TURBULENT SKIN-FRICTION DRAG REDUCTION BY SPANWISE WALL OSCILLATION WITH GENERIC TEMPORAL WAVEFORM

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BACKGROUND

- Turbulent skin-friction drag reduction
- Open-loop spanwise forcing (oscillating wall, travelling waves, etc)
- Excellent performance but still far from practical applications

WHY (CO)SINUSOIDAL?

$$F_z = Ae^{-y/\delta} \sin(k_z z - \omega t)$$ Du & Karniadakis, 2002

$$V_w = V_m \sin(k_x x - \omega t)$$ Min et al, 2006

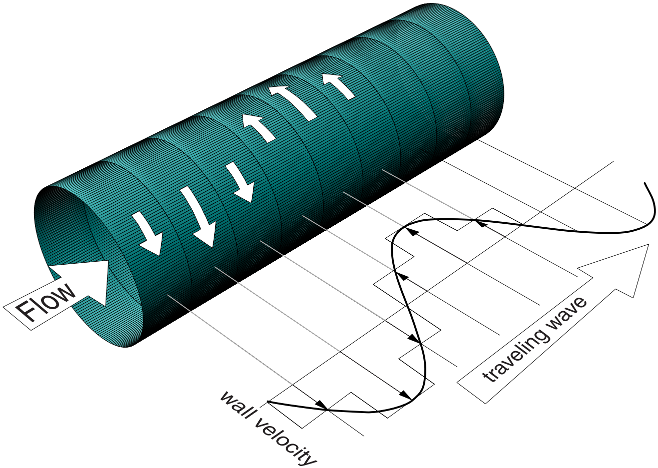
$$W_w = W_m \sin(k_x x - \omega t)$$ Quadrio et al, 2009

Space / time waveform always assumed to be sinusoidal, but:

- No compelling reason to do so!
- Experiments must cope with non-sinusoidal waveforms.

SINUSOID NOT CONVENIENT IN EXPERIMENTS (1)

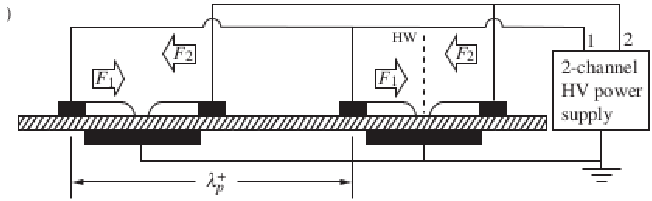
STREAMWISE-TRAVELING WAVE IN THE MILANO PIPE EXPERIMENT



Auteri et al, PoF 2010

Sinusoid not convenient in experiments (2)

Spanwise-traveling wave of body force with plasma actuators



Choi et al, Phil.Trans.R.Soc. A, 2011

OBJECTIVE

Explore characteristics of non-sinusoidal (periodic) waveforms

- Can non-sinusoidal oscillations provide ”better” performance?
- Can we develop a tool to deal with non-sinusoidal waveforms when designing an experiment / actuator?

Results evaluated in terms of:

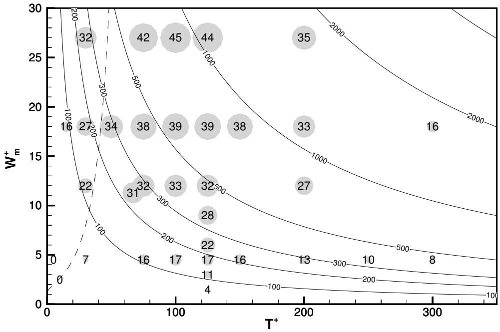
$$R = \frac{P_0 - P}{P_0}; \qquad P_{in}; \qquad S = \frac{P_0 - (P + P_{in})}{P_0}$$

This study: oscillating wall only

Only temporal waveform is considered

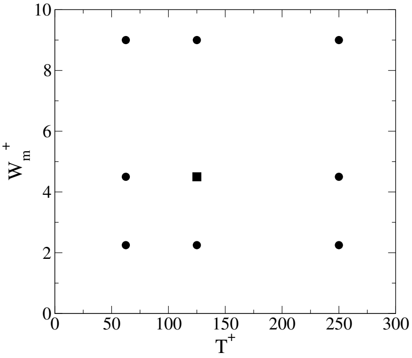
$$W_w = W_m \sin(\omega t)$$

- Simplest technique (minimal number of parameters)
- $D_m = W_m T/\pi$ introduced by Quadrio & Ricco 2004.

