Swirl Switching in bent pipes studied by numerical simulation

Philipp Schlatter
Linné FLOW Centre, KTH Mechanics
SE-100 44 Stockholm, Sweden
pschlatt@mech.kth.se

Lorenz Hufnagel
Linné FLOW Centre, KTH Mechanics
SE-100 44 Stockholm, Sweden
hufnagel@kth.se

Jacopo Canton
Linné FLOW Centre, KTH Mechanics
SE-100 44 Stockholm, Sweden
jcanton@mech.kth.se

Elia Merzari
Argonne National Laboratory
Lemont, IL 60439, USA
emerzari@anl.gov

Oana Marin
Argonne National Laboratory
Lemont, IL 60439, USA
oanam@mcs.anl.gov

Ramis Örlü
Linné FLOW Centre, KTH Mechanics
SE-100 44 Stockholm, Sweden
ramis@mech.kth.se

ABSTRACT

Turbulent flow through pipe bends has been extensively studied, but several phenomena still miss an exhaustive explanation. Due to centrifugal forces, the fluid flowing through a curved pipe forms two symmetric, counter-rotating Dean vortices. It has been observed, experimentally and numerically, that these vortices change their size, intensity and location in a quasi-periodic, oscillatory fashion, a phenomenon known as swirl-switching. These oscillations are responsible for failure due to fatigue in pipes, and their origin has been attributed to a recirculation bubble, disturbances coming from the upstream straight section and others. The present study tackles the problem by direct numerical simulations (DNS) of turbulent pipe flow at moderate Reynolds number, analysed, for the first time, with three-dimensional proper orthogonal decomposition (POD) in an effort to distinguish between the spatial and temporal contributions to the oscillations. The simulations are performed at a friction Reynolds number of about 360 with a divergence-free synthetic turbulence inflow, which is crucial to avoid the interference of low-frequency oscillations generated by a standard recycling method. Two different bends are considered, with curvature 0.1 and 0.3, preceded and followed by straight pipe segments. Our results indicate that a single low-frequency, three-dimensional POD mode is responsible for the swirl-switching. This mode represents a travelling wave, and was previously mistaken by 2D POD for two different modes. Low-order reconstruction clearly shows that the upstream turbulent flow does not play a role for the swirl-switching.

INTRODUCTION

The flow in bent pipes is an important natural extension of straight pipe flow, however, significantly less studies are devoted to bent pipes as compared to their straight counterparts. Due to the curvature, the azimuthal symmetry of the flow is broken, and centrifugal forces lead to the appearance of a secondary flow, *i.e.* an inplane flow which manifests itself in the formation of two so-called Dean vortices. This secondary flow is skew-induced, and appears for both laminar and turbulent flow. The strength of these Dean vortices depends on the (bulk) Reynolds number Re_D, the curvature δ (usually defined as the ratio of pipe radius to the radius of the curvature), and also the extent of the bend. A recent comparison of the laminar flow in pipe bends for a variety of curvature and flow parameters is given by Canton *et al.* (2017). The curvature parameter distinguishes the flow in a torus (see *e.g.* Noorani & Schlatter (2016)) from the one in spatially developing pipes, as for instance the 90° bend studied in the present contribution. An illustration of the typical mean-flow development in such a bend is shown in Figs. 1 and 2. The mean velocity clearly shows the profound impact the bend has on the cross-stream distribution of the velocity magnitude; faster flow is deflected towards the outer bend, which in turns generates the secondary Dean cells (visible in the contours of the stream function). Note that for the present cases, only a small region of flow with reversed direction is observed downstream of the bend. The flow slowly recovers from the bend, and approaches the axisymmetric profile further downstream.

