. © Cambridge University Press 2012 246
doi:10.1017/jfm.2012.129

Pulsating pipe flow with large-amplitude oscillations in the very high frequency regime. Part 1. Time-averaged analysis

M. Manna[1], A. Vacca[2] and R. Verzicco[3,4]†

International Journal of Heat and Fluid Flow 88 (2021) 108783

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

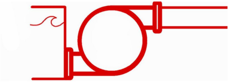
journal homepage: www.elsevier.com/locate/ijhff

ELSEVIER

Prediction of the drag reduction effect of pulsating pipe flow based on machine learning

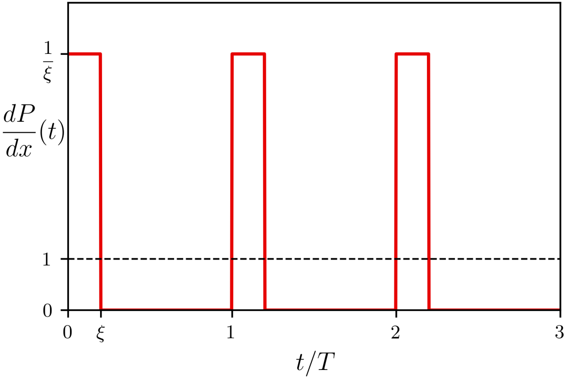
Wataru Kobayashi, Takaaki Shimura, Akihiko Mitsuishi, Kaoru Iwamoto*, Akira Murata

On-off pumping



- $Re_\tau = 180$
- Two parameters only, since

$$\frac{1}{T}\int_0^T \frac{dP}{dx}dt = 1$$



$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{dP}{dx}\delta_{i1} - \frac{dp}{dx_i} + \frac{1}{Re_\tau}\frac{\partial^2 u_i}{\partial {x_j}^2}$$

Our model problem

- DNS of a plane turbulent channel flow

$$3\pi h \text{ x } 1.5\pi h \text{ x } 2h \Rightarrow 6\pi h \text{ x } 3\pi h \text{ x } 2h$$

$$\Delta x^+ = 6.6,\ \Delta y^+ = 3.3,\ \Delta z^+ = 0.5 - 3.2$$

Higher resolutions employed for verification purposes, up to:

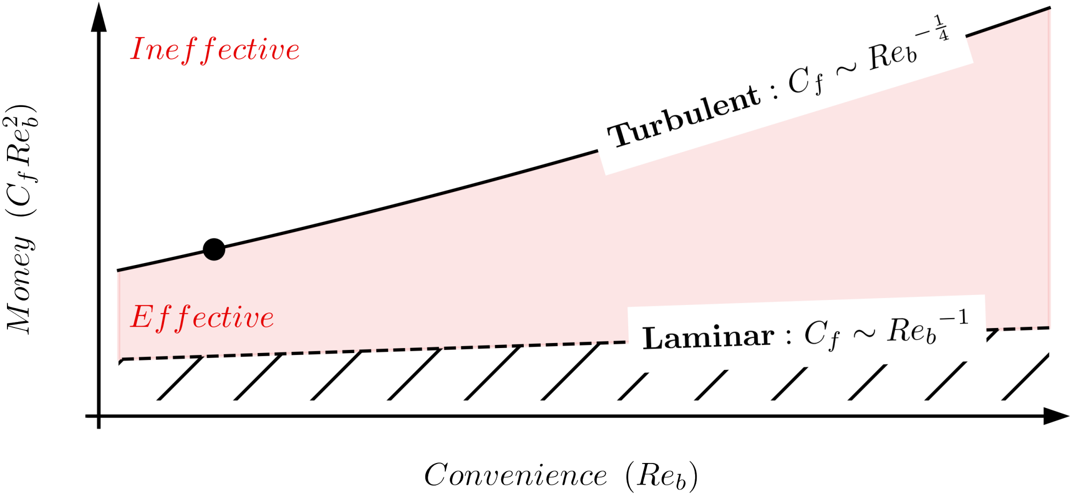
$$\Delta x^+ = 2.2,\ \Delta y^+ = 1.1,\ \Delta z^+ = 0.15 - 1.0$$

