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

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ABSTRACT

The present work investigates the effects of a forced harmonic oscillations of fixed frequency and amplitudes on the characteristics of a turbulent pipe flow with a mean Reynolds based on the cross sectional bulk velocity and pipe diameter of 5900. The setup refers to an extremely thin Stokes layer δ so that the vorticity associated to the oscillating motion is generated in a small near wall region.

When the ratio of the amplitudes of the oscillating and bulk velocities is increased from 1 to 11, the turbulence is affected by the harmonic forcing so much that the near wall coherent structures are substantially modified. This effect results in an overall space and time averaged resistance reduction which, for the largest amplitude case, adds up to 33 % of the non pulsating flow at the same bulk Reynolds number.

The analysis is carried out processing a set of statistically independent samples obtained from wall resolved Large Eddy Simulations with a spectrally accurate Navier-Stokes code.

INTRODUCTION

There is a considerable literature available on pulsating flow in circular pipes and channels which, because of space constraints can be acknowledged only partially [1–8]. However, most if not all of the available contributions are concentrated on a region of the parameter space, viz. on the so called *current dominated* regime, while little material has dealt with the *wave dominated* regimes [7]. This is unfortunate since for a given combination of the relevant non dimensional parameters, it has been shown, both experimentally and numerically, that the cycle averaged wall shear stress may be smaller (!) than the equivalent value of the non pulsating flow. The resistance reduction phenomenon being quantitatively non negligible, there are good engineering motivations to further elaborate on the reasons of its genesis.

In this work we investigate numerically a few flow conditions for which previous studies [7,9] have indicated resistance reduction; calculated data have been processed so that the phase locked averaged statistics of the Reynolds stress tensor components, could be collected. Velocity spectra, spatial correlations and turbulent kinetic energy budgets will be presented elsewhere.

FLOW PROBLEM AND COMPUTATIONAL SETUP

The problem under investigation is the pulsating flow through a circular pipe with diameter $D = 2R$ and bulk velocity U_b driven by an harmonically time varying forcing term of appropriate amplitude and pulsation $f = \overline{f}\,[1 + \alpha \cos(\omega t)]$, with $\overline{f}$, α and ω determined so that appropriate values of the governing non dimensional parameters are achieved. More precisely these have been specified as to match the experimental setup of Lodahl et al. [7]. As discussed in [7] pulsating flows are fully characterized by three non dimensional parameters, namely: $Re_b = U_b D/\nu$, $Re_\delta = U_m \delta/\nu$, $\Lambda = U_m/U_b$, where $\delta = \sqrt{2\nu/\omega}$ is the Stokes layer thickness, ν the kinematic viscosity, and U_m the maximum value of the oscillatory flow at the center of the pipe. Other triplets are of course possible [7,6]. According to [7] there are four main regimes that completely characterize this three dimensional state space, namely the current (respectively wave) dominated regime ($\Lambda < 1$, resp. $\Lambda > 10$), with either low or high Re_δ values. Here and after we shall assume that the *current* flow is turbulent, that is $Re_b > 2300$. Unlike the oscillating flow for which the stability region is defined by a single value of Re_δ ($Re_{\delta,cr} \sim 550$ for $R/\delta > 10$), in the case of pulsating pipe flows the transition conditions are defined by a combination of both Re_δ and Re_b [7]. Experimental and computational data [7,4] have now demonstrated that in the wave dominated regime and for $Re_\delta < Re_{\delta,cr}$ a considerable drag reduction phenomenon occurs. Our previous study has concentrated on the analysis of time and space averaged statistics collected out of a set of numerical data presented and validated in [9]. The run matrix presently used is identical to the one used in [9], and recalled below for sake of clarity.

