EFFECTS OF ROTATION ON TURBULENT CHANNEL FLOWS

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A novel setup for flow visualizations and turbulence measurements in rotating high-aspect-ratio ducts is presented. Results from 3-component SPIV measurements show the significant effect of system rotation both on the mean flow and on the turbulence statistics in a clear channel. Combined 2-component PIV measurements allow detailed studies on massively separated flows subjected to rotation in both directions.

1. INTRODUCTION

Rotating flows are encountered both in geophysical and industrial fluid mechanics. The influence of the Coriolis body force on fluid motion exhibits a number of generic features which may occur irrespective of the particular field of application. Internal flows in rotating ducts and channels are typically found in rotating machinery, e.g. cyclone separators, pumps and turbines.

Background rotation is known to alter not only the mean fluid motion but also the turbulence field qualitatively as well as quantitatively; see for example Johnston et al. (1972) and Kristoffersen & Andersson (1993). In a rectangular duct which rotates about a spanwise axis, the background rotation results in a transverse pressure gradient, intended to balance the Coriolis force which acts normal both to the axis of rotation and to the primary flow direction. This gives rise to the notion of suction and pressure sides, which corresponds to cyclonic and anti-cyclonic conditions, respectively. A striking effect of system rotation on turbulent channel flows is the damping of the turbulence along the suction side wall and the enhanced turbulent activity at the pressure side, accompanied by a severely distorted (i.e. distinctly asymmetric) mean velocity profile.

The objective of the presented study was two-fold: (i) to measure for the first time the distribution of all three velocity components in a rapidly rotating fully developed turbulent channel flow; and (ii) to investigate how the Coriolis force affects the massively separated flow downstream of a backward-facing step. A wide range of rotation numbers in combination with a modest range of Reynolds numbers was covered.

2. EXPERIMENTAL SETUP

In this study, we investigated well developed flows in rectangular ducts subjected to rotation using Particle Image Velocimetry (PIV). The experiments were performed on the “Coriolis” platform at the Laboratory of Geophysical and Industrial Fluid Flows in Grenoble (France). With a platform diameter of 13m, this unique facility allows the duct, pump, measurement system as well as personnel to be situated on the platform during operation. An overview of the setup can be obtained from Figures 1 and 2. The duct consisted of a closed circuit of plastic pipes, leading into a 10 m long, rectangular section of 10 cm width and 50 cm height. The test section was located downstream of a 4 m clear inflow section and entirely transparent to provide optical access.

Two different geometries were tested: A clear channel case and a backward-facing step case. In the clear channel case, measurements were performed in the duct without any obstructions, as shown in Fig. 1. With the two cameras mounted in a stereoscopic angle above the plexi-glass test section, all three velocity components could be measured.

In a second setup, a 2 m long obstruction with a blockage factor of 0.5 was introduced into the channel to measure the effects of rotation in a backward-facing step geometry. With the greatest influence of the Coriolis force acting on velocity vectors in the xy-plane, this setup was measured using 2D-2-component PIV. The cameras were mounted side-by-side, perpendicular to the lightsheet. The runs were repeated with the camera pair mounted further downstream of the step. Combining the results of 4 camera positions of the respective rotation numbers, the shape of the recirculation zone could be studied for as far as 5 channel widths.

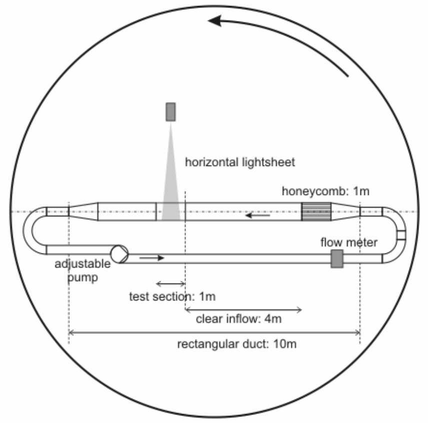

Figure 1: Plan view of the setup.

Figure 2: The duct mounted inside the turntable basin.

