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ON THE CYCLONE-ANTICYCLONE ASYMMETRY IN DECAYING ROTATING TURBULENCE

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ABSTRACT

The statistics of the vorticity fluctuations in decaying rotating turbulence is experimentally investigated by means of particle image velocimetry. Two series of experiments have been carried out, one in a small-scale rotating water tank (FAST, Paris), with an aspect ratio $\sim O(1)$*, and the other one in the large-scale 'Coriolis' plateform (LEGI, Grenoble), with an aspect ratio* $\sim O(10)$*. In both experiments, turbulence is generated by rapidly towing a grid through the fluid, providing an initial state which is approximately homogeneous and isotropic. The asymmetry between cyclones and anticyclones is characterized by the vorticity skewness* $S_\omega = \langle \omega_z^3 \rangle / \langle \omega_z^2 \rangle^{3/2}$ *(*ω_z *is the vorticity component along the rotation axis). During the decay, for times up to the Ekman timescale, a growth of the asymmetry towards cyclonic vorticity is observed as* $S_\omega \sim (\Omega t)^{0.7 \pm 0.1}$*. For larger times, a re-symmetrization of the vorticity fluctuations take place, due to the non-linear Ekman pumping which preferentially affects the cyclonic vorticity. While the power-law growth is generic of both experiments, the maximum value of* S_ω *is shown to depend on the experimental configuration.*

INTRODUCTION

In the route towards approximately two-dimensional turbulence, rotating turbulence gives rise to a population of large-scale coherent cyclonic vortices [1]. The asymmetry between cyclonic and anticyclonic vorticity is a generic property of rotating systems, which originates from a selective destabilization of the anticyclonic vorticity by the Coriolis force when the Rossby number is of order of unity [2,3]. The statistical signature of this asymmetry has been first characterized for decaying rotating turbulence by Bartello et al.[4] from large-eddy simulations (LES), showing that the vorticity skewness at a fixed time during the decay was maximum for an initial Rossby number $\sim O(1)$. As a consequence, the vorticity distribution in the two-dimensionalization process is expected to be strongly affected by the initial conditions in the decaying case, or the forcing scheme in the stationary case, and should not be universal. Accordingly, a generic behavior for the build up of a vorticity asymmetry in decaying rotating turbulence should only be expected if the decay starts from an initial homogeneous 3D turbulence, i.e. for large initial Reynolds, $Re_g = V_g M/\nu$, and Rossby, $Ro_g = V_g/2\Omega M$, numbers, where V_g and M are respectively the velocity and the mesh size of the grid. These conditions are fulfilled in the two grid-generated turbulence experiments presented here.

EXPERIMENTAL SET-UPS

Data are obtained in two different set-ups, a small-scale one and a large-scale one. The first one, hereafter called "FAST" experiment, is a small-scale water tank, $L = 0.35$ m in side and $h = 0.44$ m in height, mounted on a rotating turntable (details can be found in Morize et al. [5]). The mesh size is $M = 39$ mm, and the grid is towed vertically at a constant velocity V_g in the range 0.82 to 1.63 m.s^{-1} from the bottom to the top of the tank. The second one, hereafter called "Coriolis" experiment, is a rectangular channel with a free surface, 4 m × 9 m and $h = 1$ m in height, mounted on the "Coriolis" rotating plateform (a 13 m diameter circular tank, see Praud et al. [6]). The mesh size is $M = 170$ mm, and the grid is towed horizontally at a velocity $V_g = 0.30$ m s^{-1}. The experimental parameters are summarized in Table 1.

In both experiments, the instantaneous velocity fields in the horizontal plane at mid-height of the tank are measured by particle image velocimetry (PIV), using a corotating high resolution camera. Convergence of the statistics is achieved by computing ensemble averages over several independent realizations of the decay (50 decays for the FAST experiment, and 6 decays for the Coriolis experiment, for each flow parameter).

Table 1
Flow parameters in the two experiments.

