Pattern formation, vortex instabilities and dynamics in lid-driven cavities

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Two- and three-dimensional flows in lid-driven cavities with large cross-sectional aspect ratios (width-to-height ratio $\Gamma > 1.2$) and large span aspect ratios (span-to-height ratio $\Lambda \geq 10$) are investigated experimentally and numerically.

Introduction

The lid-driven cavity is a classical system for investigating vortex dynamics. The flow in a cuboid shaped cavity is driven by one wall. Depending on the geometry of the cavity and the location of the lid, different flows can be realized. The simple geometry reduces the numerical and experimental complexity, allowing investigations of various flow phenomena. Shankar and Deshpande (2000) gave an overview on lid-driven cavity flows and their importance for fundamental fluid dynamics.

Albensoeder et al. (2001) have performed a linear stability analysis of the basic flow in one-sided driven cavities for varying cross-sectional aspect ratios and infinitely spanwise extent. They predicted four different three-dimensional modes, depending on the cross-sectional aspect ratio, which are caused by centrifugal instability mechanisms. Experimentally, they have confirmed one of the modes. Siegmann-Hegerfeld et al. (2008a, b) have validated the remaining three modes experimentally. The structures, critical wave numbers, and oscillation frequencies show a good agreement with the numerical predictions. However, for the so called $C_4^s$-mode a particular large deviation ($\approx 30\%$) of the critical Reynolds number has been detected.

The present investigation is intended to shed some light on the cause of this deviation. Flow visualizations and PIV measurements provide insight into the flow structures. Quantitative data of LDV measurements are compared to results of three-dimensional simulations. In the experiment, the driving is realized by two large cylinders (Fig. 1) associated with two Reynolds numbers ($Re$). For investigations concerning the one-sided driving only one cylinder is rotating.

Results

In agreement with the numerics the $C_4^s$-mode arises at large cross-sectional aspect ratios ($\Gamma > 1.2$). The stationary supercritical flow consists of a wavy primary vortex exhibiting a long-wavelength modulation. Visual investigations for $\Gamma = 1.6$ and $\Lambda = 11$ show a gradual transition from the two-dimensional basic flow to the three-dimensional flow pattern. Therefore, the detection of the critical Reynolds number is made difficult. The three-dimensional flow structure becomes visible at $Re \approx 350$, and LDV measurements confirm a strongly imperfect first bifurcation. On the other hand, a linear stability analysis for periodic boundary conditions predicts $Re_c = 480\left(\Gamma = 1.6\right)$.

In Fig. 2 the axial velocity component $w$ is shown as a function of $z$. Results of full numerical simulations for periodic (dashed) and for no-slip boundary conditions ($\Lambda \approx 11$, full line) are compared to LDV data (symbols).

The LDV data show a very good agreement with the numerical data for no-slip conditions and $\Lambda \approx 11$. Therefore, the mode is considered confirmed quantitatively. The perturbation amplitude in the center is smaller for no-slip than for periodic boundary conditions. This effect is, therefore, be attributed to a strong end-wall effect. Secondary flows induced by the end-walls of the cavity have been verified by additional LDV measurements. We conclude that the end-wall effects are responsible for the strong imperfection of the bifurcation in the experiments.

References