- Two very diverse codes used to check robustness

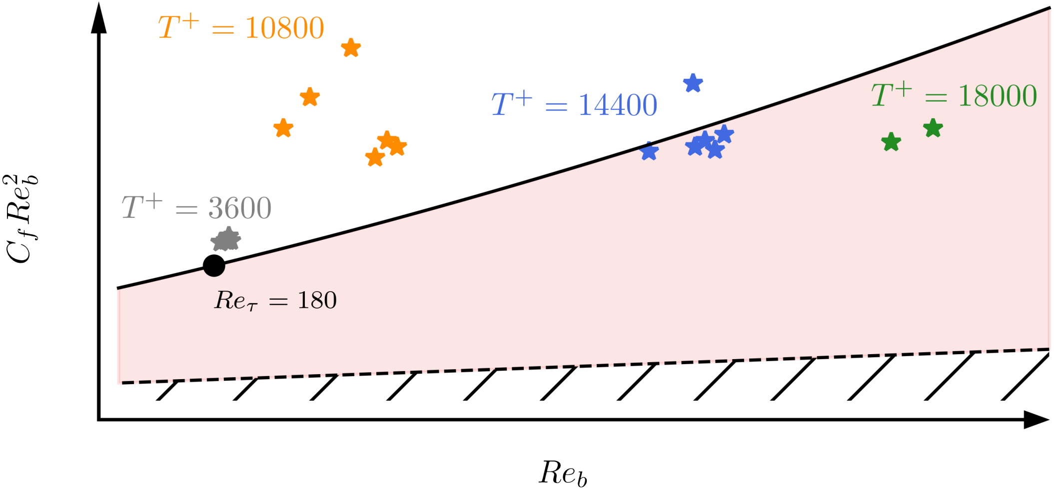
Time integration:
Fractional step method (AB)
Spatial discretization:
II order FD

Time integration:
Partially implicit method (RK3 – CN)
Spatial discretization:
Fourier – IV order compact FD

Money VS Convenience *(Frohnapfel, Hasegawa & Quadrio JFM 2012)*



It works!



A demanding investigation

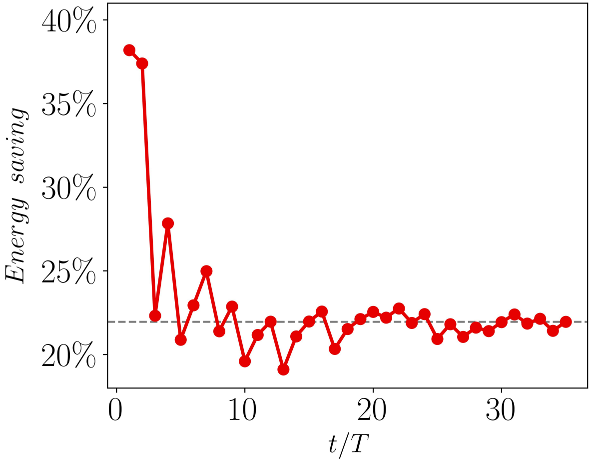


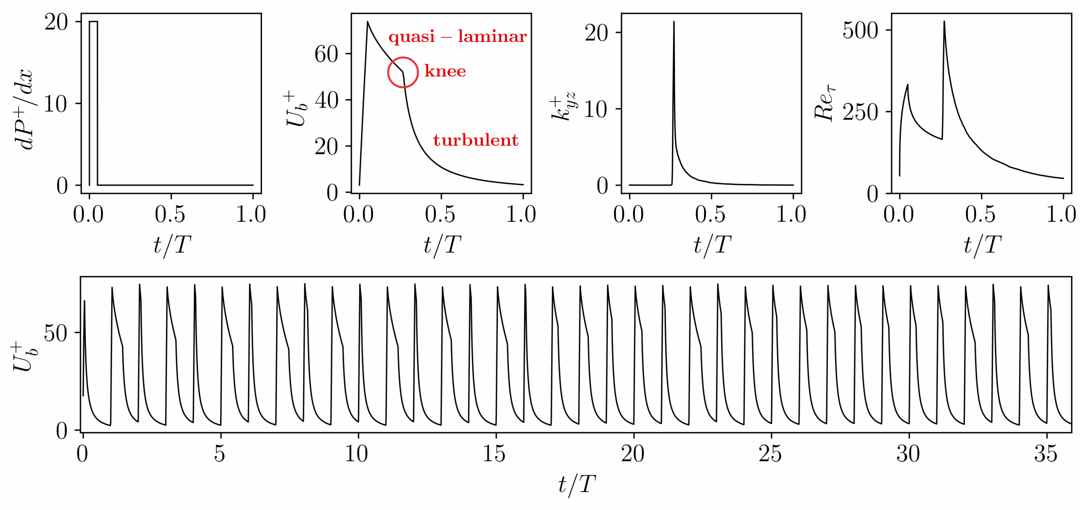
Figure: Convergence of the energy saving for our best-performing simulation