	Re_b	Re_δ	Λ
Steady flow	5900	0	0
Current dominated	6100	56	1
Wave dominated	5546	572	11

In what follows, we shall denote with u, v, w the streamwise (z), radial (r) and azimuthal (θ) velocity components, respectively. The analysis is carried out processing a set of statistically independent samples obtained from wall resolved Large Eddy Simulations with a spectrally accurate Navier-Stokes code [10]. The flow is assumed periodic in the streamwise (and obviously azimuthal) direction, with a periodicity length L_z equal to $4\pi R$, both for the steady and unsteady ($\Lambda = 1$) calculations. In the $\Lambda = 11$ case the streamwise length has been increased up to $L_z = 8\pi R$. The number of points is roughly 6.6×10^5 for $\Lambda = 0$ and $\Lambda = 1$, and it is doubled in the $\Lambda = 11$ calculation.

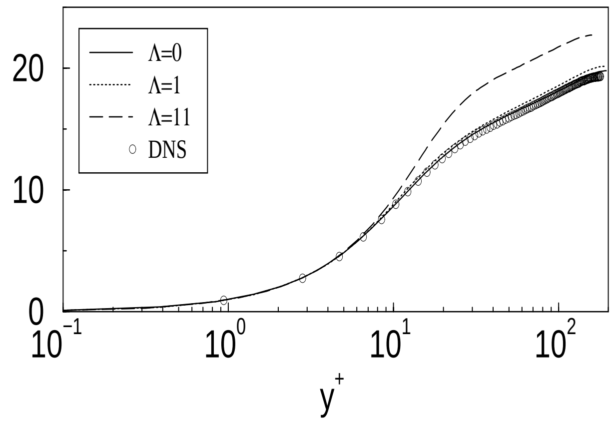

Fig. 1. Mean velocity profiles in inner coordinates; DNS data by [11]

Results and Discussion

Space and time averaged streamwise velocity profiles shown in Fig. 1, enlighten a considerable upward shift of the logarithmic region in the $\Lambda = 11$ case, connected with the resistance reduction phenomenon. The friction coefficient is indeed 33% of the corresponding steady value. Fig. 2 puts into evidence a substantial modification in the contributions of the individual normal stress components to the overall turbulent kinetic energy radial distribution. While the radial component remains practically unaltered, both the streamwise and the azimuthal ones are increased and decreased, respectively. The shear stress profile also undergoes a remarkable attenuation, especially in the wall layer, a fact that supports the friction reduction. It's worth of note that in the wall layer the structure parameter (i.e. the ratio of the shear stress and the turbulent kinetic

