EXPERIMENTAL OBSERVATION OF A TWO-REGIME SPECTRUM IN ROTATING TURBULENCE

Frédéric Moisy, Cyprien Morize, Marc Rabaud
FAST, Bât. 502, Campus Universitaire, 91405 Orsay Cedex, France

Summary Transition from three-dimensional to quasi-two-dimensional turbulence in a rotating frame is experimentally investigated. A decaying turbulent field is generated from oscillating a grid in a rotating water tank, and velocity measurements are performed using particle image velocimetry. The power spectrum, $E(k)$, measured in the plane normal to the rotation axis, shows a transition from the classical Kolmogorov $k^{-5/3}$ spectrum towards a k^{-2} spectrum as the Rossby number is decreased. For intermediate values of Ro, a two-regime spectrum can be observed, showing a crossover between the 3D and quasi-2D regimes, in good agreement with the phenomenology proposed by Zhou [Phys. Fluids **7**:2092 (1995)]. This mixed regime takes place in a narrow band of Rossby numbers, from $\mathrm{Ro}_{3D} \simeq 0.15 \pm 0.10$ down to $\mathrm{Ro}_{Q2D} \simeq (0.10 \pm 0.03)Re^{-1/2}$.

INTRODUCTION

The statistical properties of rapidly rotating turbulence, of great importance for the geophysical and astrophysical applications, are not completely understood. The limit of vanishing Rossby numbers is expected to give rise to two-dimensional flows, where inverse energy cascade and enstrophy cascade may eventually take place. In the case of moderate rotation, the usual description in terms of direct energy cascade should be modified to account for the effect of the Coriolis force. Adding rotation to an otherwise 3D homogeneous turbulence introduces a new characteristic time, Ω^{-1}, that may affect the largest scales associated with low levels of vorticity compared to the background vorticity 2Ω. On this phenomenological ground, Zhou (1995) [1] proposes to use the timescale Ω^{-1} instead of the characteristic turn-over time based on the Kolmogorov estimate, leading to a k^{-2} power law spectrum for the small wavenumbers instead of the classical $k^{-5/3}$ law. This k^{-2} behaviour may dominate the whole spectrum for sufficiently small Rossby number [2]. The aim of the present experiment is to characterize the intermediate regime, where both the two scaling laws may be simultaneously observed over distinct ranges of scales.

EXPERIMENTAL SET-UP

The experimental cell, similar to the one from Hopfinger *et al.* (1982) [3], is sketched in figure 1(a). It consists of a square water tank, 55 cm in height and 35 cm in side, mounted on a rotating turntable, whose angular velocity Ω can be adjusted between 0 and 4.8 rad/s. A cover is placed below the free surface to avoid surface waves and unwanted β-effects. A turbulent velocity field is generated by means of a vertically oscillating grid through the height of the tank. The grid consists of 1 cm square bars with a mesh $M = 39$ mm. Typical velocity fluctuations $u' \simeq 0.1$ m/s are obtained by imposing a grid velocity of order of 0.8 m/s. The turbulent fluctuations rapidly decay, with a characteristic timescale of order of $10M/u' \simeq 4\ s$.

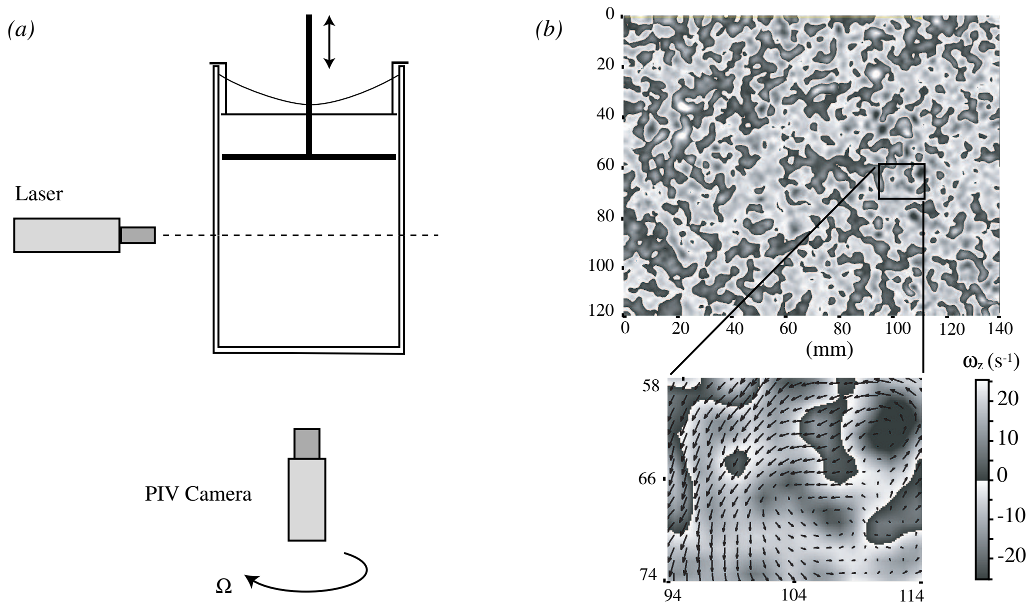

Figure 1. (a) Schematic of the experimental set-up. The water tank, the oscillating grid and the camera are in the rotating frame, while the pulsed laser remains in the laboratory frame. (b) Example of vertical vorticity field measured by PIV.

Instantaneous velocity fields in the horizontal plane (x, y) are obtained using a particle image velocimetry (PIV) system. The flow is seeded with small glass spheres, and illuminated by a horizontal laser sheet produced by a double pulsed laser. Images are acquired with a double-buffer high resolution camera in the rotating frame, synchronized with the laser at a rate of 4 frames pair per second.

