Time Varying Characteristics of First and Second Order Moments of Pulsating Turbulent Pipe Flow

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Outline

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Flow Problem

Circular Pipe with Diameter D

Relevant Non Dimensional Parameters

$$Re_b = \frac{U_b D}{\nu}, \qquad Re_\delta = \frac{U_m \delta}{\nu}, \qquad \Lambda = \frac{U_m}{U_b},$$

$\delta = \sqrt{2\nu/\omega}$	Stokes layer thickness
U_b	bulk velocity
U_m	max. value of the osc. flow

$$\chi = R/\delta, \longrightarrow \chi = Re_b \Lambda / (2 Re_\delta)$$

Regimes

1- Current dominated ($\Lambda < 1$); Re_δ small

2- Current dominated ($\Lambda < 1$); Re_δ large

3- Wave dominated ($\Lambda > 10$); Re_δ small

4- Wave dominated ($\Lambda > 10$); Re_δ large

Motivations for the Study

Critical Values

Bulk Flow; $Re_b > Re_{b,cr} = 2500$
Oscillating Flow; $Re_{\delta,cr} \sim 550$ for $\chi > 10$
Pulsating Flow; depend on both Re_δ and Re_b for fixed χ.

Experimental results *Lodahl et al. (1998)*, *Mao et al. (1994)* indicate that in the wave dominated regime and for $Re_\delta < Re_{\delta,cr}$ a **drag reduction** phenomena occurs.

Flow Regimes

	Re_b	Re_δ	Λ
Steady flow	5900	0	0
Current dominated	6018	56	1
Wave dominated	5688	572	11

with $\chi = R/\delta = 53$.

Motivations for the Study

- Investigate the Occurrence of Drag Reduction Phenomena

- Database for Validation of RANS Models: Flow Features are Extremely Involved Despite the Simple Geometry

- Improve Existing Correlations in Parameters Space

Investigation Tool

Large Eddy Simulation (LES)

Decompose the turbulent signal in large (resolved) and small (unresolved) scales. The separation based on the definition of a spatial filter:

$$\overline{f} = \int_{\Omega} f\left(\mathbf{x}'\right) G\left(\mathbf{x},\mathbf{x}'\right) d\mathbf{x}'$$

where Ω is the physical domain and G the filter function.

The most commonly-used filters are:

$$\widehat{G}(k) = \begin{cases} 1 & \text{if} \quad k \leq \pi/\overline{\Delta} \\ 0 & \text{otherwise} \end{cases}$$

$$G(x) = \sqrt{\frac{6}{\pi \overline{\Delta}^2}} \exp\left(-\frac{6x^2}{\overline{\Delta}^2}\right)$$

$$G(x) = \begin{cases} 1/\overline{\Delta} & \text{if} \quad |x| \leq \overline{\Delta}/2 \\ 0 & \text{otherwise} \end{cases}$$

Sharp Fourier, *Gaussian* and *Tophat*, respectively.

Investigation Tool (cont'd)

The filtering operation of the Navier–Stokes equations leads to:

$$\frac{\partial \overline{\mathbf{u}}}{\partial t} + \nabla \cdot \overline{\mathbf{u}}\,\overline{\mathbf{u}} = -\nabla \overline{p} + \frac{1}{Re} \nabla \cdot \overline{\mathbf{S}} - \nabla \cdot \boldsymbol{\tau},$$

$$\nabla \cdot \overline{\mathbf{u}} = 0,$$

where $\overline{\mathbf{S}}$ and $\boldsymbol{\tau} = \overline{\mathbf{u}}\,\overline{\mathbf{u}} - \overline{\mathbf{u}\mathbf{u}}$ are the resolved rate of strain and the subgrid–scale tensors. The isotropic part of $\boldsymbol{\tau}$ is added to the pressure term and the anisotropic part is parameterized:

$$\boldsymbol{\tau} - \frac{1}{3} Tr(\boldsymbol{\tau}) = -2\nu_T \overline{\mathbf{S}} = -2C(r,t)\overline{\Delta}\,|\mathbf{S}|\overline{\mathbf{S}},$$

where $|\mathbf{S}| = \sqrt{Tr(2\overline{\mathbf{S}}^2)}$, Tr the trace operator and $\overline{\Delta}$ the length associated with the filter. The scalar function $C(r,t)$ is computed with the dynamic procedure of Germano (1991), as modified by Lilly (1992).

