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Two time and two point shifted velocity measurements in decaying homogeneous turbulence

Mesures en 2 points 2 temps glissants dans une turbulence homogène décroissante

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Obtention of some characteristics as Eulerian 2 times 2 points shifted velocity correlations for isotropic homogeneous turbulence is still difficult to obtain. Nevertheless, it is necessary, particularly for 2 points and 2 times or Lagrangian turbulence modelling, to improve our knowledge of the deduced characteristic turbulent time scales. In the present work the flow is a water decaying turbulence. We use particle image velocimetry (PIV) to obtain velocity field measurements in a first fixed point x and in a second moving point $x + \Delta x$. The velocity field at x is obtained at time t and at $x + \Delta x$ at time $t + T$ (where $\Delta t = \Delta x/\overline{U}$ ($\overline{U}$ being the mean velocity at x)). Our turbulence is the same as Comte-Bellot and Corrsin (1971) [1] (GCBC) but in water. They used two hot-wire anemometers to obtain velocity field x and $x + \Delta x$ along their tunnel axis, whereas we used two PIV systems. This allows us to have measurement points closer each together, compare to GCBC. We present our PIV measurements that will be compared with the ones of GCBC (Comte-Bellot and Corrsin, 1971) [1] and Schlien and Corrsin (1974) [2] (SC). We first demonstrate the validity of our water experiment then the use of the synchronised two PIV systems. We further present the velocity correlation results and the deduced turbulent time scale.

R É S U M É

La caractérisation de la turbulence homogène isotrope par des mesures Eulériennes en 2 points 2 temps glissants est difficile à obtenir. Elle est pourtant nécessaire pour les modèles en 2 points ou les modèles stochastiques Lagrangiens fondés sur une équation du type équation de Langevin. Nous utilisons ici la Vélocimétrie par Images de Particules (VIP) pour effectuer de telles mesures du fluide au sein d'une turbulence de grille dans l'eau. Cette turbulence est similaire à celle, étudiée par Comte-Bellot et Corrsin (1971) [1] (GCBC) dans l'air avec 2 sondes à fils chauds. La première sonde était fixée au premier point de mesure x, pour la mesure ponctuelle de vitesse à l'instant t. La seconde sonde, permettait la mesure de la vitesse au point $x + \overline{U}\Delta t$, déduit comme la distance Δx parcourue par le fluide le long de l'axe du tunnel à la vitesse moyenne $\overline{U}$, un instant T après le temps t. Dans l'expérience présentée ici, nous utilisons 2 systèmes PIV synchronisés. Notre technique de mesure est non intrusive et nous obtenons des mesures en des points plus proches (70 μm) que GCBC (3 mm au mieux). Nous réalisons des statistiques d'ensemble et non temporelle (fil chaud). Nous présentons la validation de l'expérience utilisée, les conditions d'écoulement, la corrélation obtenue et les informations déduitent sur un temps

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caractéristique de la turbulence. Nous comparons les résultats à ceux issus des mesures de GCBC et de celles de Schlien and Corrsin (1974) [2] (SC).

