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A multiscale characterization of turbulence based on information theory

Carlos Granero-Belinchon^{*†}, Stéphane G. Roux[‡], Nicolas B. Garnier[‡],

We propose a multiscale statistical characterization of a stochastic process X_t based on Shannon information theory. First, we analyse the entropy of the increments of the stochastic process, $H(\delta_\tau X_t)$. It measures the information contained at the scale τ as defined by the increment $\delta_\tau X_t = X_t - X_{t-\tau}$. Second, we study the entropy rate $h^{(\tau)}(X_t)$ of the process, *i.e.* the extra information in the variable at time t that is not present at time $t - \tau$. These two quantities provide very similar, but not identical, characterizations of the dependences of the stochastic process. Finally, we introduce an index $\Delta^{(\tau)} = H(\delta_\tau X_t) - h^{(\tau)}(X_t)$ that focus on the difference between the two previous characterizations and quantifies the regularity and stationarity of the process. By varying the scale τ , these three quantities can explore a full range of scales. We thus obtain three multiscale characterizations that are not restricted to specific statistical moments of the density distribution, nor to the covariance, but that probe the complete dependence structure of the process.

We propose a new vision on the self-similarity of turbulence based on these concepts. We study experimental turbulent velocity signals from channel flows at different Reynolds numbers. On the one hand, both $H(\delta_\tau X_t)$ and $h^{(\tau)}(X_t)$ characterize the distribution of information across the scales of turbulence and allows us to estimate the Hurst exponent of the velocity signals in agreement with the Kolmogorov 1941 theory¹². On the other hand, $\Delta^{(\tau)}$ illustrates the non-stationary behavior at the small scales of turbulence with a transition to stationarity at scales of the order of the integral scale³. Very interestingly, $\Delta^{(\tau)}$ presents an universal behavior that is independent of both the experimental setup and the Reynolds number of the flow.

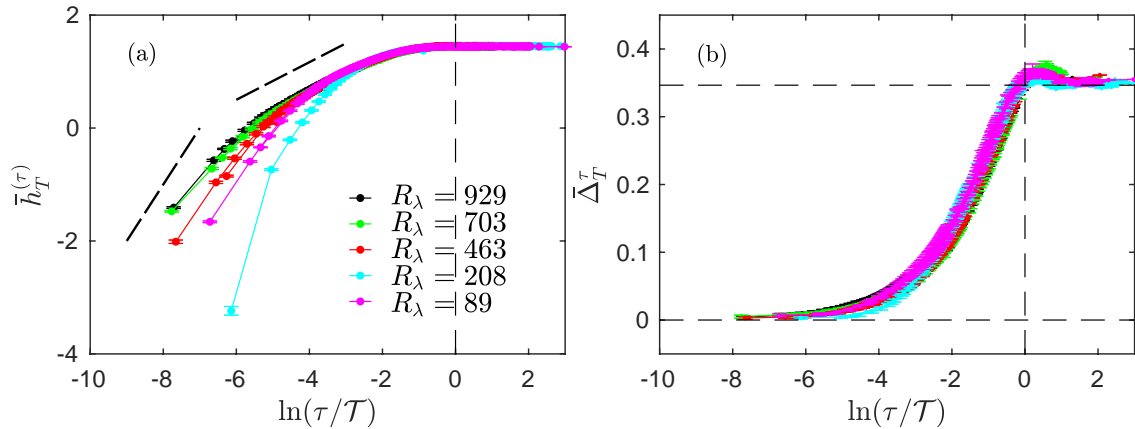


Figure 1: Entropy rate $h^{(\tau)}$ (a) and index $\Delta^{(\tau)}$ (b), in function of the analysed scale τ for experimental velocity measures of jet turbulence at different Reynolds numbers. The dotted straight lines in (a) have slopes 1 and 1/3. The horizontal dashed lines in (b) correspond to the values 0 and $\ln(\sqrt{2})$.

^{*}Department of Mathematical and Electrical Engineering, IMT Atlantique, Lab-STICC, UMR CNRS 6285, 655 Av. du Technopôle, Plouzané, 29280, Bretagne, France.

[†]Odyssey, Inria/IMT Atlantique, 263 Av. Général Leclerc, Rennes, 35042, Bretagne, France.

[‡]ENS de Lyon, CNRS, Laboratoire de Physique, 46, allée d'Italie, Lyon, F-69364, Rhône-Alpes, France

¹C. Granero-Belinchon et al., *EPL* **115**, 58003, (2016).

²C. Granero-Belinchon et al., *PRE* **97**, 013107 (2018).

³C. Granero-Belinchon et al., *Entropy* **12**, 1609, (2021).