EFFECT OF SYSTEM ROTATION ON FREE SHEAR FLOWS

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1. Preliminaries

Turbulent flows can be categorized in many different ways. Free turbulent shear flows are often considered as one class of fluid flows which on the one hand are different from homogeneous turbulence due to the presence of mean-flow shear and on the other hand are different from wall-bounded shear flows due to the absence of solid walls.

In this lecture the effects of system rotation on some different turbulent shear flows will be demonstrated and explained in terms of the considerations in the preceding lecture "*Introduction to the effects of rotation on turbulence*" (Andersson 2010). The flows to be discussed are the following:

- Plane Couette flow.
- Plane wake.
- Plane mixing-layer.
- Backward-facing step.

Some of these flows are internal rather than external or free flows. The plane Couette flow, for instance, is a wall-bounded flow which nevertheless exhibits a substantial core region which closely resembles a uniform shear flow. The backward-facing step flow is a suitable geometry in which the mixing-layer emanating from the corner of the step can be explored. Even though solid walls are present in some of these cases, the focus in the present lecture will be on flow phenomena which occur in the 'free' shear layers which are only modestly affected by the presence of the solid surfaces.

2. Plane turbulent Couette flow with system rotation

The plane Couette flow is the shear-driven motion between two parallel planar walls in relative motion. The fluid motion is induced only by the prescribed velocity difference $2U_w$ between the walls which are $2h$ apart from each other, as sketched in Figure 1. The wall-motion is in the x-direction of a Cartesian coordinate system Rf which rotates with constant angular velocity Ω about the spanwise z-axis relative to an intertial system Rf*, whereas the y-axis is perpendicular to the parallel walls. When a statistically steady and fully developed flow is considered, the streamlines representing the mean fluid motion is everywhere parallel with the walls.

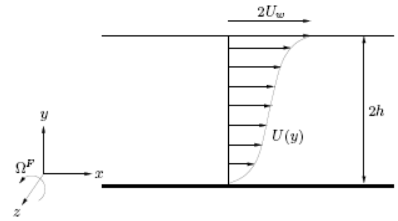

Figure 1: Plane turbulent Couette flow seen from a reference frame which rotates about the spanwise *z*-axis. The typical *S*-shaped mean velocity profile *U(y)* is indicated.

The two dimensional parameters which characterize this flow is the Reynolds and rotation numbers:

$$\mathrm{Re} = \rho h U_w / \mu; \qquad Ro = 2\Omega h / U_w . \tag{1}$$

Notice that the velocity scale *U* is taken as U_w, i.e. half of the velocity difference between the two walls, and the characteristic length scale *L* is taken as half the wall distance.

If the Couette flow is *laminar*, the velocity varies *linearly* between the walls, i.e. $u(y) = yU_w/h$, provided that the flow is either not rotating ($Ro = 0$) or as long as the rotating flow is not susceptible to a rotational instability; see the pioneering stability analysis by Hart (1971) and the recent experimental investigation by Tsukahara et al. (2010). The variety of different states which may occur at Reynolds numbers below 1000 are summarized in flow-regime maps by Tsukahara et al. (2010).

Here, we consider a flow with Reynolds number Re = 1300 which is well above Re = 500 required for fully developed turbulence to exist. The mean velocity profile *U(y)* of a plane *turbulent* Couette flow is known to exhibit a *S*-shaped variation with an inflection point midway between the two planes. All Reynolds-averaged flow statistics, including the Reynolds stresses, vary symmetrically about the mid-plane. The mean vorticity $\omega_z = -dU/dy$ has accordingly the same sign on both sides of the flow and so has the local rotation number $S = -2\Omega/(dU/dy)$. The rotating plane Couette flow is therefore either exposed to cyclonic or anti-cyclonic rotation throughout the entire flow field. This particular feature, which is not shared by the rotating Poiseuille flow, makes the Couette flow particularly attractive for investigations of effects of system rotation on turbulent shear flows.

The rotating plane Poisuille flow is, on the other hand, simultaneously affected by cyclonic and anti-cyclonic rotation since the mean velocity *U(y)* attains a maximum value somewhere in the center region and obeys no-slip at both walls. The local rotation number $S = -2\Omega/(dU/dy)$ is therefore positive on one side of the Poiseuille channel and negative at the other side. This flow is therefore exposed to cyclonic rotation ($S > 0$) on the suction side and to anti-cyclonic rotation ($S < 0$) on the pressure side of the channel. The tendency of longitudinal roll cells to develop in *laminar* Poiseuille flow was studied by Hart (1971) and Lezius & Johnston (1976). *Turbulent* Poiseuille flow subjected to system rotation has been investigated by several authors since the pioneering experiments by Johnston et al. (1972). Direct numerical simulations (DNSs) have been performed by Kristoffersen & Andersson