1. Introduction

Few experiments were carried out for obtention of shifted two points two times velocity measurements or Lagrangian time scale in homogeneous decaying turbulence for fluid. GCBC [1] used, in air, the hot-wire anemometry for measuring velocity fluctuations. Their work was concerned by two point two time measurements and the existence of universality of the deduced turbulent time scales associated to the turbulent scales. They obtained Eulerian velocity autocorrelation in time by the correlation at a fixed spatial point translating with the mean flow. Snyder and Lumley [3] were the first to publish usable (from a theoretical or computational point of view) Lagrangian autocorrelation and time scale results for inertial particles but not for fluid. They obtained time related to solid particles of various density and size transported by a decaying homogeneous (DT). They used numerous camera aligned along their channel axis with a global illumination. This last point provided an uncertainty as this introduced bias error of projection in the plane of recording. The best way to obtain a characteristic turbulent scale close to Lagrangian one was the work by SC [2] that deduced it from heat dispersion measurements behind a heated wire stretched across a wind tunnel. For this, they assumed self preservation of Lagrangian statistics. Sato and Yamamoto [4] did, for DT, direct measurements of Lagrangian autocorrelation, with an optical technic. Their measurements were too close from the grid or with particles too large compared to Kolmogorov scale to be usable as fluid Lagrangian statistics. At the best of our knowledge, there is not existing shifted two point two time or Lagrangian measurements in decaying turbulence (DT) with non-inertial particle by use of visualization technic. It is thus interesting to compare velocity correlation from shifted two points two times PIV measurements with the one of GCBC [1] and the Lagrangian autocorrelation deduction by SC [2] as PIV has other advantages compare to hot-wire anemometry. In the present work, as the works above, the main flow is decaying turbulence DT. We used Particle Image Velocimetry (PIV) to do two times two points velocity measurements as GCBC [1]. The first CCD camera was fixed and focused in a first point x along the axis whereas the second CCD camera was focused at point $(x+\bar{U}\Delta t)$ where $\bar{U}$ is the mean longitudinal velocity of the main flow. The main difference with the measurement technic used by GCBC is the fact that hot-wire measurements are time resolved signal whereas PIV is spatial resolved. It has also to be noted, without any details, that PIV allow to track particles that are used for velocity determination at the position x (in the limit of their disappearance from the sheet of light) and thus could lead to Lagrangian velocities. The PIV allows also to obtain points spatially closer each together than the ones obtained by hot-wire anemometry as there is no influence, of the first measurement point, on the other one.

2. Experimental set-up

The experiment was carried out in a water channel of 7 m long, and 20 cm $\times$ 20 cm cross-section. A grid of 1 cm mesh size was disposed upstream to generate an homogeneous turbulence along the channel flow. The solidity of the grid is 0.44. The mean velocity was $\overline{U}$ equal to 1.2 m/s. The corresponding mesh Reynolds number is 14 000. The turbulence level was about 2% of the mean velocity at the location $\frac{X}{M}=50$.

The turbulent Reynolds number Re_λ is 35 at this location. Fig. 1 shows the fluctuation power spectrum of the longitudinal velocity, $E_{11}(k_1)$, at location $\frac{X}{M}=50$ versus wave numbers k_1, dimensionalised by k_η the wavenumber corresponding to Kolmogorov length scale. It exhibits a small inertial $\frac{-5}{3}$ power law region.

Fig. 2 shows the turbulence intensity decay of the fluctuations of the longitudinal velocity. This exhibits a -1.22 power law ($\frac{u'^2}{U_e^2}=3.8*10^{-2}(\frac{X}{M})^{-1.22}$). These two results show that the flow has a behavior corresponding to homogeneous decaying turbulence.

3. Measurement methods

We used here the Particle Image Velocimetry (PIV) [5] to determine the velocity field of the flow. We had two synchronized Lavision PIV systems. The two CCD cameras were PCO 1200 cameras with $1280*1024$ pixels on the $6.7\ \text{mm}*6.7\ \text{mm}$ CCD sensor. On the CCD cameras were mounted 60 mm macro lenses. We used fluorescent particles of 10 μm diameter [6]. An high pass-band filter of minimal wavelength $\lambda_r=560$ nm was mounted on the lenses of the CCD cameras. This allowed to eliminate the noise due to illumination wavelength $\lambda_r=532$ nm from the Yag lasers and to record only light emitted from the seeding particles. Thus the particle images were about two pixels of diameter. The total recorded area has 3 cm $\times$ 2, 4 cm size corresponding to three integral scales. The analysis was done with a window of 64×64 pixel and last development of the Lavision software (adaptive mesh and image deformation accounting, in an iterative process the local velocity, ...). The window of analysis corresponded to 1.5 mm $\times$ 1.5 mm. That is few times the flow Kolmogorov scale size η_k which is equal to 146 μm at station $\frac{X}{M}=50$ of our flow. Contributions to the total error include:

