

Streamwise Auto-Correlation Analysis in Turbulent Pipe Flow Using Particle Image Velocimetry at High Reynolds Numbers

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Abstract This preliminary study focuses on determining the lengths of turbulent pipe flow structures at $Re_b \approx 60,000$ and $140,000$ using auto-correlation analysis in streamwise direction considering velocity fluctuations, where Re_b is the Re-number based on bulk velocity. These structures are usually represented in terms of wavelengths λ or wavenumbers k . The current investigations on such turbulent structures including both large-scale motions (LSM) and very large-scale motions (VLSM) showed that the streamwise extension of these structures is highly dependent on the Reynolds number. Hence, the Cottbus large pipe (CoLaPipe) as a high Reynolds number test facility is being used to understand the physical processes and dynamics of such structures. These turbulence structures have been investigated using particle image velocimetry (PIV) to validate and compare earlier results obtained utilizing hot-wire anemometry (HWA).

1 Introduction

It has been recently observed that the sizes of turbulence structures can reach even $20R$ along the pipe axis, where R is the pipe radius, and are highly dependent on the Reynolds number [4, 5]. According to [1, 2, 6] some open questions remain unsettled for identifying accurate sizes of the large-scale motions (LSM) and very large-scale motions (VLSM). The theory of [2] claimed sizes of LSMs as $\lambda_{LSM} = 2R - 3R$ and VLSMs as $\lambda_{VLSM} = 8R - 16R$ using hot-wire anemometry at high frequencies in turbulent pipe flow. The estimated turbulent structure lengths in these studies have been calculated regarding one dimensional spectral analysis and temporal development. One should also consider that these investigations were based on similar pipe geometry; e.g. [2]: $D_i = 127$ mm, [1]: $D_i = 127$ mm, [6]: $D_i = 129$ mm, where D_i

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is the inner diameter of pipe. The current study is targeting at using a non-intrusive measurement method, i.e. PIV, to scan a large domain of pipe section having larger diameter, $D_i = 190$ mm, in fully developed turbulent state at $Re_b = 60,000$ and $140,000$ to focus on spatial development of the large-scale structures.

2 Facility Description and Measurements

The CoLaPipe is providing an opportunity to approach higher Reynolds numbers, $60,000 \leq Re_b \leq 1,000,000$, with high enough resolution, $10 \leq \ell^* \leq 300$, where ℓ^* is the viscous length scale. The pipe test section is made out of acrylic glass, having inner pipe diameter of $D_i = 190 \pm 0.23$ mm with deviation less than 0.12%. The total length of the suction side, $L = 28$ m, provides a test section with a length-to-diameter ratio of $x/D_i \approx 148$. Further informations about the pipe facility and wall-layer measurements using conventional probes can be found in [3, 8].

Preliminary PIV measurements have been performed between $x/D_i = 91-101$ in collaboration with LaVision GmbH which covers 2 m of pipe test section, i.e. approximately a domain of 20R. 4 Imager sCMOS cameras with 2560×2160 pixels (provided by LaVision) with a standard Nd:YAG double-pulse laser with $f = 15$ Hz and $\lambda = 532$ nm have been used to cover this area with an acquisition frequency of $f = 15$ Hz (Fig. 1). All cameras have been synchronized to obtain simultaneous data. Calibration has been performed using a self-made calibration pattern which is inserted through the 2 m-pipe segment before the measurements. Standard fog fluid is used with aerosol generator to produce smoke particles. It should also be noted that to avoid any macro-cracks on acrylic glass surface, any kind of seeding materials with alcohol is to be renounced. For each case investigated, 100 snapshots have been taken. For post-processing only approx. 14R segment was taken into account due to stitching problems of the last camera. In terms of viscous wall unit, 64,276 mm distance between two vectors is delivering the first point at $y^+ \approx 110$, which can be considered as a low resolution study for this preliminary experiment.

