Wavenumber Dependence of Very Large-Scale Motions in CICLoPE at $4800 \leq \mathrm{Re}_\tau \leq 37{,}000$

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Abstract The present work aims at investigating the very large-scale structures of turbulent pipe flow in CICLoPE at high Reynolds numbers. According to recent studies, some open questions remain to be answered to identify accurate sizes of these turbulent structures in pipe flow. The CICLoPE facility has been therefore utilized, providing an opportunity to approach high Reynolds number flows with high enough resolution in terms of the viscous length scale, allowing us to investigate the behavior of such turbulent structures. Meandering structures, usually referred as VLSM (very large-scale motions), have been identified with claimed extension up to $20R$, where R is the pipe radius.

1 Introduction

Characterization of turbulence structures in pipe flows at high Reynolds numbers are of vital importance with respect to the Reynolds stresses and the turbulent kinetic energy production. Recently, there has been an increasing interest in observing and understanding of the large organized vortex clusters forming large-scale and very large-scale motions (LSM and VLSM). Nevertheless, a solid definition of their nature and vivid understanding of their evolutions are still progressing. Therefore, this study is mainly focusing on clarifying the nature of the VLSM as well as describing and identifying them in quantitative manner.

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Recent investigations of fully developed turbulent pipe flows, e.g. Bailey et al. [1] and Bosenberg et al. [2] showed that identification of the LSM and the VLSM in pipes are still under progressing and it might be concluded that there is still a lack of a complete and common definition for scales of those structures, in particular, at very high Reynolds numbers. Therefore, a quantitative measure of the Reynolds stresses and the energy production associated with such scales are indeed to be clearly defined.

An experimental attempt by Guala et al. [3] suggested a value of 2 for the normalized wavenumber $k_x R$ as a separator between the range of VLSMs and LSMs. It is clearly observable that according to the domain dividing method in premultiplied power spectra, the wavenumbers are converted to wavelengths independently. This is the reason why the results are shown separately for LSM and VLSM, in [3]. The line of separation is corresponding to a wavelength of πR, which is slightly longer than the accepted mean length of a turbulent bulge. They also found that the streamwise energetic modes can extend up to 12–14 pipe radii and 4–5 times longer than the length of a turbulent bulge and referred to these modes as very large-scale motions (VLSM). More recently, [4] used the whole premultiplied spectra and the observable peaks obtained to determine the wavenumbers for each radial location. The only difference to [3] was that structures were compared according to their dimensionless wavenumbers. On the other hand, [2] and [4] followed another method by associating the highest peaks in the power spectra to a possible turbulent structure.

2 Objectives and Measurements

The measurements in CICLoPE facility aim at investigating one-dimensional energy spectra over a wide range of Reynolds number. Considering similar facilities, Cottbus Large Pipe (CoLaPipe) [5, 6] covers a range of $10^3 \leq Re_\tau \leq 17 \times 10^3$ with large enough viscous length scales ($10 \leq \ell^* \leq 300$), and the Princeton/ONR Superpipe with approximately $3 \times 10^3 \leq Re_\tau \leq 10^5$ working range, however, having much smaller size of the viscous length scales ($0.5 \leq \ell^* \leq 30$). Here Re_τ is called the shear Reynolds number and defined as $Re_\tau = Ru_\tau/\nu$, where u_τ is the wall friction velocity, R is the pipe radius and ν is the kinematic viscosity of the fluid. The CICLoPE covers a region defined by $5 \times 10^3 \leq Re_\tau \leq 37 \times 10^3$ and sizes of viscous scales ($10 \leq \ell^* \leq 100$).

It is worth noting that the energy distribution in wavenumber domain helps to understand the behavior and structures of turbulence. In pre-multiplied spectra, the signature of the coherent motions can be easily observed where the spectral peaks, i.e. inner as well as outer spectral peaks, in near-wall and outer regions, respectively, provide evidences for the location of the maximum energy production and the energy content per wavenumber, see [4]. It was stated by [4] that the location, magnitude and wavelength of these spectral peaks are still open issues. Following the Kolmogorov scaling laws, i.e. k_x^{-1} and $k_x^{5/3}$ and their dependence on the Reynolds number provide

also inputs about the universal behaviour of the energy spectrum in smaller and larger length scales at different wall-normal positions.