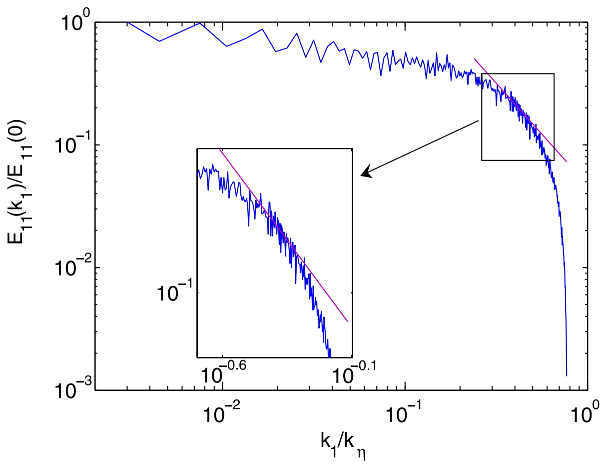

Fig. 1. Power spectrum of flow for $Re_\lambda = 35$ at $\frac{X}{M} = 50$. Non-dimensionalised energy $E_{11}(k_1)/E_{11}(0)$ versus $\frac{k_1}{k_\eta}$ compared with $\frac{-5}{3}$ power law.

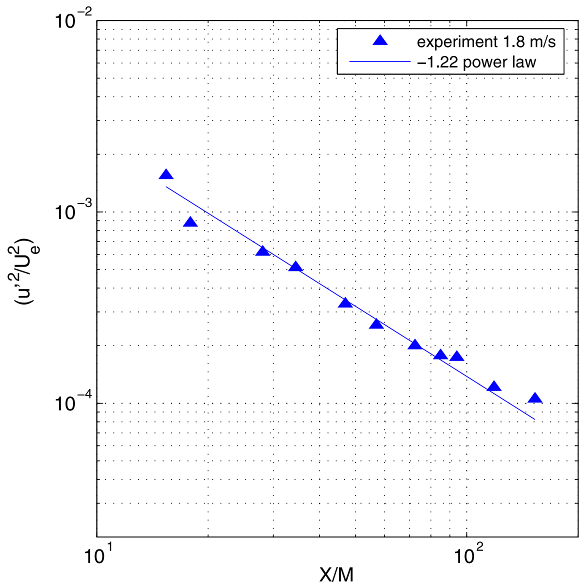

Fig. 2. Turbulence intensity decay of the fluctuations of the longitudinal velocity.

(1) classical PIV errors that have been discussed in [7–11] and more recently in [12] for acceleration and
(2) plane shifting and camera adjustment (magnification, ...) errors.

The present turbulence is "ideal" for PIV measurements as there is small instantaneous velocity gradients and as the low level of turbulence leads to negligible out-of-plane errors. We fixed experimental recordings in order to have diameter of the particle images about 2 pixels, to avoid peak locking error. This is confirmed on Fig. 3 that demonstrates no wavy shape that would be characteristics of peak locking error. For the same $X/M = 50$ location and for $\Delta X/M = 0$, with experimental conditions identical to the present DT, the difference between turbulence intensity obtained from both camera was less than 0.05%. From our experimental conditions, sub-pixel accuracy is about 0.5%. The main errors are due to the second contribution. The positioning of the second CCD camera at $(x + \bar{U}\Delta t)$ was different in the range $\Delta X/M = 0$ to $\Delta X/M = 4$ compared to the range $\Delta X/M = 4$ to the largest $\Delta X/M$. For the first range, the 2nd CCD camera was adjusted manually to match at the best the exact Eulerian position corresponding to the convected turbulent box. This was done in live before recording images. This was possible by superposing particle images, recorded with the second CCD camera at position $(x + \bar{U}\Delta t)$ and at time $(t + \Delta t)$, on particle images recorded by the first CCD camera at position (x) and time t. Indeed the turbulence was low enough to maintain, in the same longitudinal plane, the main part of the particles, present on the first CCD camera at time t, to the second one at time $(t + \Delta t)$. This procedure ensures PIV analysis with mesh positioned exactly where it has to be with 2 or 3 pixels of error, compared to the first one, in an Eulerian point of view. Velocity obtained with image shifted of 2 or 3 pixels is negligible. For the 2nd range this was not possible. Turbulence accumulates removing