Investigation Tool (cont'd)

Introducing a second coarser spatial (test) filter characterized by a width $\widehat{\overline{\Delta}}$ the $C(r,t)$ function can be evaluated as follows:

$$C(r,t) = -\frac{1}{2}\frac{\langle Tr(\mathbf{LM})\rangle}{\langle Tr(\mathbf{MM})\rangle},$$

where $< \cdot >$ denotes averaging in both (azimuthal and axial) homogeneous directions, and:

$$\mathbf{L} = \widehat{\overline{\mathbf{u}}\,\overline{\mathbf{u}}} - \widehat{\overline{\mathbf{u}}}\,\widehat{\overline{\mathbf{u}}}, \quad \mathbf{M} = \widehat{\overline{\Delta}}^2 |\widehat{\overline{\mathbf{S}}}|\widehat{\overline{\mathbf{S}}} - \overline{\Delta}^2 \widehat{|\overline{\mathbf{S}}|\overline{\mathbf{S}}}.$$

Sharp Fourier cut-off is used as both grid and test filter in streamwise and azimuthal directions, while no test filtering is performed in radial direction. The test filter width is such that $\widehat{\overline{\Delta}}/\overline{\Delta} = 2$.

Details on the potential and limitations of the dynamic eddy viscosity procedure for both steady and unsteady channel flow problems are discussed in great depth un Piomelli (1993) and Scotti and Piomelli (2001).

Flow Solver

- Incompressible, three dimensional, unsteady Navier-Stokes solver.

- Spectral Chebyshev multi–domain algorithm; implicit diffusion; explicit convection in skew-symmetric form.

- $\Lambda = 0$: $L_z = 4\pi R$
  $\Lambda = 1$: $L_z = 4\pi R$
  $\Lambda = 11$: $L_z = 8\pi R$.

- Grid size $n_{sub} \times (n_z \times n_r \times n_\theta)$
  $\Lambda = 0$: $6 \times (96 \times 12 \times 96)$
  $\Lambda = 1$: $6 \times (96 \times 12 \times 96)$
  $\Lambda = 11$: $6 \times (192 \times 12 \times 96)$

- $\Delta z^+ = 25$, $R\Delta\theta^+ = 13$, $r^+_{\min} \approx 0.1$

- Data are obtained processing 360 fields separated in time by $0.2\, tU_b/D$

Results

Mean Flow Parameters:

$$U_{cl} = \overline{u}\,|_{r=0}$$

$$\delta^+ = \delta u_\tau / \nu$$

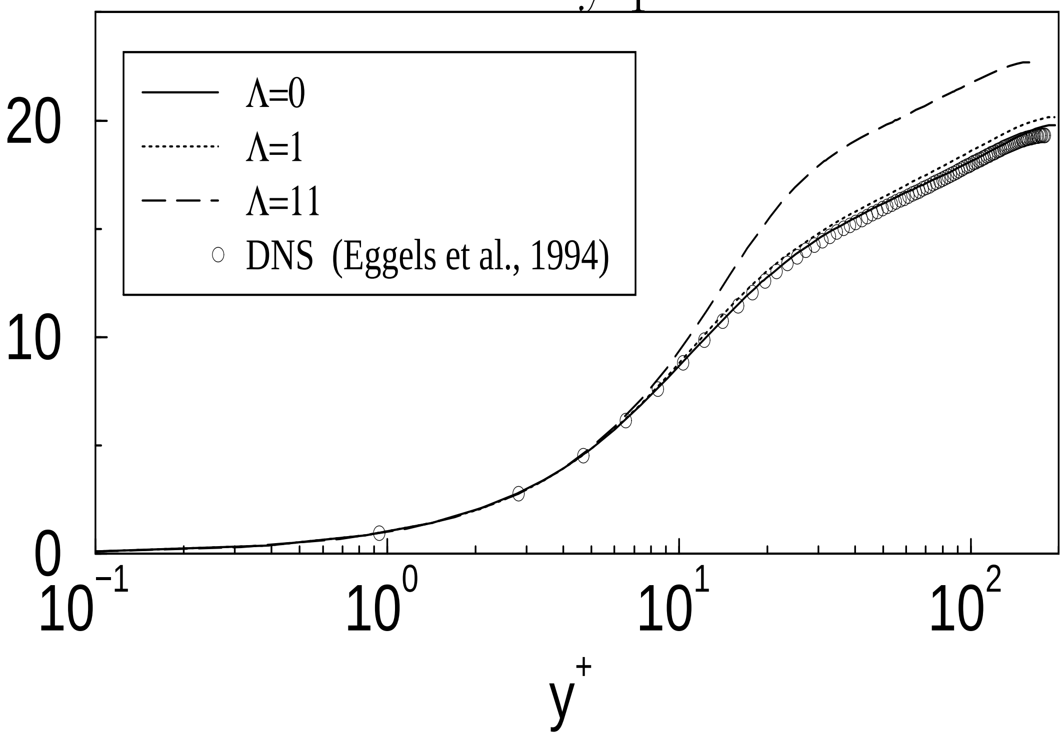
$$C_f = 2\tau_w / \left(\rho U_b^2\right)$$