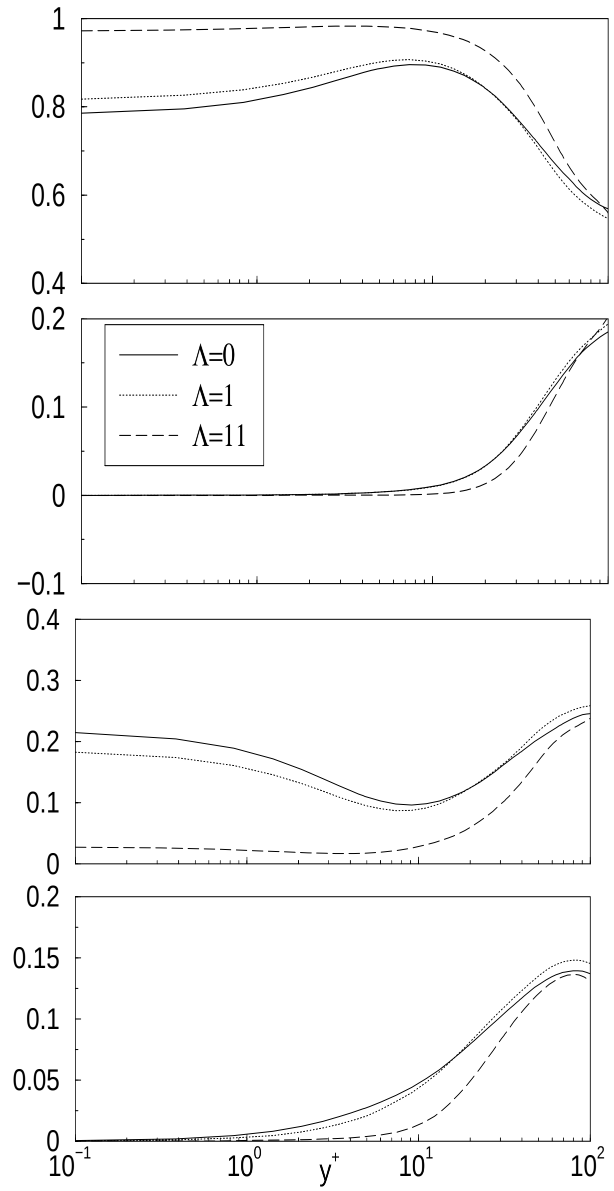

Fig. 2. Reynolds stress tensor components normalized with turbulent kinetic energy; from top to bottom $\overline{u_z'u_z'}$, $\overline{u_r'u_r'}$, $\overline{u_\theta'u_\theta'}$, $\overline{u_z'u_r'}$.

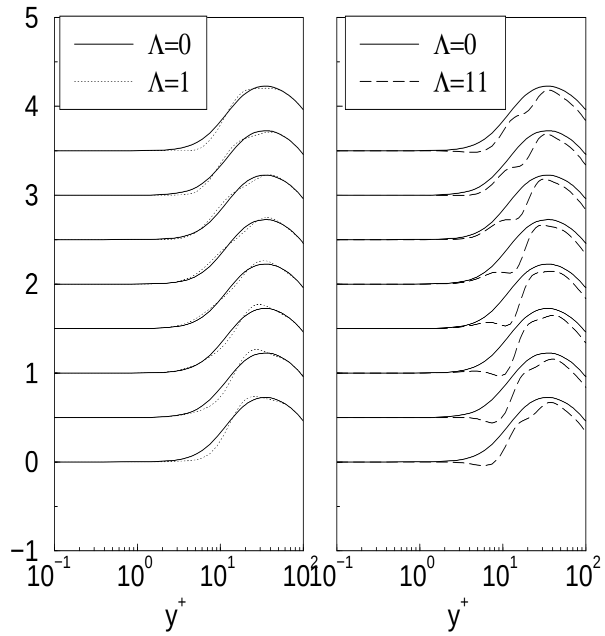

Fig. 3. Phase locked averaged turbulent shear stress normalized with mean friction velocity.

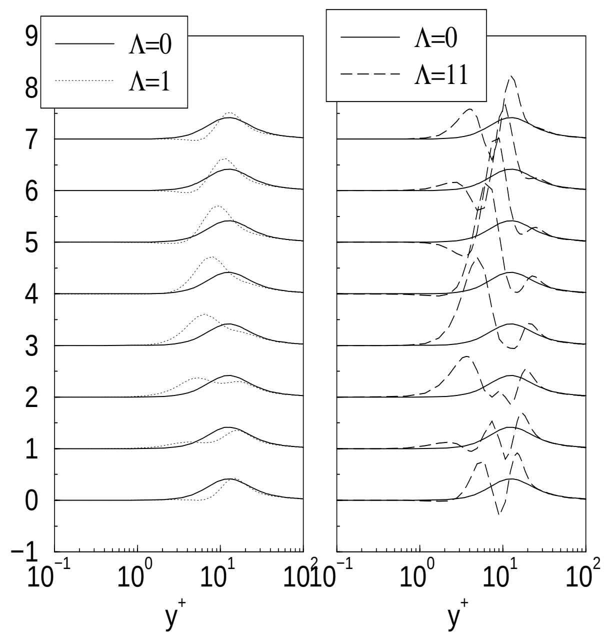

Fig. 4. Phase locked averaged turbulent kinetic energy production in inner coordinates.

energy) attains nearly identical values independently of the magnitude and frequency of the pulsation.