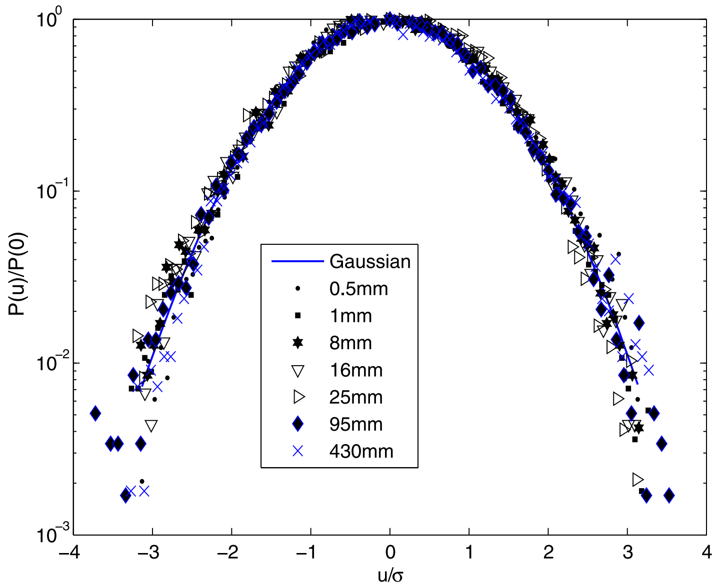

Fig. 3. Probability density function of longitudinal component of the velocity fluctuations for different stations from $X/M = 50$ to $X/M = 93$.

particles outside the plane for the second CCD camera, thus recognition was very difficult. In the first part the adjustment implies less than 2% error. For the 2nd range, PIV analysis implies to locate a mesh, for PIV analysis, with an uncertainty of half a mesh size. This uncertainty corresponds to the error in determining exactly the position $(x + \bar{U}\Delta t)$ where to locate the second CCD camera. A further PIV test was done with meshes of half size. Results were compared with velocity field obtained with plain size meshes. This produces an error about 6%. This error could be decreases in selecting the PIV grid analysis to the location corresponding to the maximum of the correlation. This implies to apply PIV analysis in every point of the mesh for every mesh. This corresponds to 64^2 more computational time for every point and separation location and is thus difficult to obtain. The total error is thus less than 3% for the first range and less than 8.5% for the 2nd range. Error bars were added on Fig. 4 only for $X/M = 50$ points for clarity.

4. Results

Fig. 3 shows the probability density functions (pdf) of the longitudinal velocity fluctuation field from the station $\frac{X}{M} = 50$ to the station $\frac{X}{M} = 93$. This pdf exhibits a clear Gaussian curve that corresponds to previous results in such flow.

We now present the 2 times 2 points shifted correlation (1) of the longitudinal velocity fluctuations:

$$R_{11}(x, x', t, t') = \frac{\overline{u(x,t) * u(x',t')}}{\sigma_u(t) * \sigma'_u(t')} \tag{1}$$

where $\overline{()}$ is the mean over the set of samples. the fluctuations of longitudinal velocity at point x and time t is $u(x,t)$ and those at point x' and time t' is $u(x',t')$. The root mean square of these fluctuations for (x,t) and (x',t') are respectively $\sigma_u(t)$ and $\sigma'_u(t')$.

On Fig. 4(a) we have compared the two times two points shifted correlations obtained by GCBC [1] and the ones from the present work at stations $\frac{X}{M} = 50$, $\frac{X}{M} = 70$ and $\frac{X}{M} = 90$. It has to be noted that GCBC [1] have corrected their results from the separation position $\frac{\Delta X}{M} = 0.4$ to $\frac{\Delta X}{M} = 8$. They did this to account for the wake of the upstream hot-wire. Here $t - t' = \Delta t = \frac{\Delta x}{\bar{U}}$ thus $t' = t + \frac{\Delta x}{\bar{U}}$ and we plot $R_{11}(x, x + \Delta x, t, t + \frac{\Delta x}{\bar{U}}) = f(x, \Delta x)$ due to stationarity. They obtain greater values than those obtained in previous works in the literature and explained this, due to their correction. Our measurements at the distances $\frac{\Delta X}{M} = 0.1$ and $\frac{\Delta X}{M} = 0.2$, for the station $\frac{X}{M} = 50$, and at the distance $\frac{\Delta X}{M} = 0.2$, for the station $\frac{X}{M} = 70$, are a few percent lower than the possible curve extrapolation from the measurements at greater distances of GCBC. Due to the previous above error review and due to Fig. 4(b) we think that this is due to barrels of the grid. It is shown on Fig. 4(b), the same quantity plot for the same but loaded case (done and not presented here). This curve is obtained in the same experimental conditions, for the same fluorescent particles used for PIV and for the same PIV analysis. The single difference is the presence of solid particles loading the main flow (few percents). Solid particles were not visible on PIV images as they were not fluorescents. From a metrological point of view the case is identical to the one presented here. On this curve the values of points for the distances $\frac{\Delta X}{M} = 0.1$ and $\frac{\Delta X}{M} = 0.2$, for the station $\frac{X}{M} = 50$, didn't exhibit such lower values. This proves that no bias errors are responsible for the lower values in unloaded flow case. For our present unloaded flow case we did supplementary measurements (Fig. 4(a)). This behavior persists for any station at the same distance as demonstrated

