REYNOLDS NUMBER DEPENDENCIES IN CLASSICAL GRID TURBULENCE

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Abstract We measured inertial and dissipation range statistics in the decaying turbulence generated by a bi-planar grid of crossed bars in a wind tunnel. We did so at Taylor Reynolds numbers between 60 and 1700, reaching higher than any previous experimental study of homogeneous and isotropic turbulence. The measurements were made in the Variable Density Turbulence Tunnel (VDTT) at the Max Planck Institute in Göttingen with both traditional hot-wire anemometers and nano-fabricated NSTAP anemometers developed at Princeton University. The data confirm that even when the large-scale conditions are controlled as the Reynolds number is raised, scaling ranges are not well-defined unless Extended Self-Similarity is employed. We also find a universal transition between the inertial and the near-dissipation ranges.

VARIABLE DENSITY TURBULENCE TUNNEL

The objective of our study is to describe the small scales of turbulence and their universal features, if they exist. A statistical description of the small scales is known to depend not only on the Reynolds number, but also on the large scales [3]. In order to isolate the Reynolds number dependence, we generated turbulence in an apparatus with fixed geometry, and varied the Reynolds number by changing the viscosity of the fluid. The VDTT was designed to make this possible through variation of the density of the working fluid.

To control the density of the working fluid, the pressure in the VDTT was set to values between 1 bar and 15 bar. The tunnel was filled with both air and sulfur hexafluoride, which is a heavy gas. The test section in the VDTT was 8.8 m long, and 1.5 m wide. The mean flow speeds were 1.7 m/s, 2.6 m/s and 4.2 m/s. We used two grids of classical construction [5], one with a mesh spacing of 107 mm, and the other with a spacing of 160 mm. These configurations produced Taylor Reynolds numbers up to 1700.

These high Reynolds number lead to small Kolmogorov scales η down to 20 μm. As commercial hot-wire probes are at least 500 μm long, they are not suited to measurement of small-scale statistics in this flow. Because NSTAPs (Nano-Scale Temperature Anemometer Probes) developed at Princeton University are as short as 30 μm, we could extend our study to the smaller scales present in the VDTT. We use the probes to look at both the inertial and near-dissipation ranges of the flow.

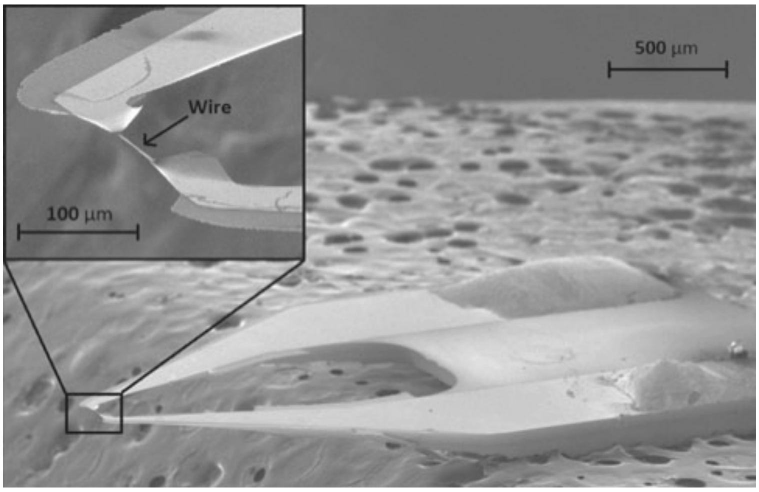

Figure 1. A scanning electron microscope image of the design of an NSTAP developed at Princeton University that resolves the small scales of the turbulence in the Variable Density Turbulence Tunnel [1].

