3rd International Conference on Turbulence and Interactions
La Saline-les-Bains, Réunion Island, 11.-15. June 2012

Numerical study on the decay and amplification of turbulence in oscillatory pipe flows

D. Feldmann[‡§] and C. Wagner[‡]

[‡] Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR)
[§] daniel.feldmann@dlr.de

Shear flow turbulence in oscillatory fluid motions is of theoretical interest and practical relevance, since the onset of turbulence can drastically change the transport and mixing efficiency. To supplement former theoretical and experimental investigations on the transition to turbulence in Sexl–Womersley (SW) flows [4, 7], summarised in fig. 1, we perform three-dimensional direct numerical simulations (DNS) of oscillatory pipe flows. Therefore, we

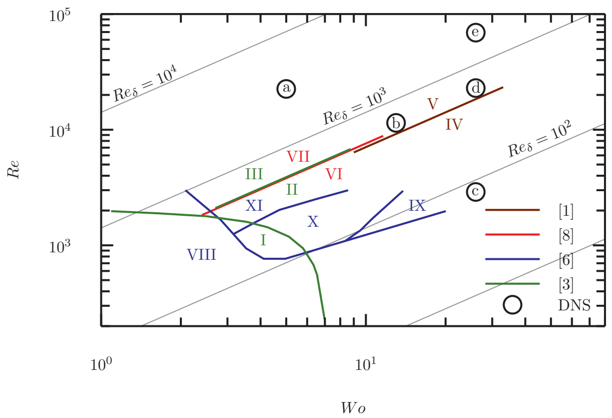


Fig. 1: Parameter map for the onset of turbulence in SW flows based on experimental investigations [3, 1, 8] and a quasi-steady stability analysis [6]. I: laminar; II: weakly turbulent; III: conditionally turbulent; IV: laminar; V: turbulent wall region and stable core flow; VI: laminar; VII: turbulent; VIII: stable; IX: weakly instable near the wall; X: unstable without significant amplification ; XI: unstable with noticeable amplification.

solve the incompressible Navier-Stokes equations in discretised form by means of a fourth order accurate finite volume method described in detail elsewhere [5]. According to e.g. [3, 6], the problem is characterised by the Reynolds and the Womersley number, defined as

$$Re = \frac{\hat{u} \cdot D}{\nu} \quad \text{and} \quad Wo = \frac{D}{2}\sqrt{\frac{\omega}{\nu}}\,, \qquad (1)$$

where D is the pipe diameter, ν the kinematic viscosity of the fluid and ω the angular frequency of the oscillatory flow. As characteristic velocity we use the peak bulk velocity $\hat{u}$ within one oscillation period.

At the conference, we will present results of five DNS for several *Wo*-*Re*-combinations also depicted in fig. 1 by black circles. As initial condition for DNS a to c, we use a fully developed and well correlated turbulent flow field predicted by a DNS of a non-oscillating pipe flow at $Re_\tau = 1440$ in a reduced pipe domain (RPD) of length $L = 1.25D$, where Re_τ is the Reynolds number based on the friction velocity. As described in [2], the length of the RPD, corresponding to $L^+ = 1800$ in wall units, is sufficiently long and the computational grid is sufficiently fine to resolve all relevant scales in the non-oscillating pipe flow at $Re_\tau = 1440$. The DNS d and e were started from the oscillatory but laminarised flow field predicted by DNS c, by keeping *Wo* constant and doubling Re_τ twice.

As an example, fig. 2 presents the time series of the axial velocity component for one oscillation cycle of the pipe flow at $Wo = 13$ and $Re_\tau = 1440$ (DNS b) after the flow was fully relaxed from the initial non-oscillating turbulent flow field. Close to the pipe wall at the radial position $r = 0.37$

