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Mean flow generation by an intermittently unstable boundary layer over a sloping wall

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Direct numerical simulations (DNS) of the flow in rotating annular confinements with variable inner wall inclination are conducted. The confinements are built changing the apex half-angle of the inner wall as a truncated cone (frustum) from 18° to 0° (straight cylinder). Flows were excited by time-harmonic modulation of the inner wall's rotation rate (so-called longitudinal libration) by prescribing the amplitude $\varepsilon\Omega_0$ and the forcing frequency $\omega = \Omega_0$. For small libration amplitudes ($\varepsilon = 0.2$), an Ekman–Stokes boundary layer (ESBL) is formed over the librating wall. Using th laminar boundary layer theory and DNS, we show that the ESBL exhibits an oscillatory mass flux (Ekman property) and an oscillatory azimuthal velocity which resembles a radially damped wave (Stokes property).

Reducing the inclination angle of the inner wall, causes the local Coriolis force to have a weaker contribution to the boundary layer dynamics, yielding three different flow regimes: rotation-dominated, libration-dominated, and a mixed regime. In the present study we focus on the libration-dominated regime. For large libration amplitudes ($\varepsilon = 0.8$), the DNS results show an intermittently unstable ESBL, which becomes centrifugally unstable during the prograde (faster) part of a libration cycle. This gives rise to a developing instability in the form of Görtler vortices which will be discussed to be due to the Stokes property of the ESBL. Intermittency occurs because of the librational forcing, which imposes periodically changing stable and unstable conditions near the wall. Unexpectedly, the Görtler vortices are found to be tilted with respect to the azimuth for nonzero wall inclination angles, which is not the case over the straight cylinder. We show that this tilt is related to the Ekman property of the ESBL with the aid of laminar boundary layer theory. This indicates that linear and nonlinear dynamics are equally important for this intermittent instability.

Our DNS results indicate further that the Görtler vortices propagate into the fluid bulk where they generate an azimuthal mean flow. This mean flow is notably different from the mean flow driven in the case of the stable ESBL. A diagnostic analysis of the Reynolds-averaged Navier–Stokes equations in the unstable flow regime hints at a competition between the radial and axial turbulent transport terms which act as generating and destructive agents for the azimuthal mean flow, respectively. We show that both terms of the mean flow balance depend on the wall inclination, that is, on the wall-tangential component of the Coriolis force, even though latter was supposed to affect only the boundary layer flow in the first place.