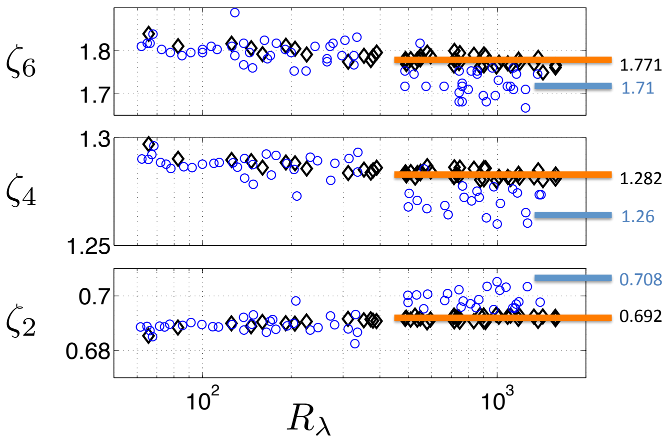

Figure 2. The Reynolds number dependence of selected Extended Self-Similarity exponents in the VDTT. Our grid turbulence data (black diamonds) compare favorably to the data gathered by Pearson et al. [7] in grid turbulence, wakes and jets. At high Reynolds numbers, we find 0.692, 1.282 and 1.771 for the 2nd, 4th, and 6th order exponents, respectively. These should be contrasted with the values 0.708, 1.26, and 1.71 found by Sreenivasan and Dhruva [9], which are indicated by blue lines in the figure. We provide an explanation for the discrepancy between our values and theirs.

EXTENDED SELF-SIMILARITY

As is well known, there is reason to expect scaling in the inertial-ranges of the structure functions with the following form [6]

$$S_n\left(r\right) = C_n\left(\langle\varepsilon\rangle\, r\right)^{n/3}\left(\frac{L}{r}\right)^{-n(n-3)\mu/18}. \tag{1}$$

Unfortunately, the scaling is not well defined in experimental data. If, however, one expresses the n-th order structure functions in terms of the third-order structure function, $S_n \propto S_3^{\zeta_n}$, one finds an extended scaling region [2]. This is the so-called Extended Self-Similarity (ESS) technique of obtaining inertial-range scaling exponents. As seen in Fig. 2, these exponents are both highly reproducible and nearly independent of the Reynolds number in the VDTT.

SMALL-SCALE INTERMITTENCY

Of considerable interest is the dependence of intermittency on the Reynolds number. A convenient and widely-used way to quantify the nongaussianity of turbulence is by the velocity-derivative flatness [8]. Through the velocity-difference flatness, $F(r) = S_4/3S_2^2$, we find empirically a connection between inertial- and dissipation-range intermittency reminiscent of the one proposed theoretically by Chevillard et al. [4]. Specifically, the slope of the near-dissipation-range inflection point in $F(r)$ is three times the slope of $F(r)$ in the inertial range, independent of Reynolds number. This feature raises the interesting possibility that the derivative flatness could be recovered through the knowledge of the inertial range flatness.

References

[1] S. C. C. Bailey, G. J. Kunkel, M. Hultmark, M. Vallikivi, J. P. Hill, K. A. Meyer, C. Tsay, C. B. Arnold, and A. J. Smits. Turbulence measurements using a nanoscale thermal anemometry probe. *Journal of Fluid Mechanics*, **663**:160–179, 2010.

[2] R. Benzi, S. Ciliberto, R. Tripiccione, C. Baudet, F. Massaioli, and S. Succi. Extended self-similarity in turbulent flows. *Physical Review E*, **48**:29–32, 1993.

[3] D. B. Blum, G. P. Bewley, E. Bodenschatz, M. Gibert, A. Gylfason, L Mydlarski, G. A. Voth, H. Xu, and P. K. Yeung. Signatures of non-universal large scales in conditional structure functions from various turbulent flows. *New Journal of Physics*, **13**:113020, 2011.

[4] L. Chevillard, B. Castaing, and E. Lévêque. On the rapid increase of intermittency in the near-dissipation range of fully developed turbulence. *Eur. Phys. J*, **45**:561–567, 2005.

[5] G Comte-Bellot and S. Corrsin. The use of a contraction to improve the isotropy of grid generated turbulence. *J. Fluid Mech.*, **25**:657–682, 1966.

[6] A. N. Kolmogorov. A refinement of previous hypotheses concerning the local structure of turbulence in a viscous incompressible fluid at high reynolds number. *Journal of Fluid Mechanics*, **13**:82–85, 1962.

[7] R. A. Pearson, B. R. anf Antonia. Reynolds-number dependence of turbulent velocity and pressure increments. *Journal of Fluid Mechanics*, **444**:343–382, 2001.

[8] K. R. Sreenivasan and R. A. Antonia. The phenomenology of small-scale turbulence. *Annual Review of Fluid Mechanics*, **29**:435–472, 1997.

[9] K. R. Sreenivasan and B. Dhruva. Is there scaling in high-reynolds-number turbulence? *Progress of Theoretical Physics Supplement*, **130**:103–120, 1998.