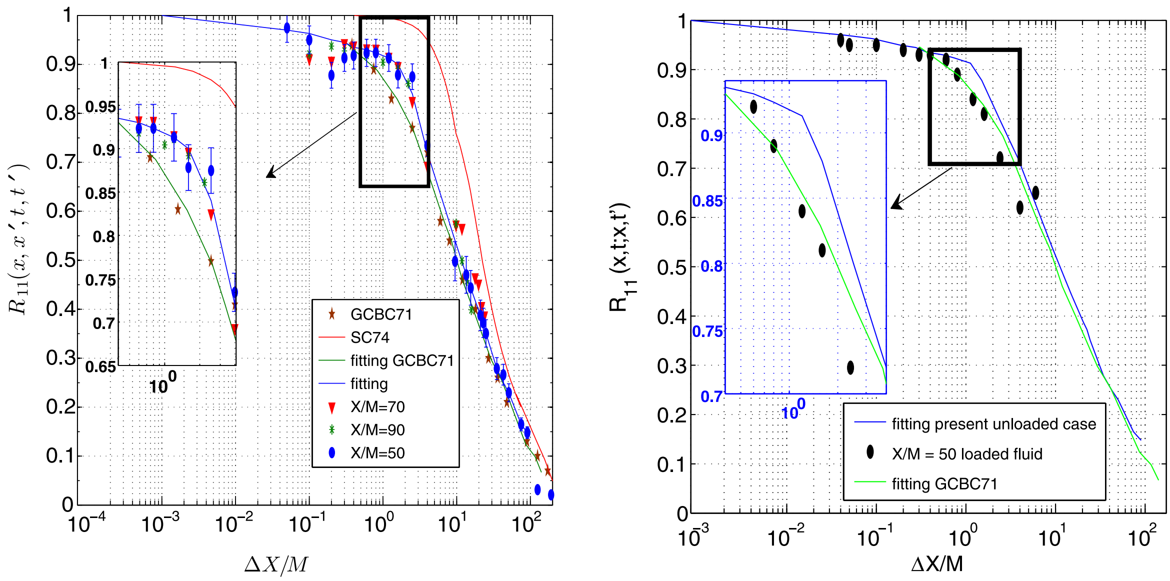

Fig. 4. (a) The two time two point correlations of the fluctuations of longitudinal velocity at the stations $\frac{X}{M} = 50$, $\frac{X}{M} = 70$, $\frac{X}{M} = 90$, GCBC [1] and SC74 Lagrangian data. A zoom is done on the "bump". (b) idem as previously with only $\frac{X}{M} = 50$ for loaded fluid and GCBC [1] Eulerian data and SC74 Lagrangian data.

on Fig. 4(a) for stations $\frac{X}{M} = 70$ and $\frac{X}{M} = 90$. Such behavior disappears gradually from $\frac{X}{M} = 50$ to $\frac{X}{M} = 90$. We don't explain such behavior but suspect some fine scale memory effect from grid barrels. Whatever the elsewhere results have a greater values than GCBC [1] from distances $\frac{\Delta X}{M} = 0.4$ to $\frac{\Delta X}{M} = 8$. Thus, even greater than previous works at that time (Favre, Caviglio and Dumas in [1]), their values were underestimated in this separation range. From this results we can evaluate the turbulent integral time scale $T(x,t)$ from the following equation:

$$T(x,t) = \int_0^\infty R\left(x, t, x + \Delta x, t + \frac{\Delta x}{\bar{U}}\right) \mathrm{d}\Delta x \tag{2}$$