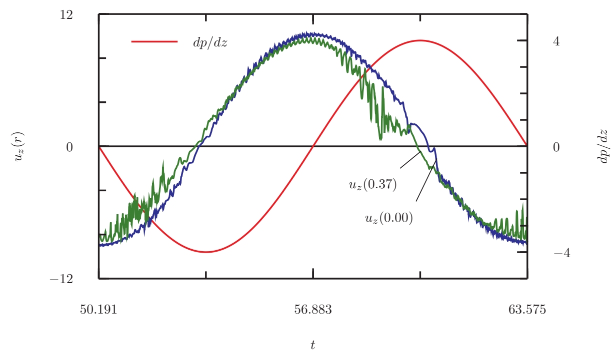
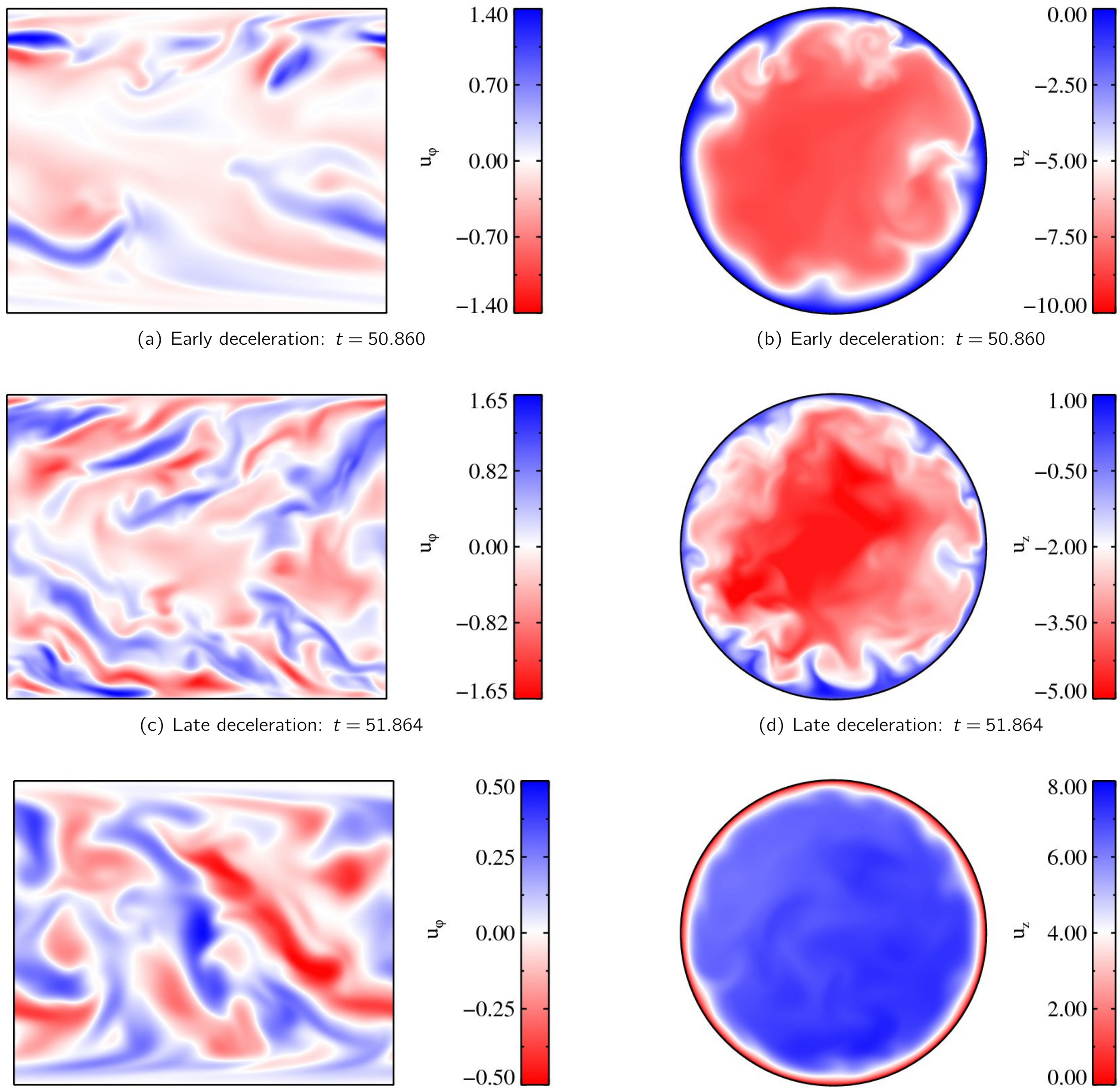


