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SPIRAL TURBULENCE :
LONG WAVELENGTH PATTERN OF TURBULENT SHEAR FLOWS

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Abstract

Since the first observation of "spiral turbulence" in Taylor-Couette flow, the "barber pole structure of turbulence" as used to call it R. Feynmann, remains one of the most striking feature of the Taylor-Couette flow. In this presentation, we describe careful experiments conducted in large aspect ratio Taylor-Couette and plane Couette flows. It is revealed that spiral turbulence does not only occur in Taylor-Couette flow but also has an equivalent in plane Couette flow. It is shown that spiral turbulence does not consist in a single turbulent helix on a laminar background, but actually is a long range periodical structure whose wavelength is large compared to the shear scale. Finally, investigating the transition from the fully turbulent flow to the "spiral turbulence" one, it is shown that the pattern actually results from a supercritical bifurcation of the homogeneous turbulent flow, in the same way as a nonlinear state would emerge from an homogeneous laminar state, following a classical Ginzburg Landau schema. Careful measurements allowed us to approach quantitatively the coefficients of the amplitude equation describing the pattern. To our knowledge, it is the first time that such a regular spatio-temporal pattern emerging from a turbulent basic state is observed.

Introduction

Spiral turbulence is usually described as alternating helical stripes of laminar and turbulent flow. There are a few quantitative studies of this puzzling regime and all previous studies [1,2,3,4,5,6] were limited by their relative small size. Only one helical turbulent strip, winding no more than twice along the cylinders axis, could be observed.

Performing new experiments in large aspect ratios flows, we show that spiral turbulence is a long wavelength periodic pattern for which we reveal for the first time an equivalent in plane Couette flow (PC). Study of this pattern and its dependence on Reynolds numbers in the Taylor-Couette flow (TC) lead us to propose to see it as the result of a supercritical instability of the homogeneous turbulent flow. This hypothesis is validated by the quantitative determination of coefficients of the Ginzburg-Landau equation which describes generically this type of instability.

After a brief presentation of the experimental set up, we describe the pattern observed in both plane Couette and Taylor-Couette flows. Then emergence of the spiral turbulence from turbulence is studied in the Taylor-Couette flow. Finally, the Ginzburg-Landau (G-L) equation coefficients are determined.

Experimental set up

PC apparatus already describe in [7], has been modified reducing gap size between plates down to d=1.5 mm. It has now aspect ratios Γ_x^{CP} = 385 and Γ_z^{CP} = 170 but uncertainty on determination of the Reynolds number $R^{PC} = Uh/\nu$ with h the ½ gap and U the speed of one plate, may reach 10%. However, at least at a semi-quantitative level, good comparison with TC flow can still be conducted.

Main part of this work has been realised in a TC apparatus characterised by the following parameters: the gap d = 0.872 mm, the radius ratio η = 0.983 and the aspect ratios Γ_θ^{CP} = 362 and Γ_z^{CP} = 442. A second one with d = 1.872 mm, η = 0.963 and Γ_θ^{CP} = 362 and Γ_z^{CP} = 442 allowed us to perform LDV measurements of velocity. Inner (resp. outer) Reynolds numbers are written $R_{i,o} = r_{i,o}\Omega_{i,o}d/\nu$. Both apparatus are thermalised. Flow visualisation is achieved by seeding it with kalliroscope flakes. The inner cylinder is recovered by a fluorescent film and the entire apparatus is lighted by two long UV neon lights parallel to the cylinders axis. Two plane mirrors reflect the two third of the flow hidden to the camera and the full flow image is reconstructed, (see [8] for more details).

Turbulent strips in PC & TC flows

Figure 1 and 2 display two snapshots of PC and TC flows for different Reynolds numbers values. In both cases tilted periodically spaced turbulent strips appear. In the plane Couette flow, they are stationary and are observed for $340 < R^{PC} < 415$. When $R^{PC} < 340$, the pattern is unstable and replaced by turbulent spots that disappear when $R^{PC} < 325$. Above $R^{PC} = 415$, the flow is fully turbulent.

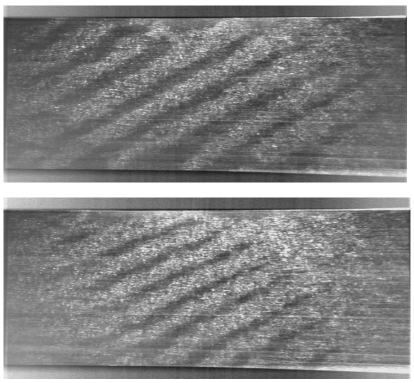

Figure 1: Turbulent strips in PC flow : (a) $R^{PC} = 384$, (b) $R^{PC} = 358$

In the Taylor-Couette flow, strips correspond to the “Spiral turbulence” regime. They are observed in the SPT area of the phase space diagram, presented on figure 3, which is qualitatively the same as the one done by Andereck et al. [4] with $\eta = 0.883$. As Van Atta in [2], the spiral rotates at the mean angular velocity of the two cylinders. LDV measurements show that spiral turbulence consist in a modulation of axial velocity component as well as of its fluctuations.