3 Results

To apply auto-correlation function, the streamwise velocity fluctuations over 14R pipe segment at various wall-normal locations (y/R) were considered. For each y/R , all instantaneous velocity data were taken where the mean velocity of each y/R location is subtracted from these values. As seen in Fig. 2, which shows a correlation curve corresponding to only a single PIV snapshot, after applying the correlation method some periodic behaviors can be observed. The first point in the velocity domain is taken as a reference point and the neighbor points are correlated with this reference point. It can be easily observed from the figure that by moving

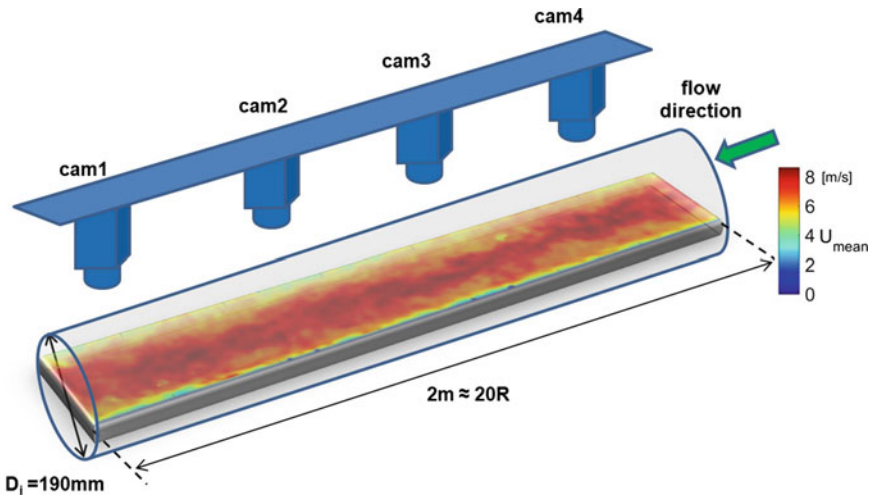


Fig. 1 Schematic of streamwise PIV arrangement in CoLaPipe using four sCMOS cameras, at $Re_b \approx 60,000$

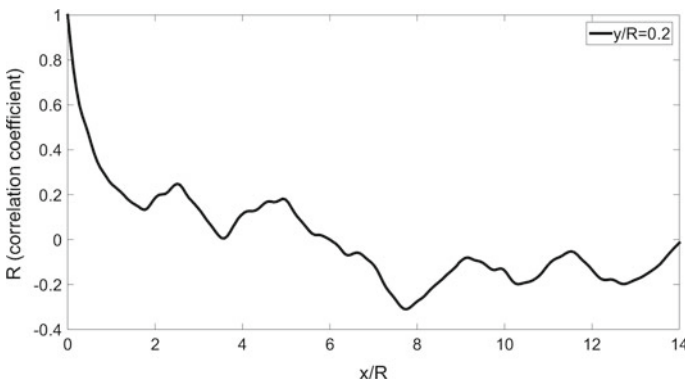


Fig. 2 The behavior of correlation coefficients over the 14R pipe domain at $Re_b \approx 60,000$ ($y/R = 0.2$) in a single PIV snapshot

in streamwise direction the correlation coefficient is decreasing but at some points repeated peaks can be distinguished.

A contour map illustrated in Fig. 3 exposes the variation of the streamwise correlations R_{uu} at $y/R = 0.2$ at lower Reynolds number case in a time-space plot. By checking all 100 streamwise PIV data, it should be noted that not all snapshots are delivering consistent velocity behavior which shows a periodic correlation. Figures 4 ($Re_b \approx 60,000$) and 5 ($Re_b \approx 140,000$) show the average distance between those correlation peaks (normalized by pipe radius) regarding all 100 snapshots. These repeated periodic distances are considered as signs of turbulent structures. A moving-average-function is applied to eliminate noises to capture the peaks properly. For