The instantaneous velocity fields are characterized by the Reynolds number, $\mathrm{Re} = u'M/\nu$, and the Rossby number, $\mathrm{Ro} = u'/2\Omega M$, based on the velocity fluctuation u' and the mesh size M. As the turbulence decays, both numbers decrease, with the ratio $\mathrm{Ro}/\mathrm{Re} = \nu/2\Omega M^2$ remaining constant. This ratio is the Ekman number of the experiment, and is imposed by the angular velocity of the turntable. The Reynolds number takes values between 400 and 2500, and the Rossby number lies in the range 0.02 – 6.

RESULTS

Figure 2 shows two power spectra, measured in the horizontal plane, for weak and strong rotation. For the first spectrum, obtained 3 s after the end of the grid oscillation, the Rossby number is 0.25. A pure Kolmogorov scaling law, $k^{-5/3}$ is shown, indicating weak influence of the rotation. The second spectrum, obtained 8 s after the end of the grid oscillation, has a Rossby number of 0.07, and important deviation from the $-5/3$ slope is observed. Two distinct scaling laws, k^{-2} up to a transition lengthscale k_c and $k^{-5/3}$ from k_c up to the dissipation cut-off, are shown to fit reasonably well the data. In this case, the rotation only affects the largest scales of the flow, $r > r_c = 2\pi/k_c \simeq 13$ mm, while the smaller scales can be seen as essentially three-dimensional. Further decreasing the Rossby number, the $k^{-5/3}$ part of the spectrum eventually disappears.

The experiments for which both the k^{-2} and $k^{-5/3}$ regimes can be simultaneously observed lie in a very narrow range of Rossby numbers, that we note [$\mathrm{Ro}_{\mathrm{Q2D}}$, $\mathrm{Ro}_{\mathrm{3D}}$]. For $\mathrm{Ro} > \mathrm{Ro}_{\mathrm{3D}} \simeq 0.15 \pm 0.10$, the slope of the spectrum remains close to $k^{-5/3}$, i.e., no significant deviation from the non rotating case is observed. The important uncertainty for this upper bound originates from the lack of statistics due to the rapid decay of turbulence. The lower bound, $\mathrm{Ro}_{\mathrm{Q2D}}$, is expected to decrease as the Reynolds number is increased, since the range of scales that may be affected by rotation becomes wider at larger Re. A preliminary estimate for this lower bound can be inferred from our data, $\mathrm{Ro}_{\mathrm{Q2D}} \simeq (0.10 \pm 0.03)\mathrm{Re}^{-1/2}$. For the Reynolds numbers spanned in the present study, values around 0.02 – 0.06 are obtained for $\mathrm{Ro}_{\mathrm{Q2D}}$. Within this limited range of Rossby numbers [$\mathrm{Ro}_{\mathrm{Q2D}}$, $\mathrm{Ro}_{\mathrm{3D}}$], the crossover scale r_c is found to decrease as time proceeds, indicating that the effect of rotation progressively invades the whole range of scales of the flow.

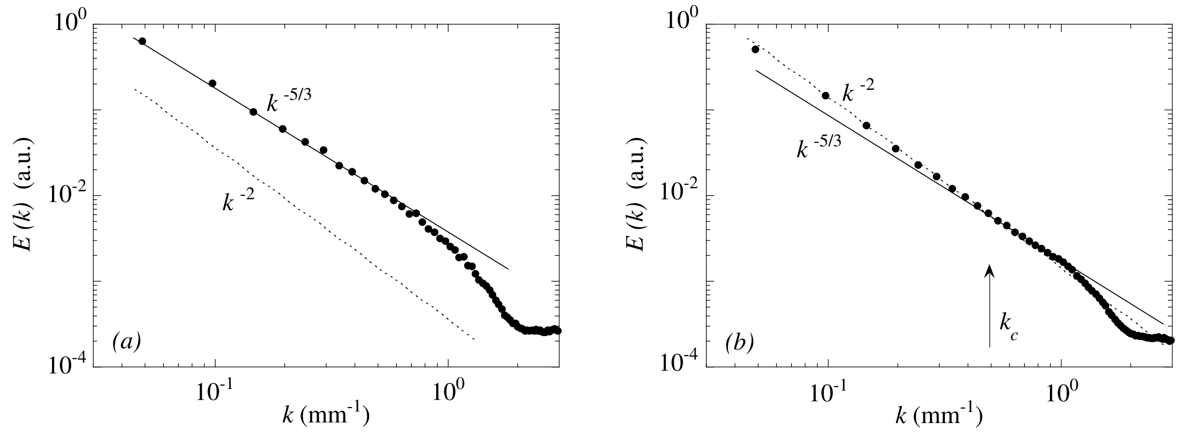

Figure 2. Power spectra in the horizontal plane. (a), Weak rotation case ($\mathrm{Ro} \simeq 0.25$), showing a pure $k^{-5/3}$ scaling. (b), Strong rotation case ($\mathrm{Ro} \simeq 0.07$), showing a mixed regime k^{-2} and $k^{-5/3}$, with a crossover at a scale $r_c = 2\pi/k_c \simeq 13$ mm $\simeq 0.33M$.

References

[1] Zhou Y.: A phenomenological treatment of rotating turbulence. *Phys. Fluids* **7**:2092, 1995.

[2] Baroud C. N., Plapp B. B., She Z.-S., Swinney H. L.: Anomalous Self-Similarity in a Turbulent Rapidly Rotating Fluid. *Phys. Rev. Lett.* **88**:114501, 2002.

[3] Hopfinger E. J., Browand F. K., Gagne Y.: Turbulence and waves in a rotating tank. *J. Fluid Mech.* **125**:505, 1982.