$$C_f^B = 0.079 Re^{-1/4}$$

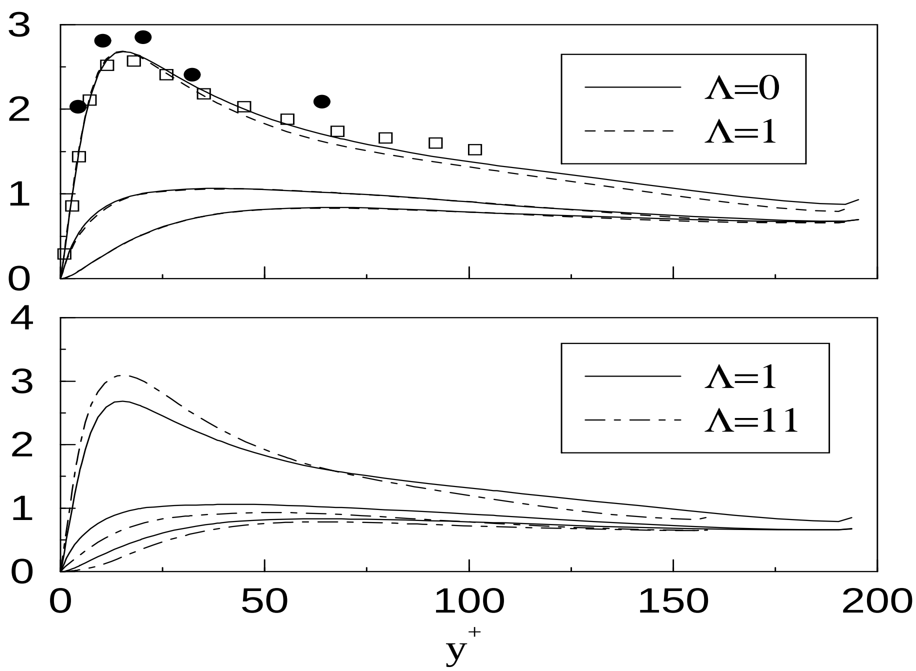
Λ	Re_b	U_{cl}/U_b	δ^+	C_f/C_f^B
0	5900	1.31	–	0.98
1	6018	1.30	3.66	0.92
11	5688	1.29	3.02	0.70