Several cycles needed

Best performance from long periods

Total time: 50*x* standard channel

0D statistics



The quasi-laminar flow state

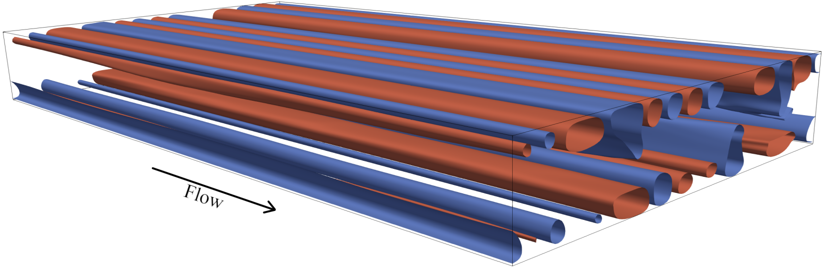


Figure: Positive (red) and negative (blue) contours of the streamwise velocity fluctuations

Streamwise velocity structures

- Remains of the low-*Re* flow phase at the beginning of every cycle
- Their instability is responsible for the breakdown to turbulence (knee)

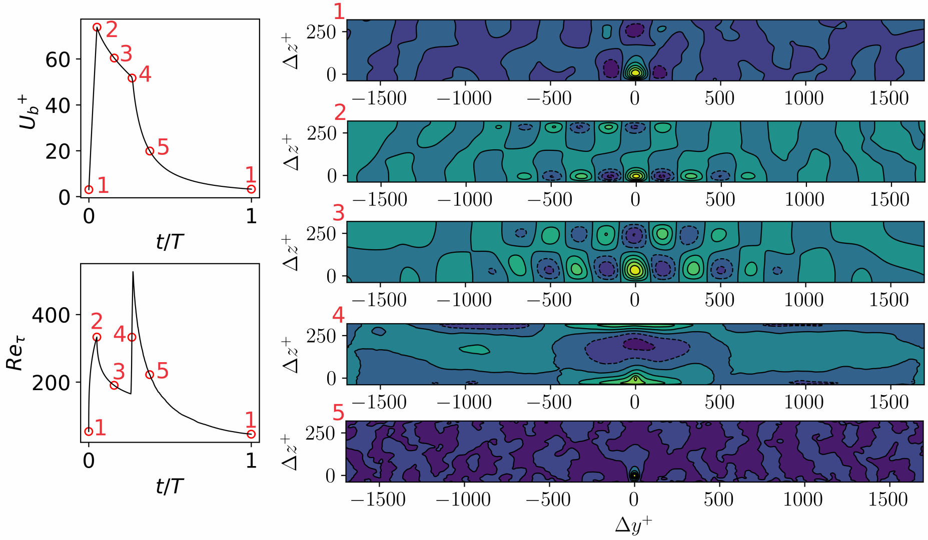
Conclusions

- Unsteady pumping yields significant energy savings (up to 22%, for the parameters considered)
- Large room for improvement, both in terms of searching for the optimal parameters and understanding of the complex flow physics
- Practical applications?

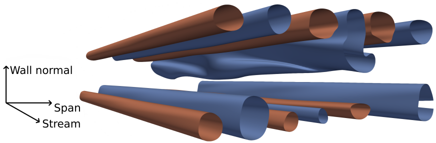
The End

Questions?

Spanwise correlations of the streamwise velocity ($z^+ = 40$)