The mean pressure gradient along the CICLoPE pipe test section was monitored using pressure taps equally-spaced and distributed along the pipe section. Utilizing the mean pressure gradient obtained, the wall shear stress and consequently the wall friction velocity are determined. In order to obtain turbulence statistical quantities, instantaneous velocity field is resolved using thermal anemometer. The most common thermal anemometry used to obtain information on time-averaged and fluctuating velocities is the hot-wire anemometry (HWA), working in constant temperature mode. Further processing of the HWA time trace data acquired, i.e. the statistical and spectral quantities, were carried out in order to assess the behavior of the CICLoPE turbulent pipe flow. It is worth noting here that only naturally generated turbulence was considered in this piece of work.

In order to compare the CICLoPE data with those from the CoLaPipe, a common shear Reynolds number range $4,800 \leq Re_\tau \leq 17,000$ is considered for a viscous length scale approximately $\ell^* \leq 100$, see Fig. 1 in [5]. The main goal is to scale the turbulent spectra at different Reynolds numbers and wall-normal positions to identify the signs of any possible LSMs and VLSMs. Spectral peak locations at inner and outer regions were studied for each Reynolds number. Within this context the size effect of the three different facilities (incl. Superpipe) on the spatial development of turbulent structures can be clarified in further studies. Similar measurements have been already conducted by Princeton team [2, 4].

3 Results and Discussions

Figure 1 shows the premultiplied spectra normalized by the shear velocity $(k_x \Phi_{uu}/u_\tau^2)$ at the lowest and highest Reynolds number cases in the CICLoPE facility. A good collapse is observed for $k_x R < 3$ (Fig. 1a), and for $k_x R < 2$ (Fig. 1b), in particular for $y/R < 0.3$ at $Re_\tau = 4800$ and $Re_\tau = 37,000$, respectively. The first peaks of premultiplied power spectra at various wall-normal locations seem to appear for similar normalized wavenumber. The first peak of spectra is considered as an evidence of the VLSM which is originating at lower wavenumbers. The magnitudes of the VLSM peaks are observed to decreas at higher wall-normal positions in good agreement with [4] which might be attributed to the decay of the total momentum transport as the wall distances increases beyond the outer limit of the inertial sublayer $y/R > 0.15$. In order to find the peaks of the energy spectra and estimate the wavenumber peak location the methodology adopted by [2] was followed. To reduce the scatter in the data a Gaussian window is applied to smooth the existing plots. Figure 1 shows significant differences in magnitudes of premultiplied spectra as observed in DNS results of [7] in comparison to [4]. CICLoPE delivers a viscous length scale $(\ell^* = \nu/u_\tau)$ of 10.1 µm where Superpipe reaches only 1.7 µm at $Re_\tau = 37,000$. For this reason scaling
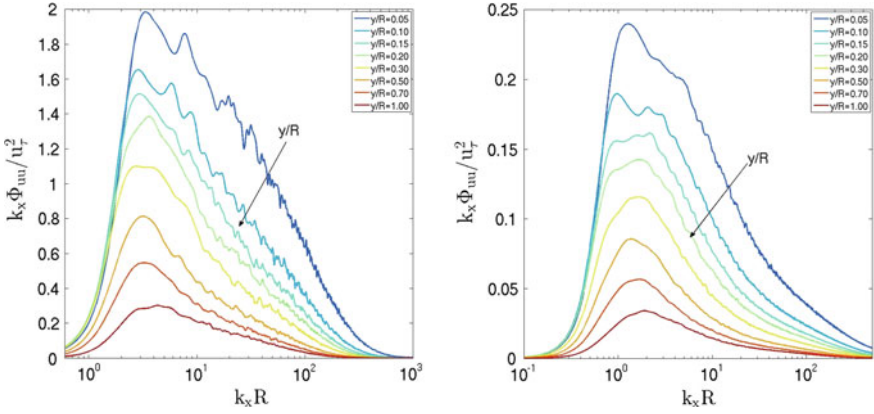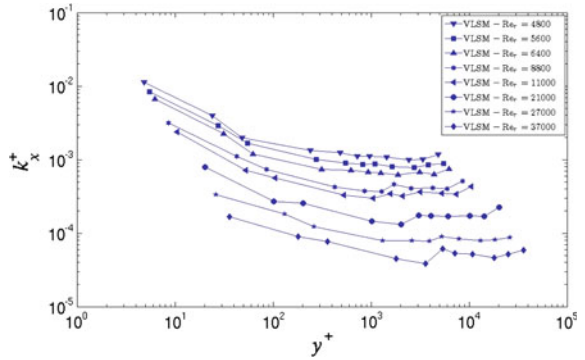
Fig. 1 Spectra with varying wall-normal distances at $Re_\tau = 4800$ (*left*) and $Re_\tau = 37,000$ (*right*)

Fig. 2 Inner scaling of spectral peak locations of VLSMs for $4800 \leq Re_\tau \leq 37000$


of $k_x \Phi_{uu}$ with various u_τ in two facilities may deliver different magnitudes at the same shear Reynolds numbers.