Results

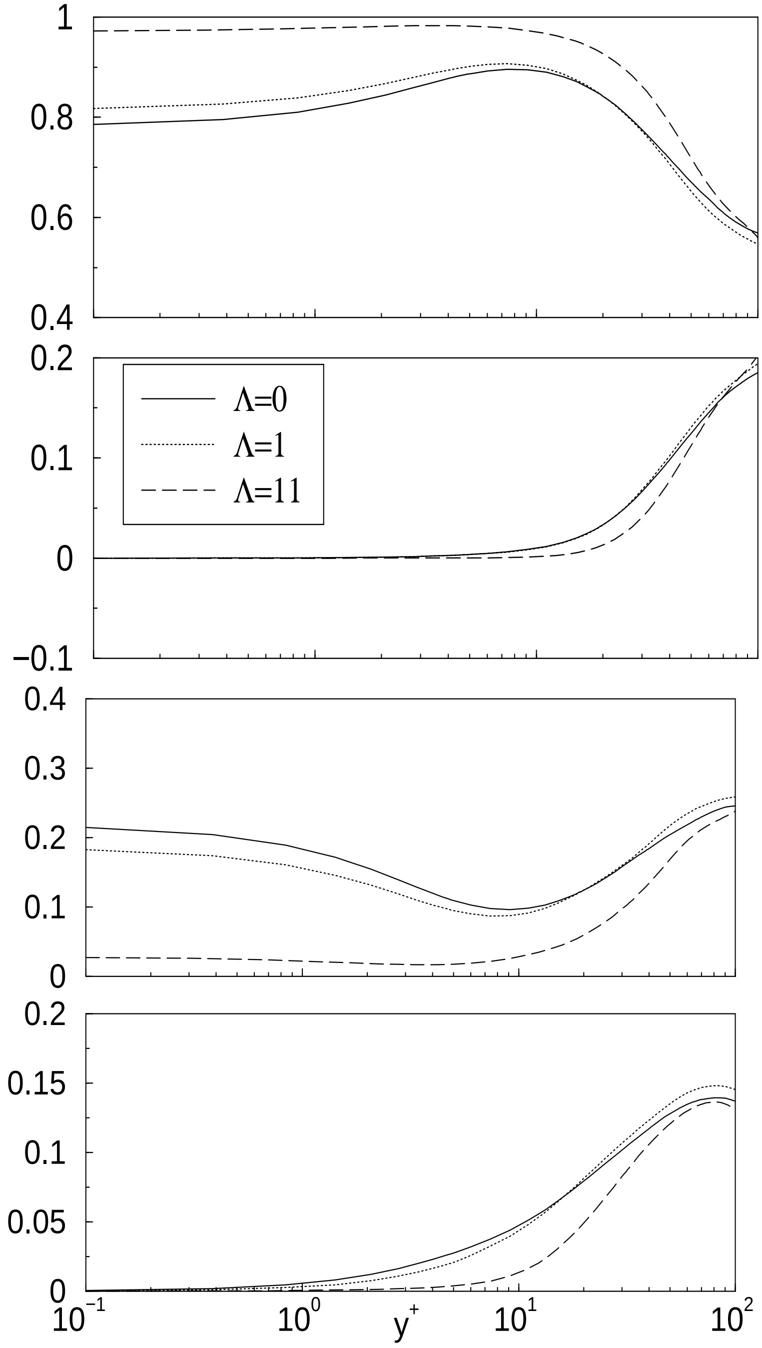
Mean velocity profiles



Mean turbulent intensities; ● exp (Tardu et al., 1994); □ LES (Scotti and Piomelli, 2001)