The two governing parameters are the Reynolds number Re = $U_b H/\nu$ (based on the bulk flow velocity $U_b = Q/A$ and the kinematic viscosity ν) and the rotation number Ro = $2\Omega H/U_b$. Here, Ω is the constant angular velocity with which the duct is rotating about the vertical z-axis. The clear channel width H is the geometric length scale perpendicular to the flow direction and the axis of rotation. The measurements comprised a variety of parameter combinations, as shown in Table 1.

Table 1: Test parameters for both geometries.

Reynolds number	Rotation number
$Re = U_b H / \nu$	$Ro = 2\Omega H/U_b$
5 600	0.00; 0.10; 0.20; 0.40; 0.60; 0.80
11 200	0.00; 0.05; 0.10; 0.20; 0.40
22 400	0.00; 0.05; 0.10; 0.20

3. RESULTS FROM THE CLEAR CHANNEL

Example results from the measurements in the clear channel will be presented in this section. A detailed description of the experiment and discussion of the results can be found in (Visscher et al., 2009). The profiles shown are obtained by averaging in time and in the homogeneous x-direction. Figure 3a shows the streamwise component of the mean velocity vector for Re = 5 600 at rotation numbers in the range from Ro = 0 to Ro = 0.80, normalized by the measured averaged velocity $U_{avg} \approx$ 5.6 cm/s. The sense of rotation is always anti-clockwise (i.e. $\Omega \geq 0$), which implies that the pressure side wall is at y/H = -0.5 while the suction side is at y/H = +0.5.

Without rotation, the streamwise mean velocity component U(y) varies almost symmetrically around the mid-plane y = 0. With system rotation imposed, U(y) becomes asymmetric with the location of maximum velocity shifted from the centerline towards the suction side. For the higher rotation numbers Ro ≥ 0.4, the velocity profiles become linear over a certain interval near the pressure side, fully consistent with earlier experiments (Johnston et al. 1972) and simulations (Kristoffersen & Andersson 1993, Figure 3b).

The ratio between the wall-normal $\langle\langle v'^2 \rangle\rangle$ and streamwise $\langle\langle u'^2 \rangle\rangle$ Reynolds-stress components is shown in Figure 4. In a non-rotating channel flow, this ratio is consistently smaller than unity simply because the production of turbulence contributes only to streamwise velocity fluctuations and the two other velocity components receive their energy through pressure-strain interactions. Influenced by rotation, additional stress-generation mechanisms are involved which stem from interactions between the instantaneous flow field and the Coriolis force. The most prominent effect of these extra rotational production terms is the enhancement of the wall-normal velocity fluctuations along the unstable pressure side and the corresponding reduction and even suppression of v' near the stabilized suction side. With increasing rotation rates, $\langle\langle v'^2 \rangle / \langle u'^2 \rangle\rangle$ exhibits a fourfold increase from about 0.5 to above 2.0

on the pressure side of the duct. This reversal of the Reynolds stress anisotropy is one of the most striking features of rapidly rotating shear flows and has probably been observed experimentally for the first time herein.

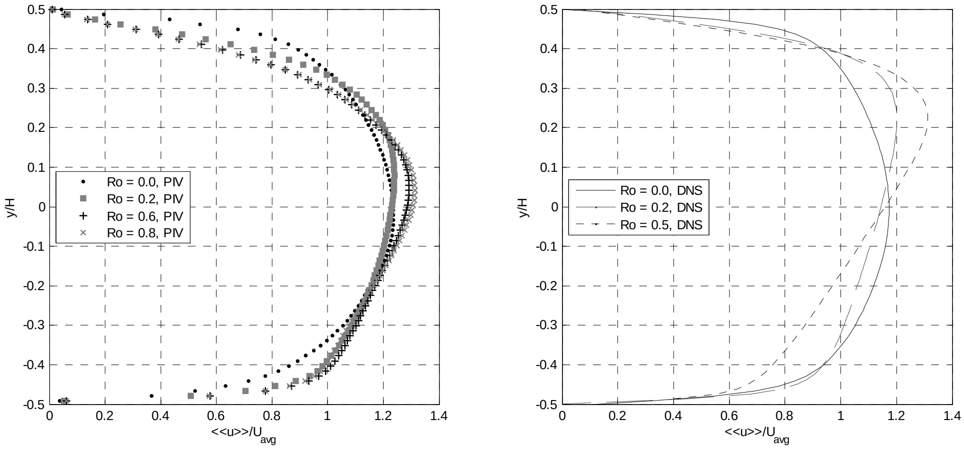

Figure 3: Mean normalized streamwise velocity at Re = 5 600.
Left: PIV measurements; Right: DNS results from Kristoffersen & Andersson 1993