Two competing transition mechanisms



Oblique waves

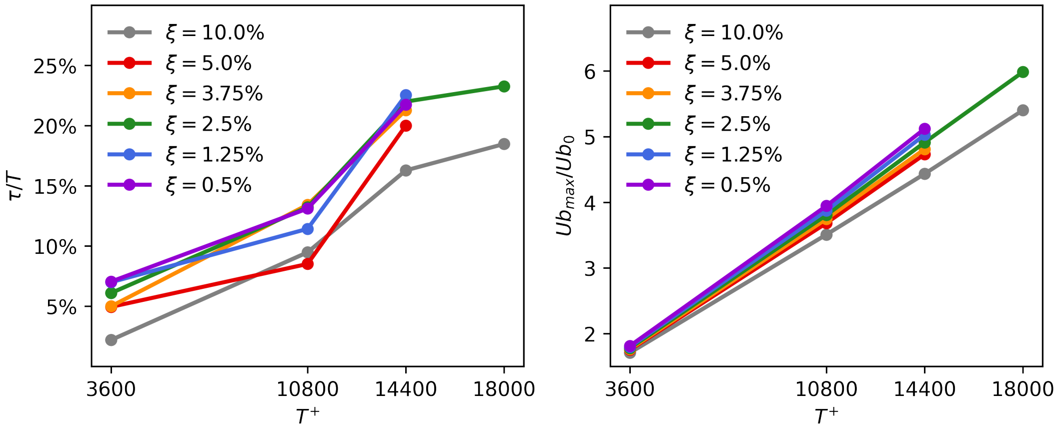
- Distort a low speed streak
- May induce an asymmetric transition
- Typically cause an ”early” breakdown to turbulence

Hairpins

- Last stage of a complex mechanism
- Induce a symmetric transition
- Typically cause a ”late” breakdown to turbulence

The Optimal Time Dependent Modes (*Kern et al., 2021*) are a promising approach for further investigations

The longer the period, the better



Parameter study

ξ \ T^+	3600	10800	14400	18000
0.50%	18	18	18	
1.25%	18	18	35	
2.50%	18	18	35	35
3.75%	18	18	35	
5.00%	18	18	35	
10.0%	18	18	35	35

Table: Number of simulated periods.
Smaller domain in light gray, bigger domain in dark gray.

Grids

Name	L_x/h, L_y/h, L_z/h	n_x, n_y, n_z
LowRes	3π, 1.5π, 2	128, 128, 128
db-LowRes	6π, 3π, 2	256, 256, 128
StdRes	3π, 1.5π, 2	256, 256, 160
db-StdRes	6π, 3π, 2	512, 512, 160
HighRes	3π, 1.5π, 2	512, 512, 256
db-HighRes	6π, 3π, 2	1024, 1024, 256
vHighRes	3π, 1.5π, 2	768, 768, 512

Robustness of the velocity streaks

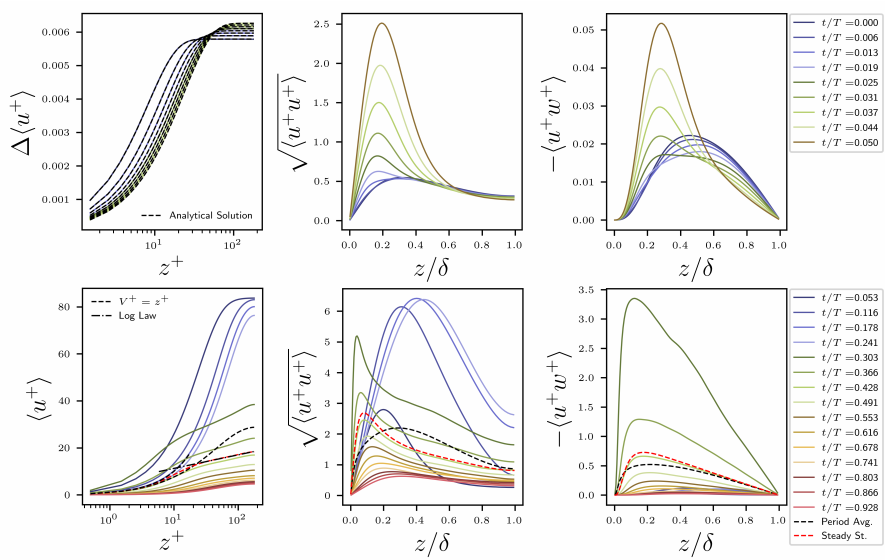
Two codes, one result: streaks!