Going back to the first observation by Tunstall & Harvey (1968), and later in more quantitative ways by *e.g.* Brücker (1998), it has been observed that under turbulent conditions (sufficient Reynolds number) these Dean vortices are not steady, but rather appear to oscillate quasi-periodically with a comparably low frequency. This so-called swirl-switching may cause premature failure of piping systems due to fatigue. An illustration of the motion of the Dean vortices is given in Fig. 3, taken from a simulation of the flow in a torus. The origin of the swirl-switching is still unknown, and explanations range from an oscillation induced by a separation in the bent pipe to an enhancement of the upstream large-scale flow structures through the bend. Whereas the explanation with separation can probably be ruled out (Rütten *et al.*, 2005), the connection to the upstream turbulent flow, in particular caused by very large-scale motions (VLSM) formed in the straight pipe section, has been reported in a number of recent publications (Sakakibara & Machida, 2012), however remains still controversial. In particular, the recent study by Noorani & Schlatter (2016) showed that swirl-switching also exists in a torus without straight section.

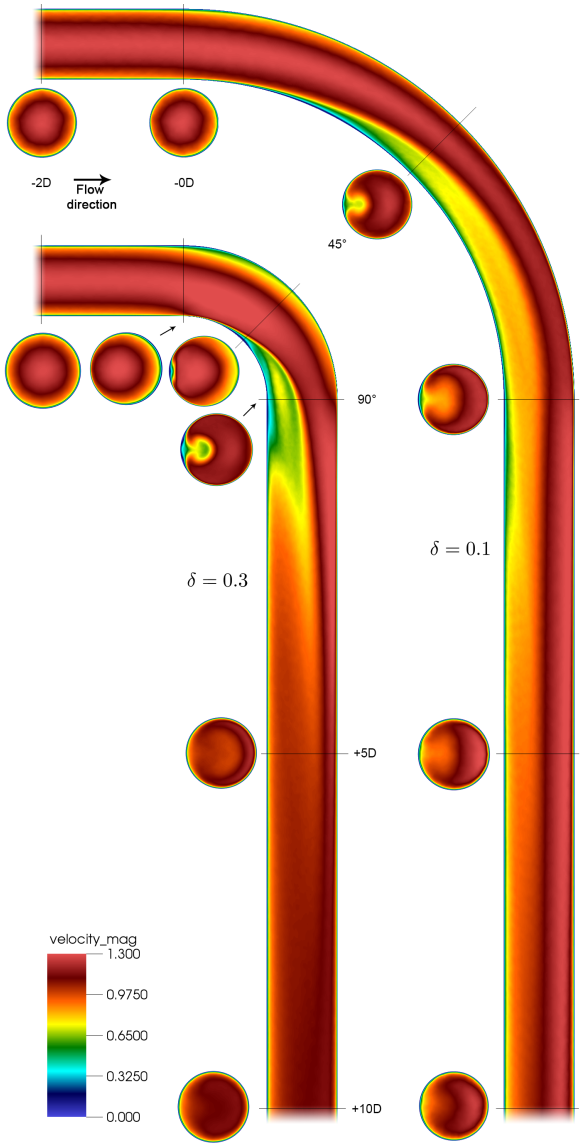

Figure 1. Mean velocity of the turbulent flow through a 90° bend for two curvatures $\delta = 0.1$ and 0.3. The flow enters from top left and exits bottom right. The inflow is a fully developed turbulent pipe flow generated using artificial turbulence. Colours of the mean velocity are shown. Depending on the curvature, retardation of the flow at the bend inside is observed, and the flow slowly goes back to the axisymmetric velocity profile downstream of the bend.

