ARE STEADY TURBULENT STATES FORCING-DEPENDENT ?

Brice Saint-Michel[1], Bérengère Dubrulle[1], Éric Herbert[1] & François Daviaud[1]
[1] *CEA, IRAMIS, SPEC, Laboratoire SPHYNX*

Abstract We experimentally study the influence of the forcing nature on the stability of steady states reached in a turbulent swirling flow (von Kármán flow). We can impose either the *torque* or the *speed* of the two counter-rotative impellers stirring the fluid. Speed control experiments display steady states exhibiting a torque hysteresis, vanishing in torque control at the benefit of multi-stable dynamics inside the (formerly) hysteresis forbidden zone. We suggest a possible connection of this effect with *ensemble inequivalence*, a characteristic phenomenon observed in long-range interacting (LRI) systems.

A HYSTERESIS CYCLE ?

Turbulent systems are intrinsically out of equilibrium, and tend to display long-range interactions. Thus, they have no reason to respect the symmetries of their forcing. It is yet generally accepted that symmetries are 'statistically' restored in turbulence. Von Kármán swirling flows are good models to generate fully-developed turbulence in a compact set-up: in a cylindrical vessel, fluid is stirred by two counter-rotating impellers with eight curved blades. Though, when the impeller speeds (f_1, f_2) are imposed, von Kármán flows might display either continuous transitions or hysteretic behaviour [2, 3, 6] depending on the rotation direction. In the latter case, when the Re exceeds the transition to turbulence [5], the steady states are found to depend on the history of the system, three turbulent states with very different torques (C_1, C_2) being – at least marginally – stable for perfectly symmetric forcing.
We have recently investigated the effect of the forcing nature on this system: we can now impose either the *speed* of the impellers or the *torque* applied to them. Speed control experiments keep $f = f_1 + f_2$ constant, to set the control parameter:

$$\theta = \frac{f_1 - f_2}{f_1 + f_2}$$

θ is therefore the reduced impeller speed difference. The observed system response is then the reduced impeller *torque*, γ:

$$\gamma = \frac{C_1 - C_2}{C_1 + C_2}$$

In contrast, *torque* control experiments keep $C = C_1 + C_2$ constant, and allows us to choose any γ in fig. 1 while θ is free to evolve. It is then possible to enter the former hysteresis cycle and examine what happens to θ in this region.

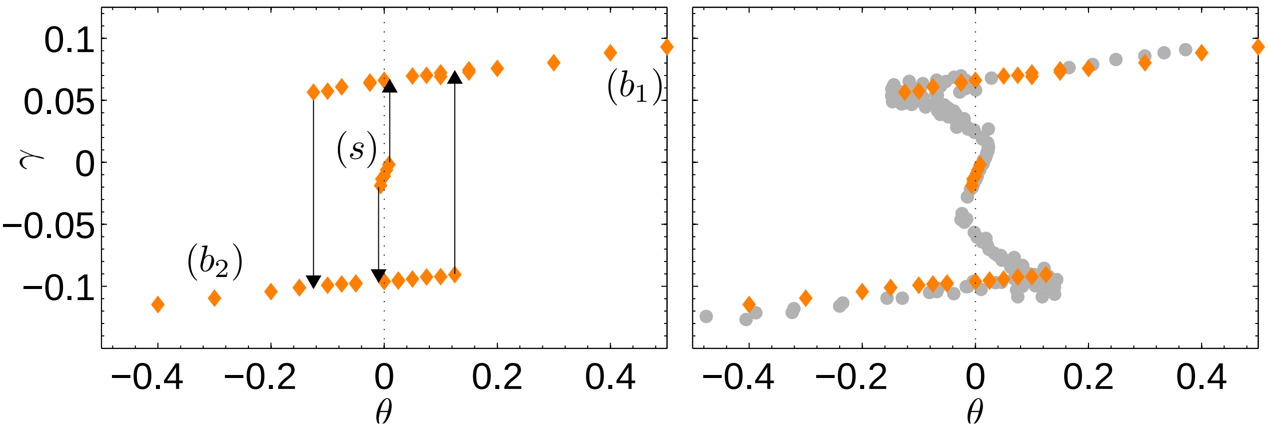

Figure 1. Diagrams of the reduced torque difference $\gamma = \frac{C_1 - C2}{C_1 + C_2}$ as a function of the reduced speed difference $\theta = \frac{f_1 - f_2}{f_1 + f_2}$. *Left* : for *speed* control (orange ⋄), the central branch, (s) is marginally stable and cannot be reached one left. For $\theta = 0$, three very distinct flows can be achieved depending on the history of the system. (*Right*), torque control: the hysteresis cycle vanishes, new multi-stable regimes connecting the steady branches (grey •). Speed control results are recalled for comparison.