In Fig. 3 the phase locked averaged shear stress profiles are compared with the steady one. While no appreciable differences are observable in the $\Lambda = 1$ case, in the other case the shear stress distribution is constantly below the steady one. Furthermore evident is the appearance of a disturbance of unsteady nature propagating from the wall to the core region, with a frequency higher than the modulating one. Interesting is the magnitude of the maximum shear stress deficit which extinguishes at a distance from the wall of about 40 units. The phase locked averaged turbulent kinetic energy production, depicted in Fig. 4, enlightens the presence of a double traveling wave appreciable in both cases, although most pronouncedly for the $\Lambda = 11$ calculation. The fact that the unsteady values largely exceed the steady ones has to be attributed to the considerable differences in the wall friction velocity due to the resistance reduction. For $\Lambda = 11$ the location of the peak moves away from the wall and its value decreases to disappear at $\phi = 3/2\pi$; simultaneously the appearance of a secondary peak, which will soon substitute the primary peak to close the cycle dynamic, is remarked. The waves are generated in the viscous sub-layer and extinguish at the end of the buffer layer.

CONCLUSIONS

Large Eddy Simulations of pulsating turbulent pipe flows have been carried out in a narrow window of the wave dominated regime. Space and time averaged quantities agree well with the experimental data [7,4], showing in the largest amplitude case a resistance reduction adding up to 33%. Radial distributions of the mean normal stress components enlighten a different split of the individual contributions for the largest amplitude case, compared with the steady non pulsating case at the same bulk Reynolds number. Likewise in the wall layer, a considerable reduction of the structure parameter is observed. Phase locked averaged turbulent kinetic energy production shows the appearance of a double traveling wave originated in the viscous sub-layer and extinguishing in the buffer layer.

BIBLIOGRAPHY

[1] S. W. Tu and B. R. Ramaprian. 'Fully Developed Periodic Turbulent Pipe Flow. Part 1. Main Experimental Results and Comparison with Predictions'. *J. of Fluid Mech.*, 137:31–58, 1983.

[2] S. W. Tu and B. R. Ramaprian. 'Fully Developed Periodic Turbulent Pipe Flow. Part 2. The Detailed Structure of the Flow'. *J. of Fluid Mech.*, 137:59–81, 1983.

[3] Z. X. Mao and T. J. Hanratty. 'Studies of the Wall Shear Stress in a Turbulent Pulsating Pipe Flow'. *J. of Fluid Mech.*, 170:545–boo, 1986.

[4] Z. X. Mao and T. J. Hanratty. 'Influence of Large–amplitude Oscillations on Turbulent Drag'. *AIChE J.*, 40(10):1601–1610, 1994.

[5] S. F. Tardu and G. Binder. 'Wall Shear Stress modulation in Unsteady Turbulent Channel Flow with High Imposed Frequencies'. *Phys. Fluids*, 5:2028–2034, 1993.

[6] S. F. Tardu, G. Binder and R. F. Blackwelder. 'Turbulent Channel Flow with Large–Amplitude Velocity Oscillations'. *J. of Fluid Mech.*, 267:109–151, 1994.

[7] C.R. Lodahl, B.M. Sumer and J. Fredosoe. 'Turbulent Combined Oscillatory Flow and Current in a Pipe'. *J. of Fluid Mech.*, 373:313–348, 1998.

[8] A. Scotti and U. Piomelli. 'Numerical Simulation of Pulsating Turbulent Channel Flow'. *Phys. Fluids*, 13(5):1367–1384, 2001.

[9] M. Manna and A. Vacca. 'Resistance Reduction in Pulsating Turbulent Pipe Flow'. *J. of Eng. for Gas Turbines and Power*, 127:410–417, 2005.

[10] M. Manna and A. Vacca. 'An Efficient Method for the Solution of the Incompressible Navier-Stokes Equations in Cylindrical Geometries'. *J. Comp. Phys.*, 151:563–584, 1999.

[11] J.G.M. Eggels, F. Unger, M.H. Weiss, J. Westerweel, R.J. Adrian, R. Friedrich and F.T.M. Nieuwstadt. 'Fully Developed Turbulent Pipe Flow: a Comparison Between Direct Numerical Simulation and Experiments'. *J. of Fluid Mech.*, 268:175–209, 1994.