We obtain an integral scale 6.5% greater than the one of GCBC from $\frac{\Delta X}{M} = 0.38$ to $\frac{\Delta X}{M} = 90$. It is to note that SC [2] give a Lagrangian time integral scale about 30% larger than that of the Eulerian correlation (Eq. (2)) of GCBC. The decrease of the correlation further downstream is faster than expected from their measurements. It has to be noticed here that our correlation curve has a similar shape and closer values to those of the deduced Lagrangian correlation curve presented by SC [2] than GCBC [1]. Particularly we have a bump, compare to the curve of GCBC [1], in the range from $\frac{\Delta X}{M} = 0.6$ to $\frac{\Delta X}{M} = 4$. In this zone our error is about 3%. The uncertainty of our measurements is low enough to confirm that correlation in this zone was underestimated by GCBC [1]. Furthermore in this zone GCBC [1] extrapolate their values. Thus their extrapolation underestimates the real value. GCBC [1] explained the problem of first probe wake due that interferes with measurements of the 2nd probe in the range $\frac{\Delta X}{M} = 0$ to $\frac{\Delta X}{M} = 8$. Their measurements were corrected by extrapolation that implies values at least about 10% more than their direct measurements. It has also to be noted that their non-corrected values are about 3% higher than previous works at this time (curve of Favre, Caviglio and Dumas in [1]). Nevertheless they detailed others kind of errors as intrinsic noise of the tunnel, acquisition, recording tapes ... that could give about 5% error. Nevertheless these errors don't explain that they didn't obtain the bump that we describe from our results in the range $\frac{\Delta X}{M} = 0.38$ to $\frac{\Delta X}{M} = 4$.

5. Conclusions

The present work concerns with two times two points shifted measurements of the longitudinal fluid velocity inside an homogeneous decaying turbulence. After presenting various results characterizing our flow, we present the corresponding velocity fluctuation correlations at three stations $\frac{X}{M} = 50$, $\frac{X}{M} = 70$ and $\frac{X}{M} = 90$. We compare these results to those by GCBC [1] with a description of measurement errors. We show results with measurement distances that are shorter than in their work, that is an advantage of PIV compare to the hot-wire anemometry. We exhibit for every point, in the range from $\frac{\Delta X}{M} = 0.6$ to $\frac{\Delta X}{M} = 4$, greater values for the correlation curve. The trends is similar to the Lagrangian deduction by SC [2] in this range, even amplitude is lower. We deduce from our results a greater integral turbulent time scale than the one deduced by GCBC. At the best of our knowledge such results don't exist for homogeneous decaying turbulence. Such measurements have two objectives:

(1) improvement of the knowledge of the turbulent integral time scale and
(2) determining in what extent universality exist in function of the spectral wave numbers (as done by GCBC).

Even if these measurements are not Lagrangian ones, these two times two points shifted velocity measurements tend to, for the small distances at every station. This is due to PIV analysis as demonstrated with comparison to SC [2] results. This demonstrates also that Lagrangian time scale for homogeneous decaying turbulence is not so far of the Eulerian time scale deduced from two times two points shifted measurements. This will be of great help for models as the LES combined stochastic modelling by Wei et al. [13] or Vinkovic et al. [14,15]. For the next future we will present the same work as GCBC about filtering the velocity field in the Fourier space to determine, if it exists, universality of the turbulent time scales. We note that the Fourier filtering in our case will be spatial one whereas for GCBC it was time filtering. For small space separations the achievement of PIV technic allows, with the present measurements, tracking till the 2nd CCD camera location of particles, used for velocity determination at location of the first CCD camera. This would lead to Lagrangian velocity and acceleration measurements. This is not yet presented as this necessitates huge supplementary analysis and computation time (about 64^2 times) to follow exactly the particles at the second location $x(t + \Delta t)$. From the Eulerian point of view this work can help to improve Eulerian modelling for turbulence in two point two time [16].

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