Utilizing the viscous length scale ℓ^*, the wavenumber k_x was normalized yielding $k_x^+ = k_x \nu / u_\tau$ and then presented versus the normalized wall distance, ($y^+ = y u_\tau / \nu$) in Fig. 2. Figure 2 illustrates a monotonic decrease of the VLSM peaks up to the inner limit of the inertial sublayer ($y^+ \approx 3 \times 10^2$), reaching an almost asymptotic behavior along the inertial sublayer for various Reynolds numbers. The normalized wavenumber k_x^+ values corresponding to the same positions are shifted at higher y^+ values due to increasing the shear velocity with increasing the Reynolds number.

Spectral peak locations in outer coordinates, i.e. scaled with R, show an interesting trend in agreement with the Superpipe data described in [2]. The normalized wavenumber decreases monotonically along the wall distance $0.001 \leq y/R \leq 0.05$. On the other hand, at higher wall-normal distances, i.e. $y/R \leq 0.05$ which is close to the inner limit of the inertial sublayer, the normalized wavenumbers ($k_x R$) values are coming close to each other, and therefore, start to stabilize for all Re_τ till reaching the

Fig. 3 Outer scaling of spectral peak locations of the VLSMs for $4800 \leq Re_\tau \leq 37000$
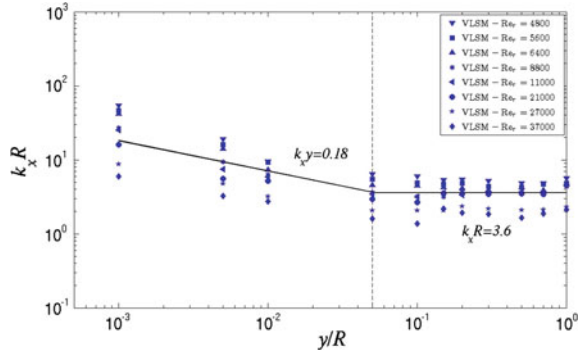
pipe centerline. One might observe from Fig. 3 that the VLSMs are about $k_x R \approx 3.6$ ($\lambda_x/R \approx 1.75$) which seem to be smaller than sizes expected according to [8] and [3]. In addition to different non-dimensionalized structure lengths, Figs. 2 and 3 show also some discrepancies according to results of [4]. One particular reason regarding the differences for inner and outer scaling can be addressed to unequal viscous conditions and different pipe radii. One should state that the inner diameter ratio of CICLoPE and Superpipe ($D_{CICLoPE}/D_{Superpipe} = 6.97 \approx 7$) is corresponding to the ratio of non-dimensionalized wavelenghts of VLSMs in both facilities which are originating at similar wavenumbers: $(\lambda_x/R_{Superpipe})/(\lambda_x/R_{CICLoPE}) \approx 14/2 = 7$. It is obvious that a scaling of dimensionalized structure lengths with a smaller R will provide larger non-dimensionalized wavelengths than a larger R. For this reason higher $k_x R$ values in outer scaling in CICLoPE (Fig. 3) may lead to much smaller non-dimensionalized VLSM lengths in comparison to Superpipe and also [8] and [3].

4 Conclusions and Future Work

The current study confirms the importance of the very large-scale structures in understanding of high Reynolds number wall turbulence. The premultiplied spectra showed good collapse for $k_x R < 3$, in particular, for high enough Reynolds number. A monotonic decrease of the VLSM peaks within the wall layer was observed up to the inner limit of the inertial sublayer. On the contrary, an asymptotic behavior along the inertial sublayer was reached for various Reynolds numbers. Existing data of the Superpipe will be compared with CoLaPipe and CICLoPE in terms of their premultiplied spectra ($k_x \Phi_{uu}/u_\tau^2$) and wavenumber dependences of VLSM & LSM peaks. The normalization & scaling procedures of the turbulent structure lengths at different high Reynolds numbers pipe flow facilities with friction veloctiy (u_τ) and various diameters ($D_{Superpipe} = 0.129$ m, $D_{CoLaPipe} = 0.19$ m, $D_{CICLoPE} = 0.9$ m)

will be reviewed again considering the smaller non-dimensionalized wavelengths obtained in CICLoPE than those reported earlier in literature.

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