Extreme events and metastability in transitional shear flows

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Transition to turbulence in shear flows is characterized by intermittent laminar-turbulent patterns that statistically proliferate or collapse depending on the Reynolds number. In pipe, channel or plane Couette flow, those turbulent puffs (or bands) either decay to an absorbing state or proliferate via a process known as splitting. Both are effectively memoryless processes associated with large mean first passage times. The lifetimes are found to depend super-exponentially on the Reynolds number and lead to crossing Reynolds number above which proliferation is more likely than decay. However, the determination of those lifetimes requires numerous long-time direct numerical simulations.

We therefore apply a rare event algorithm, the Adaptative Multi-level Splitting (AMS) [1], to the deterministic Navier-Stokes equations to study the transition paths and estimate large time scales with a reduced cost. The numerical domain is tilted with respect to the streamwise direction, thus controlling the obliqueness of the turbulent pattern and limiting complex 2D interactions between bands. Trajectories are selected via an importance function that describes the distance from a flow state to the one-band or two-band attractor. The choice of this function is crucial for the convergence of the algorithm towards the time scale previously computed with direct simulations [3]. The AMS was already used for a stochastic model of transitionary flows with similar metastable properties [2], and opens new possibilities for computing passage times in different flow situations (large 2D domains, different shear profiles...).

Splitting or decay events approach a most-probable pathway or instanton which paves the way for an out-of-equilibrium description of transition to turbulence. Pathways are intrinsically linked with nucleation processes that approach and leave an edge state in the phase space. Those transitions between metastable states can be described by the theory of extreme values, as initially suggested by Goldenfeld *et al.* [4] and recently demonstrated by Nemoto & Alexakis [5]. The connection between fluctuations within the turbulent region and Fisher-Tippett distributions accounts for the super-exponential dependence with the Reynolds number. We show that the process of turbulent band spreading and splitting throughout a laminar domain also enters this description.

References

1. F. Cérou, A. Guyader & M. Rousset, Adaptive multilevel splitting: Historical perspective and recent results, *Chaos*, **29**, 043108 (2009).
2. J. Rolland, Extremely rare collapse and build-up of turbulence in stochastic models of transitional wall flows, *Phys. Rev. E*, **97**, 023109 (2018).
3. S. Gomé, L. Tuckerman & D. Barkley, Statistical transition to turbulence in plane channel flow, *Phys. Rev. Fluids*, **5**, 083805 (2020)
4. N. Goldenfeld, N. Guttenberg & G. Gioia, Extreme fluctuations and the finite lifetime of the turbulent state, *Phys. Rev. E*, **81**, 035304(R) (2020).
5. T. Nemoto & A. Alexakis, Do extreme events trigger turbulence decay?–a numerical study of turbulence decay time in pipe flows, *J. Fluid Mech.*, **912** (2021).