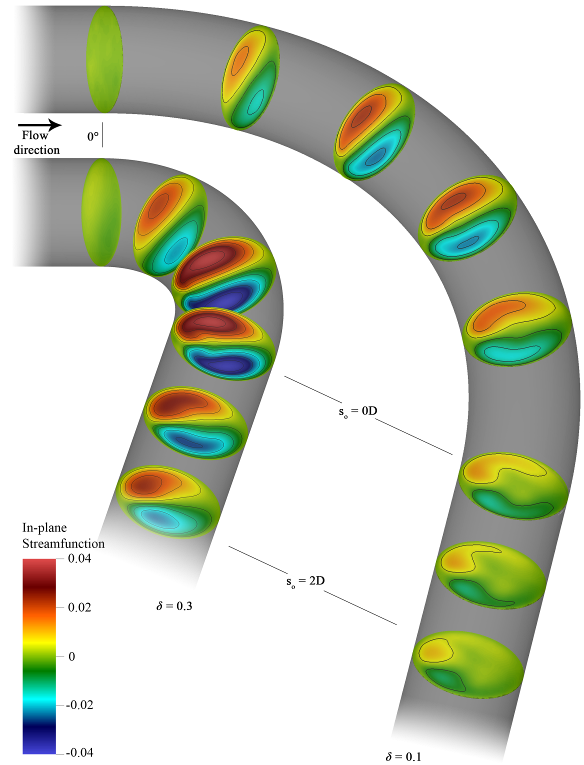

Figure 2. Averaged turbulent flow in a 90° bend for two curvatures $\delta = 0.1$ and 0.3. The in-plane stream function is shown. The appearance of Dean vortices in the bend, and their subsequent decay can clearly be appreciated.

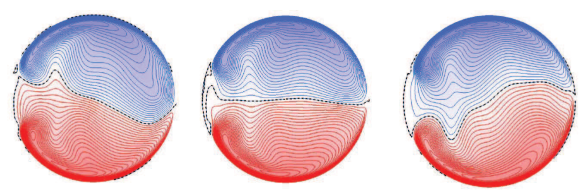

Figure 3. Illustration of the swirl-switching as an alternate dominance of one Dean vortex over the other; shown are contours of the in-plane stream function for three time instants. This particular figure is obtained in a torus flow, *i.e.* without straight inflow or outflow sections (Noorani & Schlatter, 2016). The inner side of the bend is on the left-hand side.

The swirl-switching has been studied in the past using modal analysis, in particular proper orthogonal decomposition (POD), see *e.g.* Sakakibara & Machida (2012), Hellström *et al.* (2013), Kalpakli & Örlü (2013) and in the torus by Noorani & Schlatter (2016), however no firm conclusion on the nature of the swirl-switching could be established. The present contribution is a first attempt to use direct numerical simulations (DNS) on the case of a spatially developing bend, in order i) to reproduce the swirl-switching, ii) to extract 2D and 3D POD modes, and iii) examine potential origins of the swirl-switching.

SETUP

The present work is entirely based on direct numerical simulations using a high-accuracy method. Our fully resolved simulations are performed using Nek5000 (Fischer *et al.*, 2008), a high-order spectral-element code, in a similar way as discussed in Noorani & Schlatter (2016) for the torus and El Khoury *et al.* (2013) for straight-pipe flow. In order to generate a turbulent inflow for the spatially developing bend, the synthetic eddy method (Jarrin *et al.*, 2006) has been adapted to the current setup, with special attention to imposing divergence-free disturbances (Poletto *et al.*, 2011). This choice was particularly important in order to avoid spurious frequencies in the flow that would arise when using recycling conditions. Our experience with the current inflow method is very good, and the flow can be considered a canonical turbulent pipe flow already after 5 diameters downstream of the inflow. The development of selected integral quantities along the streamwise direction is shown in Fig. 4. All monitored quantities, including the skin friction u_τ, the fluctuations of the friction $\tau_{w,rms}$ and the shape factor quickly reach the values of the reference DNS (El Khoury *et al.*, 2013) obtained in a periodic pipe. Similarly, the dynamics of the velocity field