It is possible to attain the previously-existing branches (s), (b_1) and (b_2) in torque control. In this case, the results observed in both controls are equivalent. Regardless of the control type, the injected powers are identical and steady, and the Particle Image Velocimetry (PIV) average flows are indistinguishable, provided that a sufficient number of samples are used for averaging.

SYSTEM DYNAMICS IN THE “FORBIDDEN" ZONE

However, for the torque control experiments inside the hysteresis cycle, steadiness is lost (see fig. 2) and the flow becomes multi-stable, transiting between a small number of attracting states, some of which are similar to (s), (b_1) and (b_2). We define the flow susceptibility as:

$$\chi = \frac{\partial \gamma}{\partial \theta}. \tag{1}$$

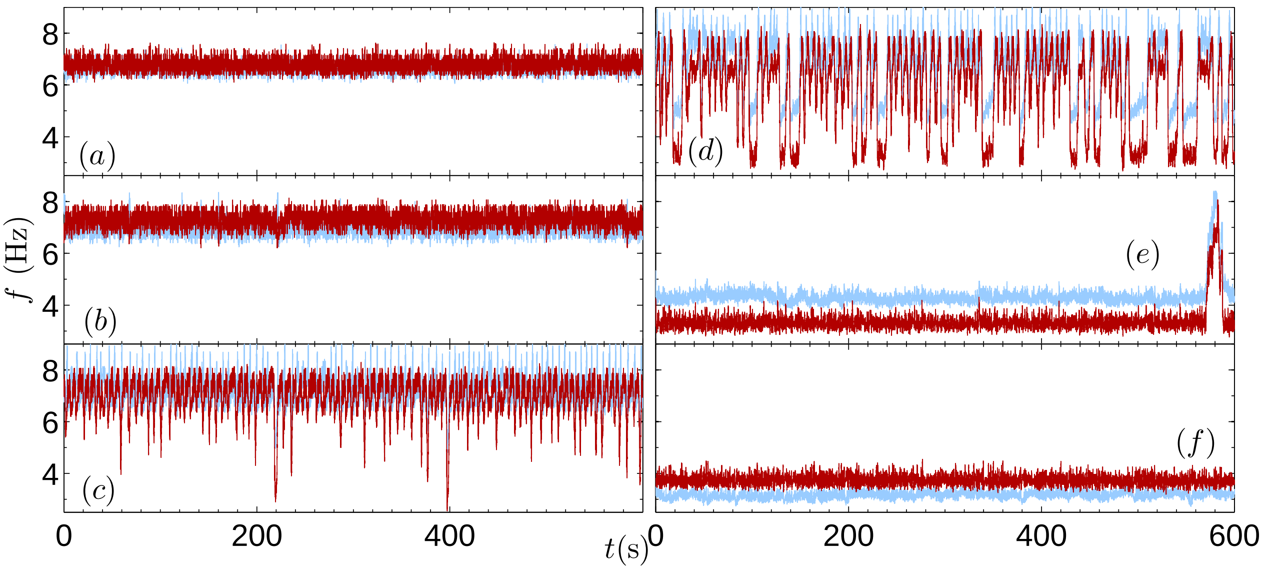

Figure 2. Temporal series of the speed of the bottom (light blue) and top (dark red) impellers in *torque control*, for decreasing values of γ starting from a symmetrical (a) experiment. Small oscillations escaping the fast-symmetrical attracting state are first observed (b), which quickly grow larger (c) to saturate in a multi-stable regime (d) where three quasi-steady states coexist. For higher asymmetries (e), the flow is nearly-stuck in the slow (b_1) state only to leave it during “rare events". The system eventually reaches the steady (b_1) branch.

In this region, χ is negative if we consider the time-average value of θ to be relevant. In addition, a new attracting state is found to be steady in the multi-stable regime, holding longer ($>$ 50 impeller revolutions) than any characteristic time scale of the experiment (see fig. 2 (d)). This new state, $(\tilde{i_1})$, does not exist in speed control. Such uncommon features are similar to what has been observed in long-range interacting systems [1, 4]. It therefore seems that our torque control is to some extent the equivalent of studying long-range interacting systems in the *micro-canonical* ensemble, whereas speed control might be a counterpart of the *canonical* ensemble for which $\chi \leq 0$ is, by construction, not possible. It also suggests that the energy injection mechanism alone might play a role stabilising specific flow configurations.

In this poster, we characterise these speed and torque states using PIV (local) and global impeller speed and torque measurements, and we present some features of the dynamics (transitions, distribution of events and time residences) observed in the multi-stable region of the hysteresis cycle.

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