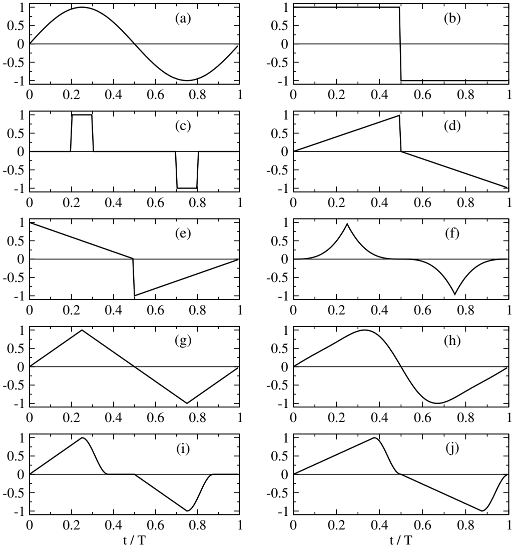


STARTING POINT: DNS PARAMETRIC STUDY

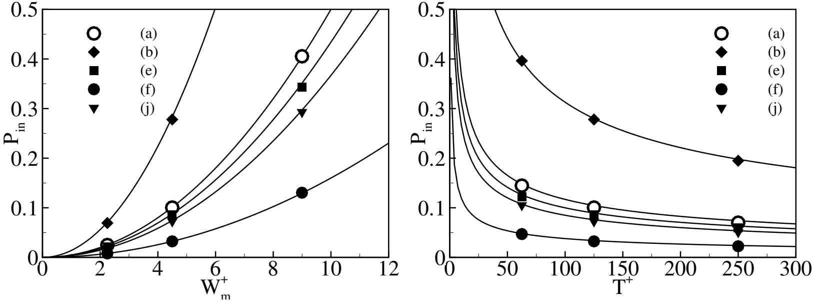
- Plane turbulent channel flow, $Re_\tau = 200$
- Baseline: conditions for maximum S, i.e. $T^+ = 125$ and $W_m^+ = 4.5$
- 3×3 test matrix: period and amplitude doubled and halved
- 10 temporal waveforms tested for each case