- Equally observed employing a finite difference or a spectral code
- Visible for all the forcing waveforms considered
- Similar smaller structures are documented (*He & Seddighi, 2013*)
- Their lifetime τ is grid and code independent

$T^+ = 10800, \;\; \xi = 5.0\%$	
Setup	τ^+
StdRes	965
HighRes	864
vHighRes	1127

$T^+ = 14400, \;\; \xi = 5.0\%$	
Setup	τ^+
db-LowRes spectral	2851
db-StdRes	2882
db-HighRes	2911

1D-statistics



Spectra

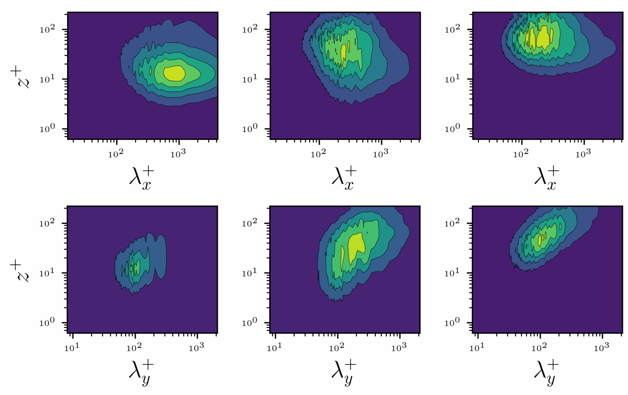
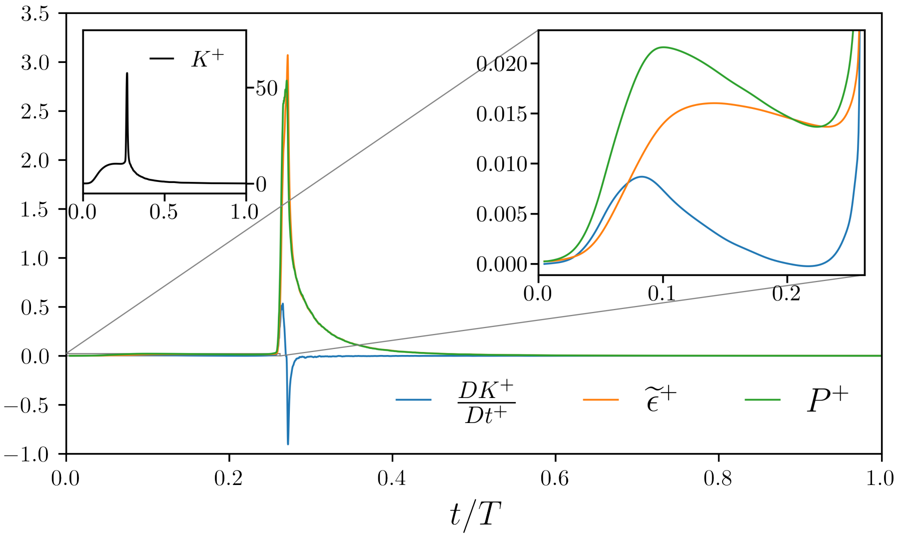


Figure: Pre-multiplied energy spectra in instantaneous wall units corresponding to the 5th correlation plot. The first (second) line refers, respectively, to the stream-wise (span-wise) direction. The stream-wise, span-wise and wall-normal velocity components are varied from left to right.

TKE balance



K^+
50
0
0.0
0.5
1.0
0.020
0.015
0.010
0.005
0.000
0.0
0.1
0.2
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
0.0
0.2
0.4
0.6
0.8
1.0
$\frac{DK^+}{Dt^+}$
$\tilde{\epsilon}^+$
P^+
t/T

References

Frohnapfel, B., Hasegawa, Y. & Quadrio, M. (2012)
Money versus Time: Evaluation of Flow Control in Terms of Energy Consumption and Convenience
J. Fluid Mech. *700*, 406–418.

He, S. & Seddighi, M. (2013)
Turbulence in Transient Channel Flow
J. Fluid Mech. *715*, 60–102.

Iwamoto, K., Sasou, N. & Kawamura, H. (2007)
Direct numerical simulation of pulsating turbulent channel flow for drag reduction
Advances in Turbulence *XI*, 709–711

Kern, J. S., Beneitez, M., Hanifi, A. & Henningson, D. S. (2021)
Transient Linear Stability of Pulsating Poiseuille Flow Using Optimally Time-Dependent Modes
J. Fluid Mech. *927*.

Kobayashi, W., Shimura, T., Mitsuishi, A., Iwamoto, K. & Murata, A. (2021)
Prediction of the Drag Reduction Effect of Pulsating Pipe Flow Based on Machine Learning
Int. J. Heat Fluid Flow *88*, 108783.

Monti, A. (2015)
Skin Friction Drag Reduction in a Turbulent Channel Flow via Pulsating Forcing
Master's Thesis at *Politecnico di Milano*.