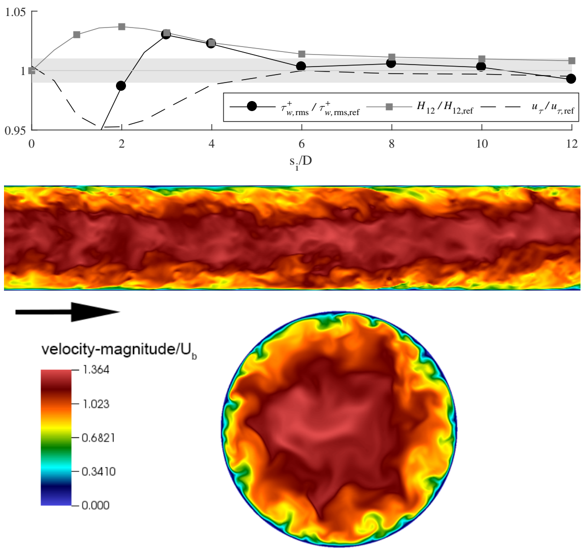

Figure 4. Development of selected integral quantities along the axial direction in turbulent pipe flow, downstream of the artificial inflow condition. The reference values are take from the DNS performed by El Khoury *et al.* (2013) at the same $Re_\tau = 360$.

is similar to a turbulent pipe flow already very close to the inlet, indicating that the synthetic conditions quickly promote the typical near-wall cycle of wall turbulence.

The POD analysis performed on the DNS data is classical in the sense that the snapshot matrix is assembled, and then the modes, the energies and the time coefficients are calculated using singular-value decomposition. The only two noteworthy aspects are that i) the resolution of the data is slightly reduced using spectral interpolation prior to performing the POD analysis, and ii) that the statistical symmetry of the flow (mirror symmetry) is exploited in our decomposition. The former point was carefully assessed, and no difference in the large-scale properties of the modes were observed, and the latter point leads to perfectly symmetric (or anti-symmetric) modes as would be expected in a flow that shows such a symmetry. In order to be able to compare to experiments, we have performed both 2D-POD (in cross-flow planes) and 3D-POD. It is important to realise that these two decompositions (2D and 3D) do not need to give the same results, as in 2D-POD the axial convection might lead to spatio–temporal misinterpretation.

The current simulations are run in a pipe of total length approximately $25D$; upstream of the bend $7D$ are employed, and downstream of the bend the flow is tracked for another $15D$. The bulk Reynolds number is set to $Re_D = 11700$ which corresponds in the straight section to a friction Reynolds number of $Re_\tau \approx 360$. The resolution is chosen such that all relevant scales of motion are resolved, *i.e.* as direct numerical simulation (DNS). Two curvatures, $\delta = 0.1$ and 0.3 are employed.

RESULTS

In this section, some selected results pertaining to the performed DNS are presented. Two-dimensional POD, considering all three velocity components, is employed as a first step in the analysis of swirl-switching. The first three modes for both curvatures are shown in Fig. 5 by means of streamlines of the in-plane velocity components. We do not show the mean flow, which would typically be denoted as zeroth mode. Two out of three modes are antisymmetric: modes 1 and 2 for $\delta = 0.3$ and modes 1 and 3 for $\delta = 0.1$. These antisymmetric modes are of the form of a single swirl covering the whole pipe section and its harmonic, displaying

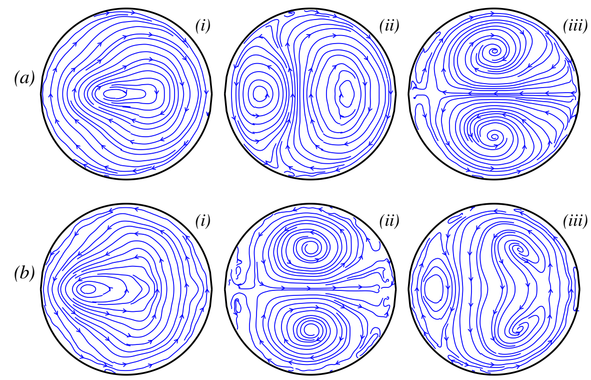

Figure 5. Comparison of the first POD modes obtained from our DNS. The top row a) corresponds to the pipe with curvature $\delta = 0.3$, while the bottom row b) corresponds to the pipe with $\delta = 0.1$. The modes are oriented as in Fig. 3. In both cases the snapshots were extracted at a streamwise position of $2D$ downstream of the bend.

two counter-rotating vortices disposed on top of each other along the symmetry plane. The other mode, number 3 for $\delta = 0.3$ and number 2 for $\delta = 0.1$, resembles a harmonic of the (mean) Dean vortices. These findings are in very good agreement with previous experimental work, such as that of Sakakibara & Machida (2012) and Kalpakli & Örlü (2013), which attributed the dynamics of swirl-switching to the antisymmetric modes. Apart from the ordering of the modes (energy content) in particular the excellent agreement between DNS and the experiments by Kalpakli & Örlü (2013) is noteworthy.