	FAST	Coriolis
	$\mathbf{V}_g \,//\, \Omega$	$\mathbf{V}_g \perp \Omega$
L_1(m)$\times L_2$(m)	0.35×0.35	4×9
h (m)	0.44	1
M (m)	0.039	0.17
V_g (m s^{-1})	0.82 - 1.63	0.30
Ω (rad s^{-1})	$0.13 - 4.50$	$0.05 - 0.21$
$V_g M/\nu$	$(31-62)\times 10^3$	51×10^3
$V_g/2\Omega M$	$2.4 - 120$	$4.2 - 17$

VORTICITY SKEWNESS

In order to quantify the prevalence towards cyclonic vorticity as time evolves, the vorticity skewness factor is computed [4,5]

$$S_\omega = \frac{\langle \omega_z^3 \rangle}{\langle \omega_z^2 \rangle^{3/2}},$$

where the brackets $\langle \cdot \rangle$ denote spatial and ensemble average. The time histories for S_ω are shown in Fig. 1 as a function of the number of tank rotations $\Omega t/2\pi$ for the two experiments (filled and open symbols). For small times, the curves remarkably coincide, showing an approximate power law

$$S_\omega \simeq 0.4(\Omega t/2\pi)^{0.7\pm0.1}. \quad (1)$$

Using Ωt as the non-dimensional time shows no significant influence of V_g and Ω in that range, indicating that Ω^{-1} is the relevant time scale for the build up of the vorticity asymmetry. This observation suggests that this growing asymmetry is supported by inertial waves, of maximum frequency given by 2Ω.

As a result of the confinement, the vorticity skewness saturates for larger times, up to values $S_\omega \simeq 1$ (FAST) and $S_\omega \simeq 3$ (Coriolis), and then sharply decreases. As the characteristic length of the coherent cyclonic vortices reaches the height of the tank, the Ekman layers on the bottom wall (resp. top and bottom walls) in the Coriolis (resp. FAST) experiment induce a vertical pumping, that weakens the circulation of the vortices on a time scale given by $t_c \simeq h(\nu\Omega)^{-1/2}$. However, the *decrease* of S_ω for $t > t_c$ cannot be explained within this classical linear Ekman theory, which

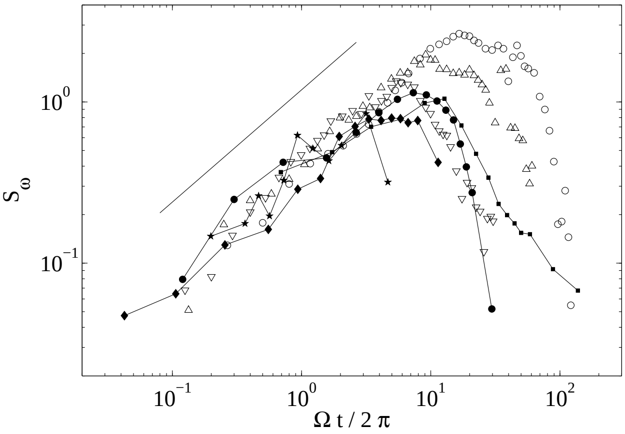

Fig. 1. Vorticity skewness as a function of the number of tank rotation. Full symbols: FAST experiment (Morize et al. [5]), for $\Omega = 0.13$ ($\star$), 0.53 (♦), 1.5 (●) and 4.5 rad s^{-1} (■). Open symbols: Coriolis experiment, $\Omega = 0.052$ ($\triangledown$), 0.105 ($\triangle$) and 0.209 rad s^{-1} ($\circ$). The solid line shows the slope $S_\omega \propto t^{0.7}$.

should equally affect the cyclonic and the anticyclonic vorticity, leading to exponentially decreasing vorticity of both sign and a constant S_ω. On the other hand, for finite Rossby numbers, nonlinear corrections to the Ekman pumping should be considered, which are shown to enhance the damping of the cyclonic vortices (e.g., Zavala Sansón and van Heijst [7]). As a result, a gradual re-symmetrization of the vorticity distribution should be expected on a time scale $O(t_c)$, and may explain the observed decay of S_ω. Accordingly, the self-similar growth (1) may be considered as a generic feature of decaying rotating turbulence, while the maximum of S_ω is constrained by the finite size effects.