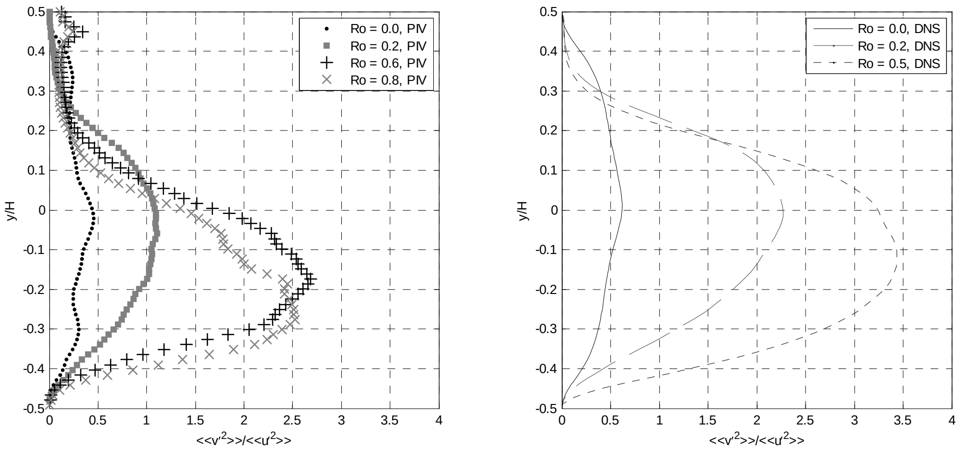

Figure 4: Normal stress ratio <<v’2>/<u’2>> at Re = 5 600.
Left: Present PIV results; Right: DNS results from Kristoffersen & Andersson 1993.

4. RESULTS FROM THE OBSTRUCTED CHANNEL GEOMETRY

The second objective of the present project was to investigate how a massively separated flow reacts on spanwise system rotation. The duct cross-section was reduced by 50% just upstream of the test section. In that way, a backward-facing step flow was established with a step height h to channel width H ratio of 1:2. Since the turntable only rotates counter-clockwise, the obstruction could be mounted on both side walls of the duct. Analogous to the clear channel setup, results with the obstruction on the suction will be denoted with positive Rotation numbers hereafter. Simulating clockwise rotation, results with the obstruction on the pressure side will denoted with negative Rotation numbers and flipped upside-down for better comparability.

The mean streamwise velocity component is visualized in Fig. 5. Without rotation, the reattachment point is located at ≈ 35 cm, i.e. about 7 step-heights h downstream of the step (center image). The top frame shows how destabilizing rotation of Ro = -0.60 reduces the reattachment length significantly to about 4h. A second recirculation bubble forms on the opposite wall additionally. On the contrary, rotation in the positive, counter-clockwise direction stablizes the mixing layer enough to shift the reattachment point beyond the downstream end of the measurement area (bottom image). This is fully consistent with findings by Rothe & Johnston (1979) who observed that destabilizing rotation reduced the reattachment length while stabilizing rotation increased it. More detailed results and discussions are currently in preparation to be published soon.