It is interesting to note that the symmetry imposed by the geometry is not fully recovered by the modes presented in Hellström *et al.* (2013), however a linear combination of the symmetric and antisymmetric modes could probably be used to recover those modes. Nevertheless it should be stressed that the correct POD modes need to carry the symmetry of the underlying geometry.

However, the time coefficients of the two-dimensional POD modes do not reveal significant information about the swirl-switching. An analysis of the power spectral density estimate for the time coefficients (not shown) of the first three modes does not reveal any distinct peaks. The reason is that swirl-switching is caused by a three-dimensional travelling wave, as will be shown below, a two-dimensional cross-flow analysis cannot distinguish between the spatial and temporal amplitude modulations created by the passage of the wave.

For the 3D POD, the same snapshots as for 2D POD were used. As mentioned above, in order to reduce memory requirements, the snapshots were interpolated on a coarser mesh before computing the POD. This is, however, not a problem because the swirl-switching is related to larger-scale fluctuations in the flow and thus not affected by the finest details. Note however that the actual simulation of course includes all scales of turbulence.

The four most energetic modes for the pipe with the higher curvature $\delta = 0.3$ are depicted in Fig. 6 by means of pseudocolors of normal and streamwise velocity components, as well as streamlines of the in-plane velocity. It can be observed that the modes come in pairs, modes 1 and 2, and modes 3 and 4. This is a common feature for (real-valued) POD modes in a convection-dominated flow. The first coherent structure is formed by the two modes 1 and 2 in Fig. 6; these modes are phase-shifted by a quarter of a period and characterise a travelling wave with a wavelength of approximately $7D$. This travelling wave is formed by two counter-rotating swirls, visible in the 2D cross-sections, which move along the streamwise direction while decaying in intensity and, at the same time, moving from the