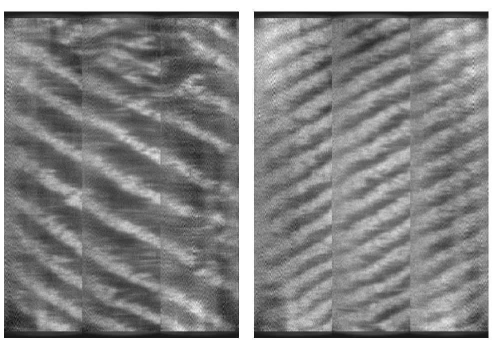

Figure 2: Turbulent strips in TC flow : : (a) $R_i = 703$ $R_o = -699$, (b) $R_i = 672$ $R_o = -699$

Following path E, where $R_i = -\eta R_o$, spiral turbulence is stationary. It gives us opportunity to make a comparison with PC flow. Indeed, along E both walls move in opposite direction at the same speed and flow is governed by only one Reynolds number. We define it in the same way in both flows, as the ratio of viscous time over shear characteristic time with length scale given by the ½ gap h . Thus $R^{PC} = Uh/\nu$ and $R^{TC} = R_i/(1+\eta)$. Beyond the remarkable visual resemblance between both patterns, measure of their geometrical properties as well as their dependence on the Reynolds number bring us clear evidence of an identical physical phenomena. In both cases but also in all spiral turbulence cases, the streamwise/azimuthal wavelength is a constant of the order of 50 times the gap. The spanwise/axial wavelength decreases with the Reynolds number.

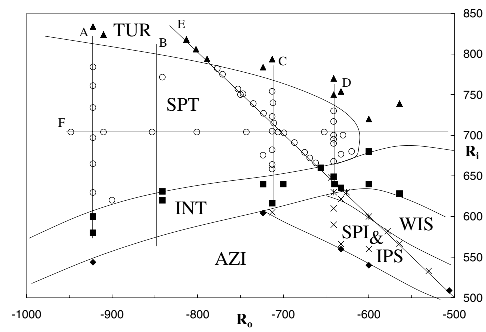

Figure 3: Zoom on the region of interest of the phase space diagram ($\eta = 0.983$). Solid straight lines show paths along which measurements are conducted.

Emergence of the spiral turbulence

In order to understand origin of the stripes pattern, we study its emergence from homogeneous turbulent flow when reducing the inner Reynolds number in TC flow. The TC case, experimentally well controlled, allow accurate and quantitative description of the transition. Moreover, benefiting by the periodicity of the pattern, we record light intensity along one line along the cylinders axis during time. When reducing R_i down from turbulent flow, a long wavelength modulation of light intensity, homogeneous in the turbulent regime, appears as soon as $R_i < R_i^c(R_o)$. Modulation amplitude increase as the square root of threshold distance $\varepsilon = |R_i - R_i^c|/R_i^c$, indicating a supercritical bifurcation. In that spirit, quench experiments are conducted : coming down from the fully turbulent state, R_i is instantaneosly dropped below R_i^c. The temporal growth rate of the wave that settles, increase linearly with ε. It confirms the scenario of a linear instability of the homogeneous turbulent state.

Description by a G-L equation

Does this wave of turbulence obey to a non-linear saturation as the one describe within the framework of Ginzburg-Landau equations ? Using Hilbert transformation on light intensity spatio-temporal diagram $I(z, t)$ we obtain its amplitude and phase which gives the local frequency and wavenumber [9]. Given that one may observe contra-propagating waves, two coupled CGL3 equations + noise are necessary [10]. We propose to test the description :

$$I(z,t) = A_L(z,t)e^{i(-k_0 z - \omega_0 t)} + A_R(z,t)e^{i(k_0 z - \omega_0 t)} + c.c.$$

where $A_{R,L}$ are complex amplitudes obeying to the two coupled CGL3 equations + noise for which we determine all coefficients for three outer Reynolds numbers R_o= -850, -1066 and -1200. The coefficients of the imaginary part of the equations equal zero in agreement with the former observation according to which the pattern propagation is completely governed by the mean angular velocity of the two cylinders. Our results are coherent and emphasise the pertinence of a description of spiral turbulence in terms of nonlinear pattern resulting of a supercritical instability of the homogenous turbulent flow. Our results are also in agreement with numerical simulations of two coupled real Ginzburg-Landau equations with additive noise.

Conclusions

In this study, existence of turbulent strips in plane Couette flow has been revealed. We have shown that this pattern and spiral turbulence are identical. This result call for the search of similar laminar-turbulent ordered pattern in other systems and show that shear is a sufficient ingredient for the emergence of such a pattern.

Study of the emergence of spiral turbulence has underlined the existence of a supercritical bifurcation. The pattern associated to this bifurcation, stationary in the frame rotating at the mean angular velocity of the two cylinders is well described by two coupled Ginzburg-Landau equations with real coefficients.

To our knowledge, it is the first observation of such a pattern emerging, trough a global spatio-temporal bifurcation, from a state intrinsically fluctuating at the scale of the description.

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