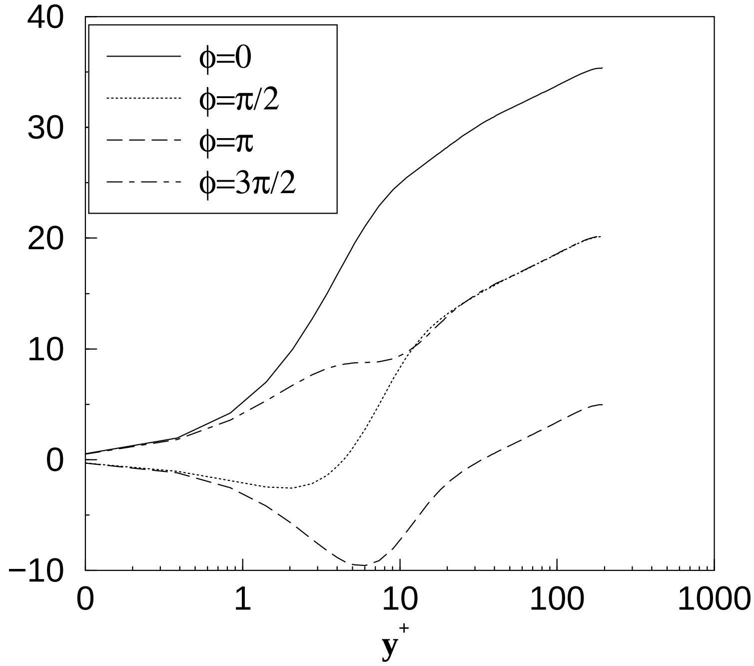
Results



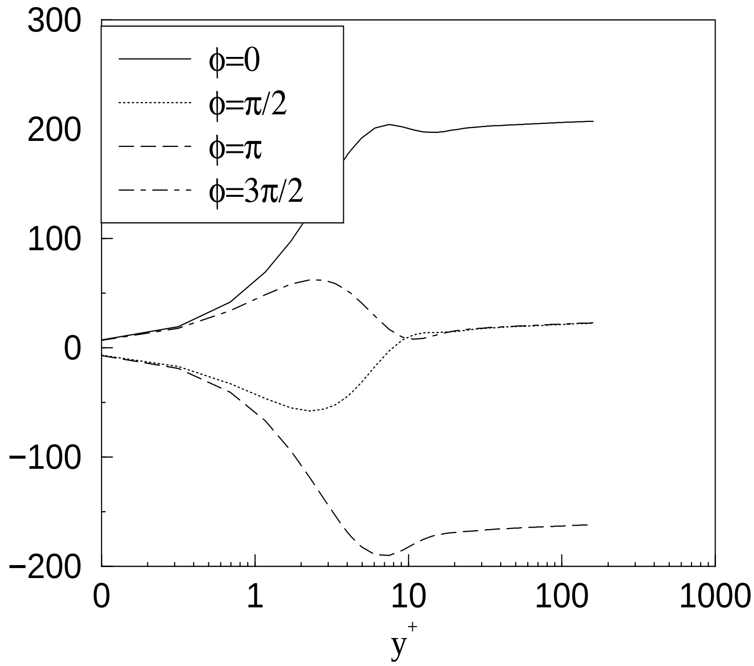
Reynolds stress tensor normalized with T.K.E.

Results

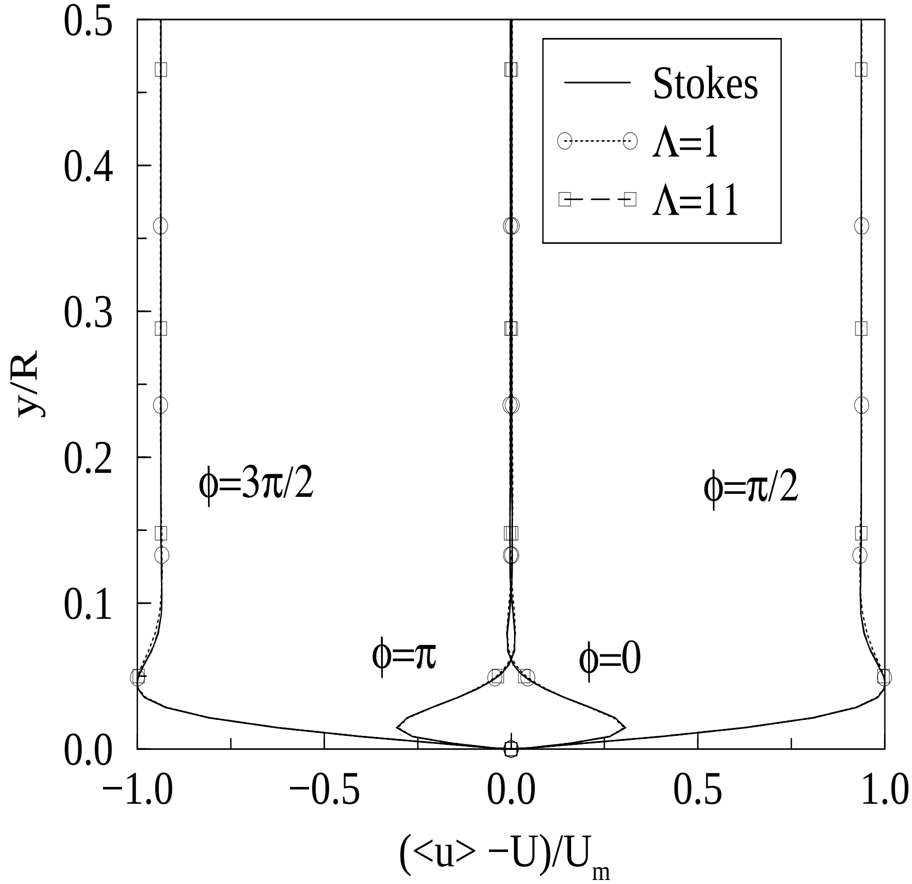
Phase averaged streamwise velocity ($\Lambda = 1$)



Phase averaged streamwise velocity ($\Lambda = 11$)