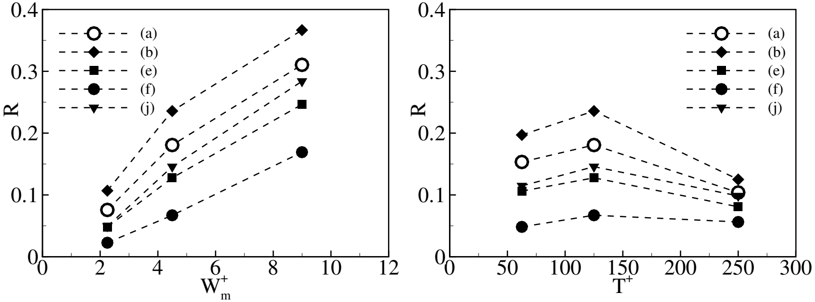
A SET OF WAVEFORMS



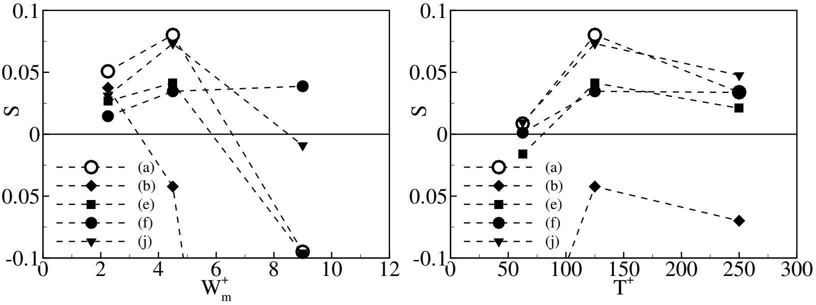
ENERGY BUDGET: P_{in}



ENERGY BUDGET: R

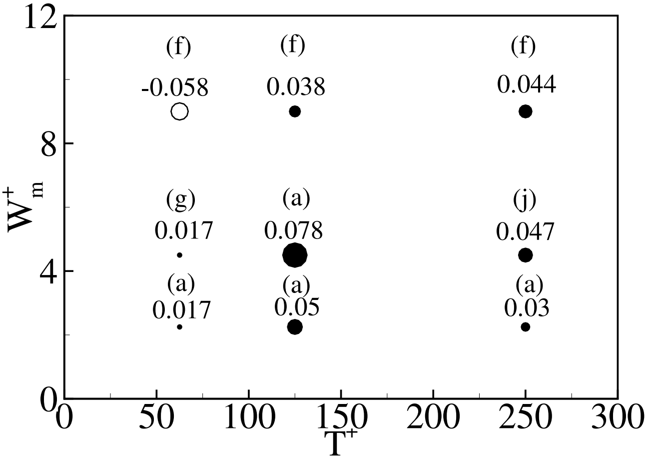


ENERGY BUDGET: S



SINUSOID CAN BE SUB-OPTIMAL

NET ENERGY SAVING WITH BEST LOCAL WAVEFORM

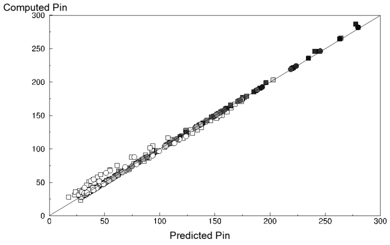


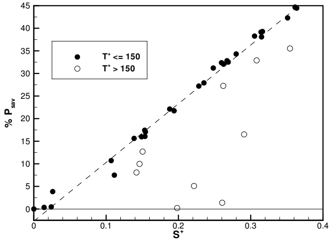
Stokes solution: the sinusoidal case

The analytical solution $w_{St}(y,t)$ of the Stokes 2nd problem cohincides with the space-averaged spanwise velocity profile:

$$w_{St}(y,t) = W_m e^{-y/\delta} e^{j[(2\pi t/T)-y/\delta]} + c.c.$$

$w_{St}(y,t)$ relates to S and R:





Stokes solution: the non-sinusoidal case

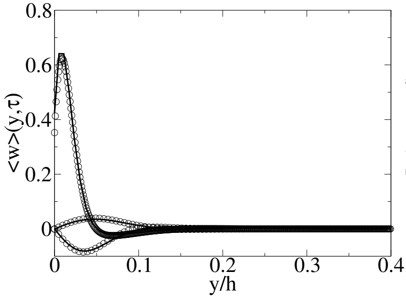
Waveform expanded as:

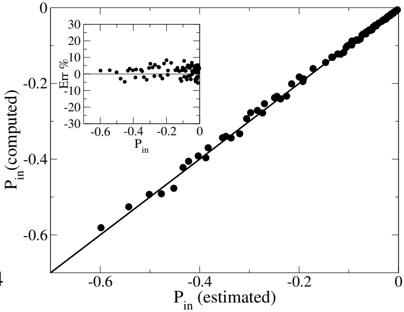
$$W_w(t) = W_m \sum_{n=1}^{+\infty} A_n e^{j(2\pi n/T)t} + c.c.$$

Linear equation, hence solution by superposition:

$$w_{St}(y,t) = W_m \sum_{n=1}^{+\infty} A_n e^{-\sqrt{n}y/\delta} e^{j[(2\pi n/T)t - \sqrt{n}y/\delta]} + c.c.$$