Fig. 2: Temporal evolution of the axial velocity component (u_z) at two different probe positions in the oscillatory pipe flow at $Wo = 13$ and $Re_\tau = 1440$ driven by a sinusoidally varying driving pressure (red).

the fluctuations are abruptly amplified in the early deceleration phase and decay during bulk flow reversal. This confirms experimental observations [1] of growing fluctuations and an asymmetry in the oscillatory half-cycle for the considered $Re_\delta = 1/\sqrt{2}Re/Wo^2 = 623$, where Re_δ is the Reynolds number based on the Stokes layer thickness. In fig. 3(a) and 3(b) the colour-encoded contour plots of the instantaneous axial and azimuthal velocity components of the same DNS highlight the development of three-dimensional large-scale flow structures close to the wall in the decelerating phase of the oscillation cycle, while the core flow remains nearly stable. These structures are amplified during the deceleration phase, while associated length scales are decreasing until the late deceleration, as reflected by fig. 3(c) and 3(d). The azimuthal fluctuations are now spread over the entire pipe domain and the flow structures are oriented in the direction of the bulk flow with an inclination with respect to the wall, which is typical for wall bounded turbulent shear flows. These correlated regions are the fingerprints of sweep and ejection events which organise the momentum transport normal to the wall. During the flow reversal these orientation collapses and all the velocity fluctuations are damped considerably in the following acceleration phase, as shown in fig. 3(e) to 3(f).

At the conference we will compare all oscillatory pipe flows by analysing the statistical moments of the velocity com-



(a) Early deceleration: $t = 50.860$ (b) Early deceleration: $t = 50.860$

(c) Late deceleration: $t = 51.864$ (d) Late deceleration: $t = 51.864$

(e) Acceleration: $t = 54.876$ (f) Acceleration: $t = 54.876$

Fig. 3: Colour encoded contour plots of instantaneous axial (u_z) and azimuthal (u_φ) velocity components in a longitudinal plane at $\varphi = 9\pi/16$ (left) and a cross-sectional plane at $z = 0.25$ (right) in the RPD at three instants during the oscillatory pipe flow at $Wo = 13$ and $Re_\tau = 1440$ resulting in $Re_\delta = 623$ and an oscillation period of $T = \pi Re_\tau/(2Wo^2) = 13.384$.

ponents with an order up to four at different instants during the oscillation cycle. Furthermore, we will discuss any possible influence of the different initial conditions.

References

[1] D. M. Eckmann and J. B. Grotberg. Experiments on transition to turbulence in oscillatory pipe flow. *Journal of Fluid Mechanics*, 222:329–350, 1991.

[2] D. Feldmann and C. Wagner. Direct numerical simulation of fully-developed turbulent and oscillatory pipe flows at $Re_\tau = 1440$. *submitted to Journal of Turbulence*, 2011.

[3] M. Hino, M. Sawamoto, and S. Takasu. Experiments on transition to turbulence in an oscillatory pipe flow. *Journal of Fluid Mechanics*, 75(02):193–207, 1976.

[4] T. Sexl. Über den von E. G. Richardson entdeckten Annulareffekt. *Zeitschrift für Physik A*, 61:349–362, 1930.

[5] O. Shishkina and C. Wagner. A fourth order finite volume scheme for turbulent flow simulations in cylindrical domains. *Computers & Fluids*, 36(2):484–497, 2007.

[6] K. E. Trukenmüller. *Stabilitätstheorie für die oszillierende Rohrströmung*. Phd thesis, Helmut–Schmidt–Universität, Hamburg, 2006.

[7] J. R. Womersley. Method for the calculation of velocity, rate of flow and viscous drag in arteries when the pressure gradient is known. *Journal of Physiology*, 127:553–563, 1955.

[8] T. S. Zhao and P. Cheng. Experimental studies on the onset of turbulence and frictional losses in an oscillatory turbulent pipe flow. *International Journal of Heat and Fluid Flow*, 17(4):356–362, 1996.