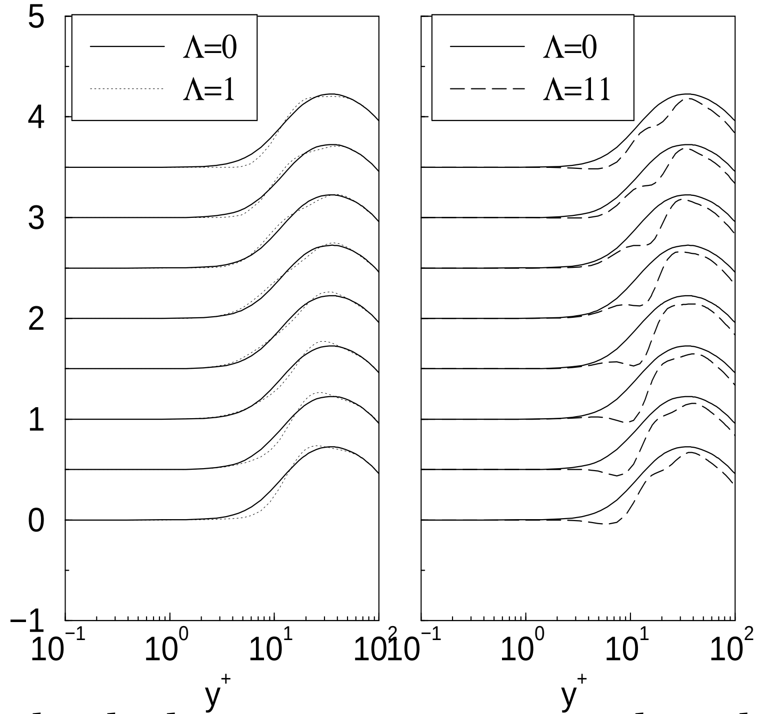


Results

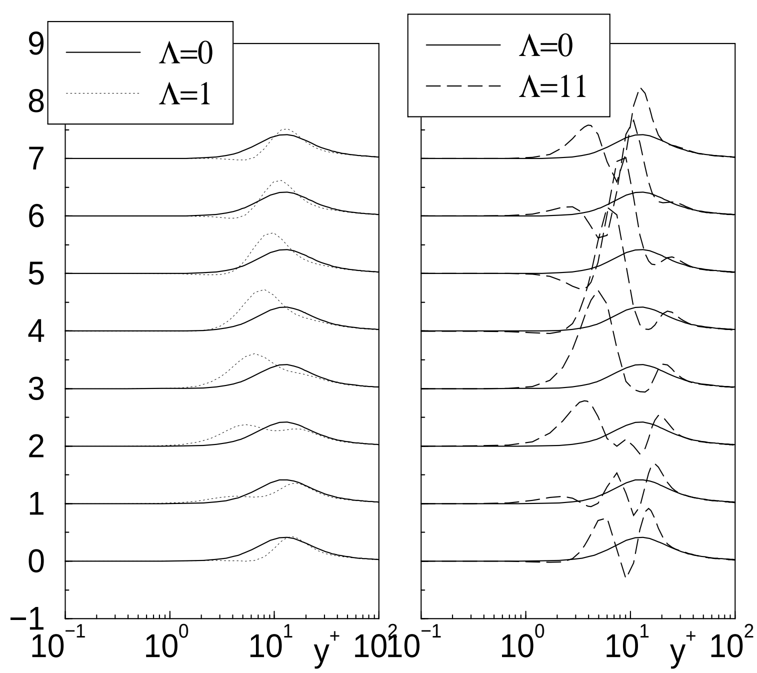


Phase locked averaged streamwise velocity profiles in outer coordinates

Results



Phase locked shear stress normalized with $\overline{u}_\tau$



Phase locked T.K.E. normalized with $\overline{u}_\tau$

Conclusions

- In the wave dominated regime the averaged (in both space and time) friction coefficient can be considerably reduced ($\sim$30%).

- The drag reduction phenomenon agrees with the experimental data.

- The analysis of the radial distributions of the time and ensemble averaged quantities reveals the the resistance reduction is not due to a flow laminarization.

- The turbulence remains sustained across the oscillation cycle although the Reynolds stress tensor components are reduced.

- The oscillating flows obey the Stokes distribution even in presence of resistance reduction.