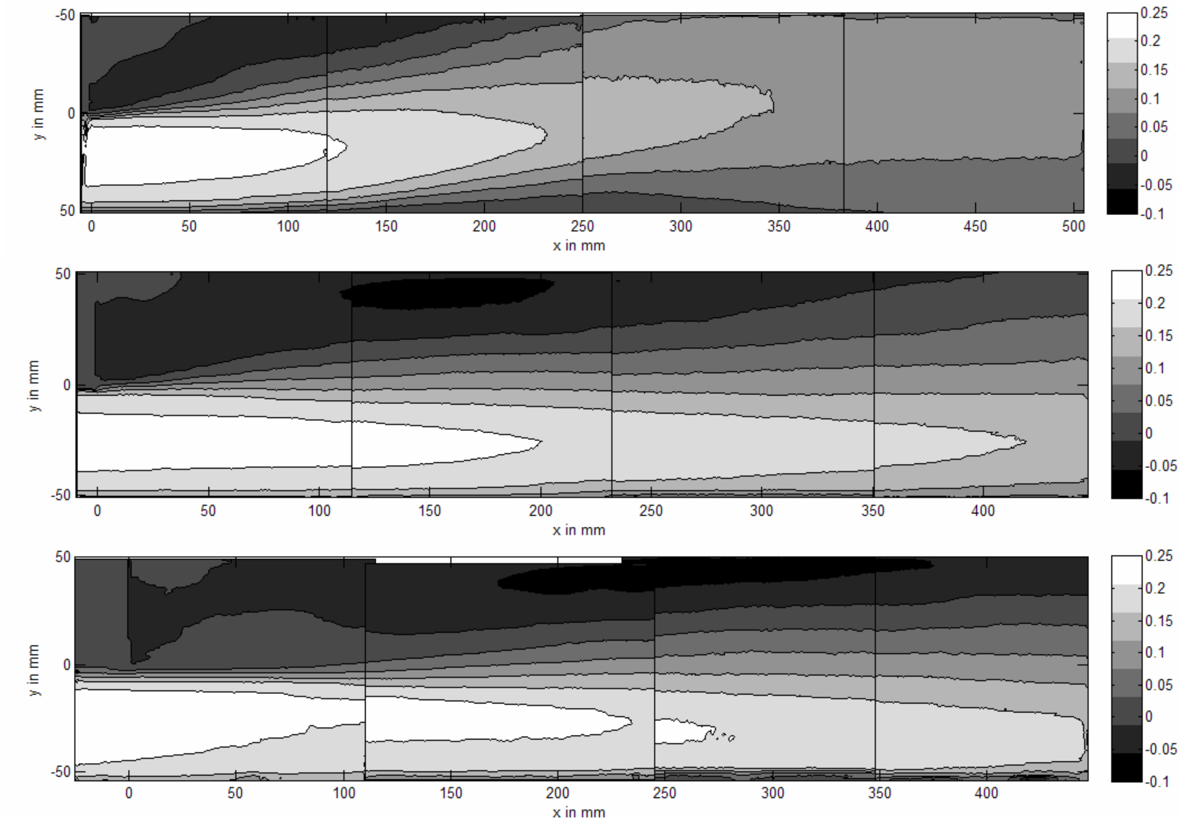

Figure 5: Mean streamwise velocity distribution at Re = 5 600, combined result from 4 measurement positions. Top: Ro = -0.60; Center: Ro = 0.0; Bottom: Ro = +0.60

5. CONCLUDING REMARKS

In the new setup we were able to reach higher rotation numbers than those reported in earlier experimental studies of developed duct flows. By means of PIV, all three velocity components were measured for the first time for a variety of different rotation numbers and at three different Reynolds numbers. The modular construction of the rectangular duct enabled obstructions to be inserted.

The results reveal the striking effect of rotation on both the mean flow and the turbulent fluctuations inside a clear channel, as well as on the mixing-layer developing from the downstream corner of a backward-facing step. All data examined so far are generally consistent with earlier experimental findings and results from DNS.

ACKNOWLEDGEMENT

The work described was supported by the European Community's 6th Framework Programme through the grant to the budget of the Integrated Infrastructure Initiative HYDRALAB III, Contract no. 022441 (RII3).

REFERENCES

Johnston, J.P., Halleen, R.M. and Lezius, D.K. 1972. Effects of spanwise rotation on the structure of two-dimensional fully developed turbulent channel flow, *J. Fluid Mech., Vol. 56, pp. 533-557.*

Kristoffersen, R. and Andersson, H.I. 1993. Direct simulations of low-Reynolds-number turbulent flow in a rotating channel, *J. Fluid Mech., Vol. 256, pp. 163-197.*

Visscher, J., Andersson, H.I., Barri, M., Didelle, H., Viboud, S., Sous, D. and Sommeria, J. 2009. A new set-up for PIV measurements in rapidly rotating turbulent channel flows. *Experiments in Fluids, in review*.

Rothe, P.H. and Johnston, J.P. 1979. Free shear layer behaviour in rotating systems, *J. Fluid Engng, Vol. 101, pp. 117-120.*