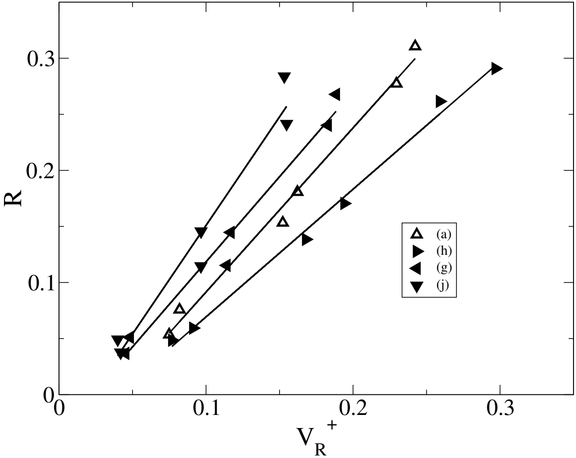
STOKES FOR P_{in}: OK





STOKES FOR R

Scaling parameter does not work



New definition of penetration length

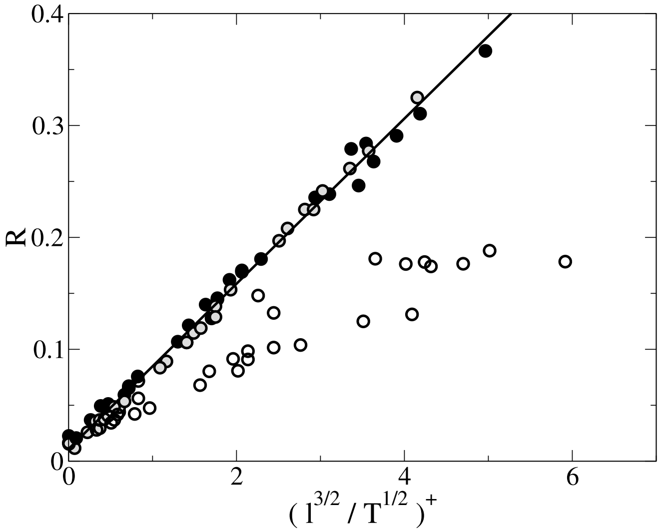
Conventional definition of thickness suffers from a phase shift among harmonics:

$$w_{St}(y,t) = W_m \sum_{n=1}^{+\infty} A_n e^{-\sqrt{n}y/\delta} e^{j[(2\pi n/T)t - \sqrt{n}y/\delta]} + c.c.$$

New definition: distance at which transversal velocity variance exceeds threshold

Stokes for R: OK!

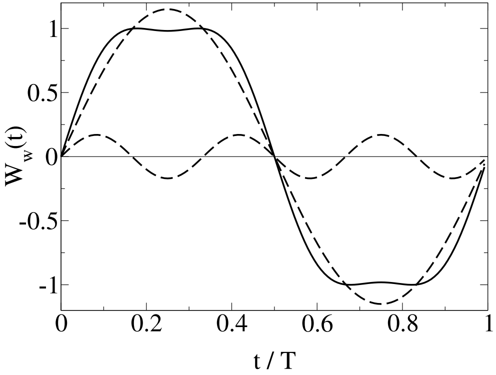
$$R = 0.075\ell^{+(3/2)} / \sqrt{T^+} + 0.016$$



Example of use

Imagine a setup with limited W_m capabilities

This non-sinusoidal waveform can increase S by 20% compared to a pure sinusoid



CONCLUSIONS

- The Stokes solution holds for the generic waveform
- Sinusoid is demonstrated to be the global best
- Sinusoid can be locally outperformed
- Prediction of P_{in} and R
- Toolbox for dealing with experiments

Reference: Cimarelli, Frohnapfel, Hasegawa, De Angelis & Quadrio, "Prediction of turbulence control for arbitrary periodic spanwise wall movement", PoF **25**, 075102, 2013

A further result by A.Cimarelli (and wife)

Pietro Cimarelli, born Aug 27 2013