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The dipole-wall collision as a model problem for vorticity production at no-slip boundaries

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The dynamics of turbulence are strongly influenced by the presence of no-slip walls. For example, in the case of two-dimensional turbulence there are strong boundary layers present. By interaction with vortices these boundary layers are detached from the wall and injected into the flow. Another aspect is the influence of the boundary layers on the energy decay of the flow. The energy decay is given by

$$\frac{dE}{dt} = -\frac{1}{Re}\iint_{\mathcal{D}} \omega^2 dA$$

where the integral is called the enstrophy Ω, a measure for the total vorticity ω. As most of the enstrophy is located in the boundary layers, the energy decay is larger for a domain with no-slip boundaries compared to a periodic domain. Numerical simulations on fully developed two-dimensional turbulence restrict us to lower Reynolds number, so a simpler set-up is chosen to investigate the role of no-slip boundaries as a vorticity source: the dipole-wall collision.

The initial condition for the dipole-wall collision consists of a dipole orientated in such a way that it will translate towards the no-slip boundary. In the first stages boundary layers of opposite vorticity are developing and grow in amplitude as the dipole moves closer. If the dipole comes even closer to the wall, both dipole halves start to separate and move along the boundary. The dipole cores are now so close that they start to strip the boundary layers from the wall. These detached, thin vorticity filaments roll-up forming new vortices. The newly formed vortices pair up with the halves of the original dipole. As a result the two new dipoles move away from the boundary, but their circular trajectory leads to a new collision with the wall. Hereafter the exact evolution of the flow is highly dependent on the Reynolds number. A number of situations are observed: multiple rebounds, a secondary dipole that translates into the interior or the formation of a large number small-scale vortices.

The early stages (till the first collision) show a similar flow behavior for different Reynolds numbers. This gives us the opportunity to investigate the production of vorticity at the boundary as function of the Reynolds number. Though the boundary layers are thinner for higher Reynolds numbers they contain more enstrophy. For high Reynolds numbers a simple scaling law holds for the peak enstrophy. At certain times the amount of enstrophy located in the boundary layers is much larger than the enstrophy in the interior region. Beneath an increased energy dissipation, the produced vorticity has a large influence on the interior flow once being detached from the wall.