INTEGRAL SCALES

In order to investigate if the confinement plays a significant role in the growth law of the vorticity skewness (1), we will now discuss the evolution of the integral scales during the energy decay.

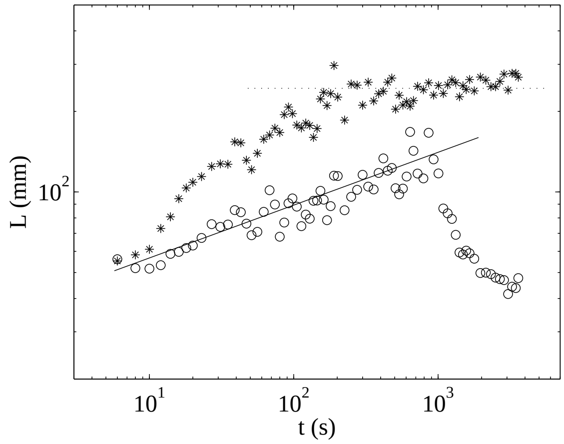

Fig. 2. Evolution of the vertical, L_v ($*$), and horizontal, L_h ($\circ$), integral scales as a function of time measured on the Coriolis experiment at $\Omega = 0.105$ rad s^{-1}. The solid line shows the slope $L \propto t^{1/5}$ and the dotted line indicates the saturation of the vertical scale.

Velocity measurements were carried out in a vertical plane, containing the rotation axis in the large-scale experiment (Coriolis). The increase of the size of the vortices can be characterized in terms of the horizontal and vertical longitudinal integral scales L_h and L_v. These scales are computed from the integral of the longitudinal velocity correlation function,

$$L_\alpha = \int_0^{r^*} C_\alpha(r)dr = \int_0^{r^*} \frac{\langle u_\alpha(\mathbf{x})u_\alpha(\mathbf{x}+r\mathbf{e}_\alpha)\rangle}{\langle u_\alpha(\mathbf{x})^2\rangle}dr,$$

where α stands for h (horizontal) or v (vertical) and the scale r^* is chosen such that $C_\alpha(r^*) = 1/2$. The time evolution of these integral scales is shown in Fig. 2, which clearly indicate the growing anisotropy of the flow. The horizontal integral scale is found to increase as a power-law of time,

$$L_h \propto t^{0.20\pm0.05}.$$

This exponent is in qualitative agreement with the numerical results of Squires *et al.* [8]. On the other hand, the vertical integral scale is found to increase much faster than the horizontal one, which may be interpreted in terms of inertial waves propagation. As a consequence, the vertical integral scale, L_v, quickly saturates at the vertical size of the tank, after a time $t \simeq 150$ s (here after 2 complete rotations). It must be noted that this saturation time is reached during the self-similar growth of S_ω, indicating that the vertical confinement indeed plays a central role during this growth.

CONCLUSION

Two decaying rotating turbulence experiments, with similar initial Reynolds and Rossby numbers but in which the confinement effects differ, are used to characterize the build up of the vorticity asymmetry. Starting from approximately homogeneous 3D turbulence with symmetric vorticity fluctuations, an asymmetry towards cyclonic vorticity gradually builds up as $S_\omega \sim (\Omega t)^{0.7\pm0.1}$, up to values $O(1)$. We have also shown that the vertical integral scale quickly saturates to the vertical size of the experiment. This indicates that, in order to model the exponent of the vorticity skewness law, the confinement along the vertical has to be taken into account. The vorticity asymmetry growth is interrupted for times larger than the Ekman timescale (typically 3 to 20 tank rotations), for which nonlinear Ekman friction on the top and bottom walls preferentially reduces the cyclonic vorticity. While the power-law growth is generic of both experiments, the maximum value of S_ω is shown to depend on the experimental parameters.

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