New Global Approaches to Flow Stability

Espen Åkervik — *espena@mech.kth.se*

Outi Tammisola — *outi@mech.kth.se*

Stefan Ivanell — *stefan.ivanell@hgo.se*

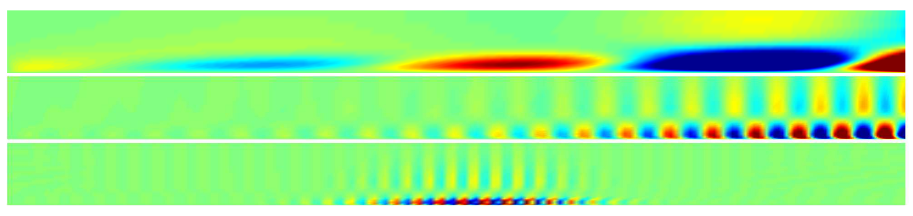
Linné Flow Centre, KTH Mechanics

Introduction

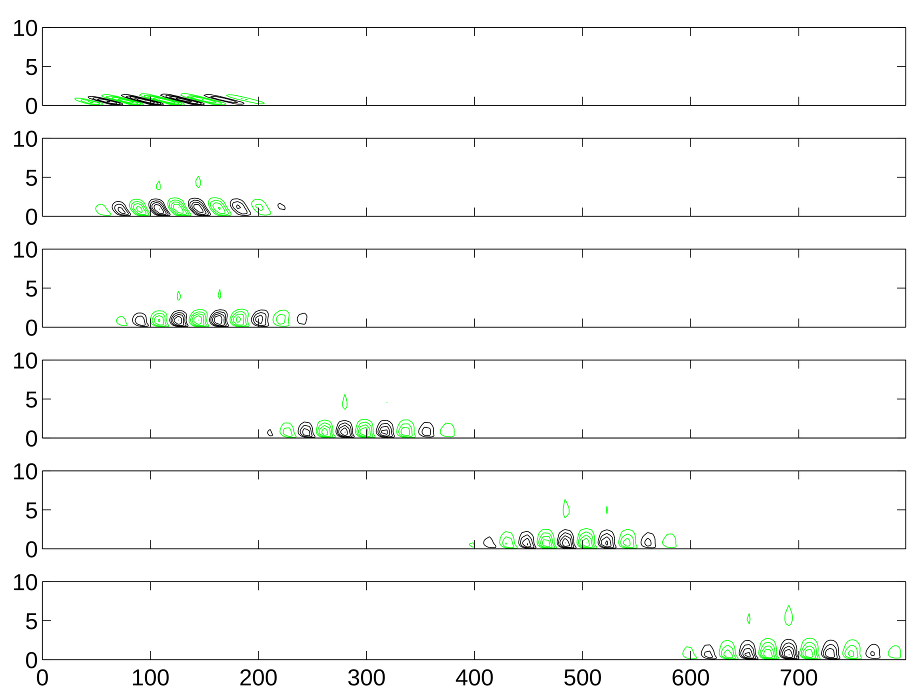
Traditionally numerical instability investigations of flows has been restricted to standard geometries. With increasing computer power and code development suitable to run on this new generation of computers, the possibility of studying the stability characteristics of complex flows has come to a new era. The standard way of examining the stability of flow systems, both experimentally and numerically, is to perturb the base flow either by an initial condition or with a time dependent forcing and monitor the time development of the disturbances. If the flow relaxes it is stable, if it does not it is unstable. The asymptotic stability may be determined by eigenvalues of the differential equation describing the flow. However since for many flow systems the breakdown to turbulence may be abrupt, in general one needs to study also the short time evolution of the disturbances. Formally this scenario may be determined by solving optimization problems. Here we show a number of ways to characterize the stability of complex flows, using both global eigenmodes and Navier–Stokes time integration schemes, exploiting the increasing computer capacities available.