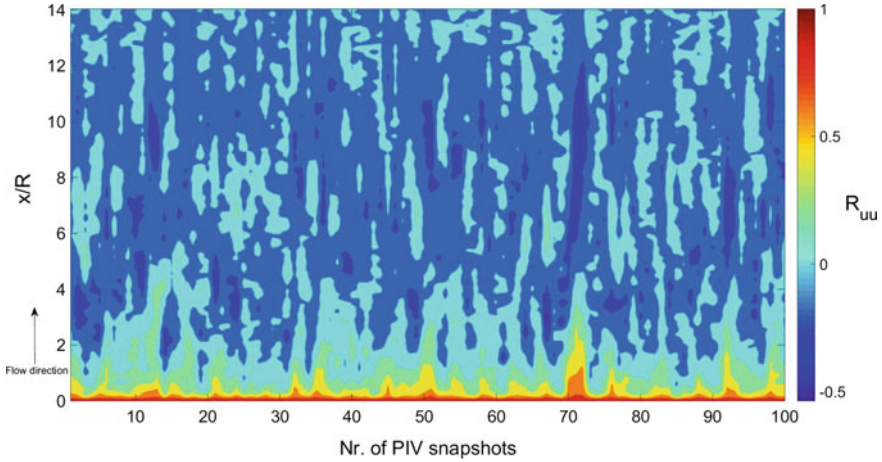


Fig. 3 Contour map showing variation of the streamwise correlation coefficients R_{uu} with 100 PIV-snapshots along 14R pipe domain at $y/R = 0.2$ and $Re_b \approx 60,000$

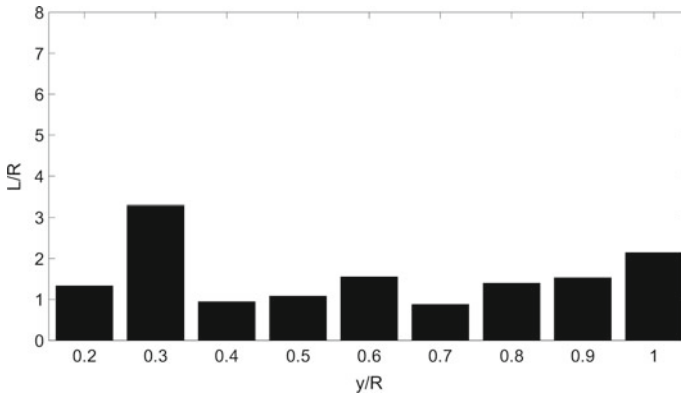


Fig. 4 Estimated mean structure lengths (L) normalized by R at $Re_b \approx 60,000$ of streamwise velocity fluctuations at various wall-normal locations over 100 snapshots

each snapshot the distances of visible peaks for a specific wall-normal location are calculated and the average values are presented in Figs.4 and 5. According to this method, mean structure lengths of 1.6 and 2.5R can be observed for $Re_b \approx 60,000$ and $Re_b \approx 140,000$ respectively.

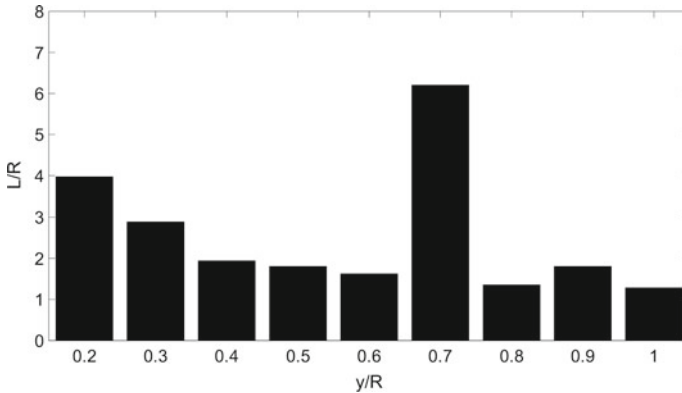


Fig. 5 Estimated mean structure lengths (L) normalized by R at $Re_b \approx 140,000$ of streamwise velocity fluctuations at various wall-normal locations over 100 snapshots

4 Future Work

High-speed PIV measurements with higher acquisition frequency and larger number of snapshots are essential to have a more precise analysis for determining the length of the structures in fully developed pipe flow. Alternatively, instead of using multi-point-correlation in a wall-normal line, applying a two-point-correlation in streamwise and spanwise directions will be implemented to investigate the spatial extend of correlated motions within the measurement plane. It should also be noted that the outer scaling factor R of the previous studies is widely used for facilities with similar pipe diameters. The effect of larger pipe diameters should be taken into account by normalization with R to determine the proper lengths of the large-scale structures.

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