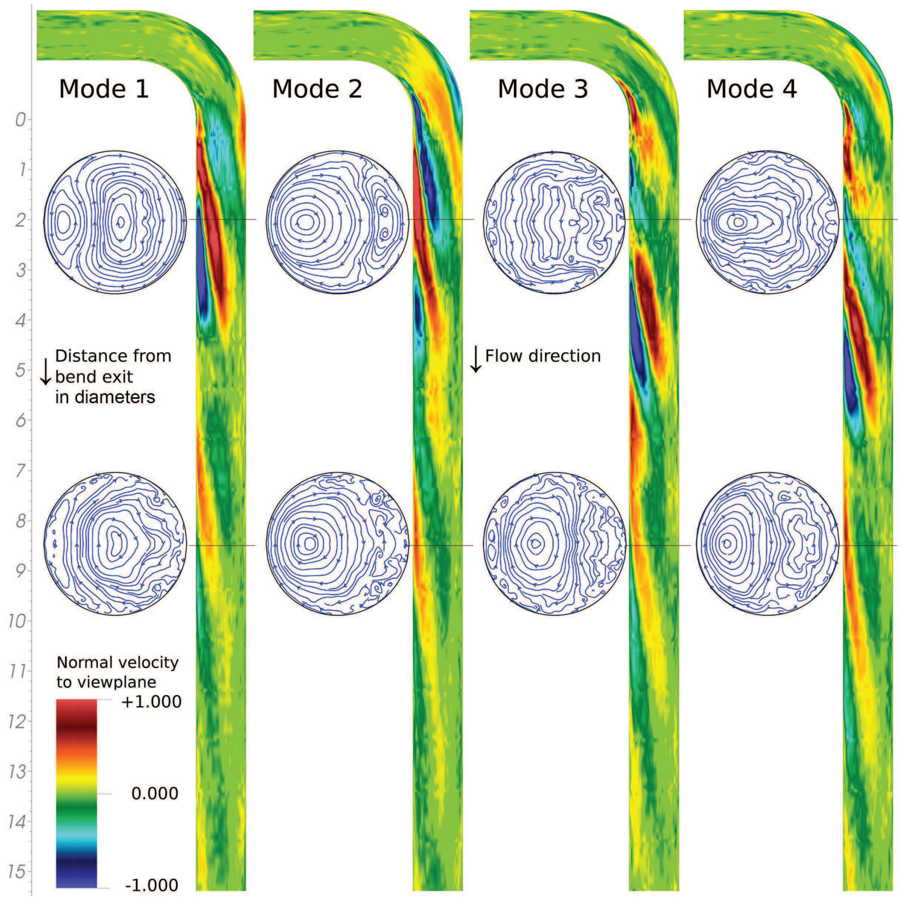

Figure 6. The first POD modes obtained from DNS using full 3D fields; shown is the normal velocity in the plane of symmetry. The first two modes correspond to a travelling wave with wave length of approximately 5, whereas modes 3 and 4 have a wave length of about 2.5, which is a superharmonic to modes 1 and 2. The travelling nature is apparent from the phase-shifted modes 1,2 and 3,4.

inside of the bend towards the outside. The second structure, modes 3 and 4, has a spatial layout that closely resembles that of the first pair and constitutes the first higher harmonic of the structure formed by modes 1 and 2, having half the wavelength and twice the frequency.

As can be further observed from Fig. 6, the modes do not present any connection to the straight pipe section preceding the bend. The entire energy of the modes is in the downstream part of the bend, indicating no coherency with the upstream part. This is a result in agreement with Noorani & Schlatter (2016) who observed swirl-switching in a toroidal pipe (*i.e.*, in the absence of a straight upstream section), but does not agree with the interpretation provided by *e.g.* Sakakibara & Machida (2012). Note however that the present study is among the first works employing full 3D POD. The power spectral density analysis of the time coefficients of these modes (not shown) shows two distinct peaks, one per pair of modes. The peak for the first modal pair is located at a Strouhal number $St = fD/U_b = 0.15$, which is in the range of Strouhal numbers found by both Brücker (1998) and Hellström *et al.* (2013). More importantly, this frequency is the lowest for this pair of modes and matches that given by the wavelength and propagation speed of the wave as well as that of the swirl-switching, as observed by reconstructing the flow field with the most energetic POD modes.

The POD analysis of the bent pipe with curvature $\delta = 0.1$ shows the same qualitative behaviour, namely, a travelling wave with a wavelength of approximately $21D$, which is responsible for the swirl-switching. Consistently with the literature, the travelling wave for $\delta = 0.1$ is characterised by a lower frequency with respect to that for $\delta = 0.3$; more specifically, a peak Strouhal number of $St = 0.045$ is found.

CONCLUSIONS

This work presents the first DNS analysis of swirl-switching in a 90° bent pipe. The simulations were performed by using a synthetic eddy method to generate high-quality in flow conditions in an effort to avoid any interference between the incoming flow and the dynamics of the flow in the bent section, as was observed in previous studies.

The main conclusions from the current analysis can be summarised as follows: i) the swirl-switching is indeed a travelling wave, originating in the bend (confirming the results by Noorani & Schlatter (2016) in the torus), ii) due to the travelling nature, two phase-shifted modes are necessary for the reconstruction, iii) the POD modes clearly show that there is no connection between the upstream turbulent inflow and the swirl-switching modes. It is therefore strongly suggested that the bend is the cause of the modes. iv) The 2D analysis in planes can only give a partial picture of the true 3D nature of the phenomenon, as due to the convection spatial and temporal evolution are mixed together.

ACKNOWLEDGMENTS

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