Global modes of the Blasius flow

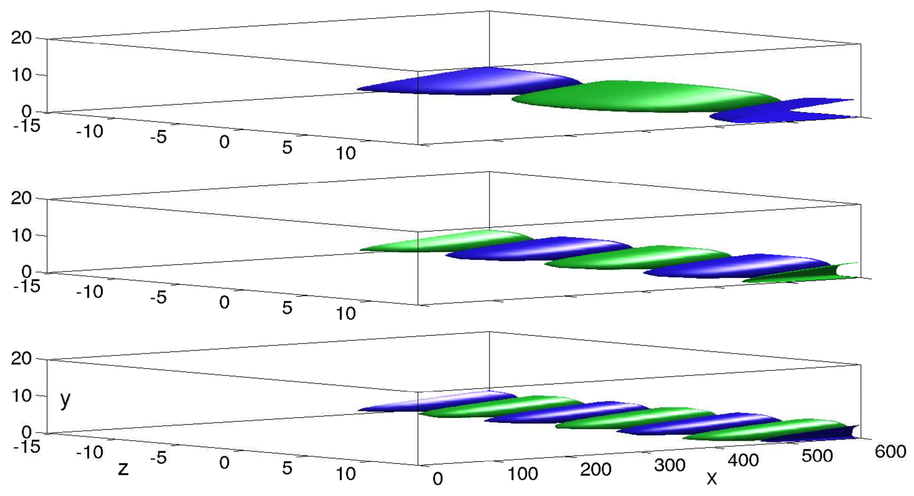
A flat plate with flow coming from left to right creates the so called Blasius boundary layer flow developing downstream. This flow case has been studied extensively under the locally parallel assumption. Here we study the stability of this flow using two- and three-dimensional global eigenmodes . Below the two-dimensional global eigenmodes related to the Tollmien Schlichting instability is shown.



The optimal initial condition is found as a sum of the computed eigenmodes. Below contours of the streamwise velocity is displayed at different times. One can observe that the initial condition consists of structures leaning against the shear, that through the Orr mechanism leads to the onset of a Tollmien Schlichting wavepacket.

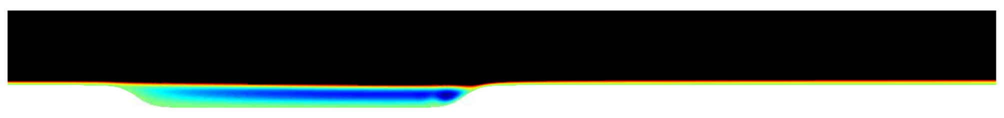


Below the streamwise component of the eigenfunctions corresponding to low frequency eigenvalues for the spanwise wavenumbers $\beta = \{0.2, 0.4, 0.6\}$ are depicted. The system is highly sensitive to low frequency three-dimensional forcing structures leading to the formation of streaks. These eigenmodes have the typical characteristics of streaks.



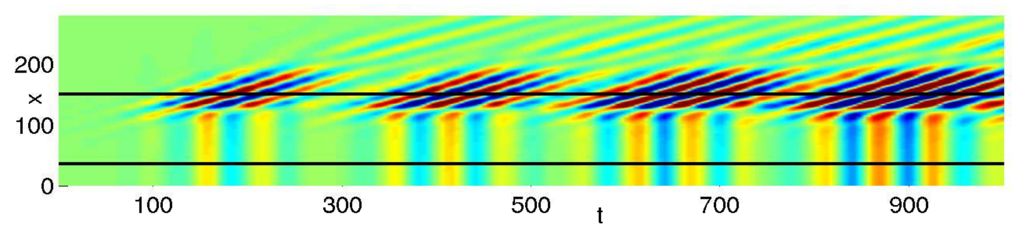
Shallow Cavity Flow

Consider a shallow cavity mounted on a flat plate with flow coming from left to right. The presence of the cavity creates a shear layer and a separation bubble as seen from the steady state stream function.



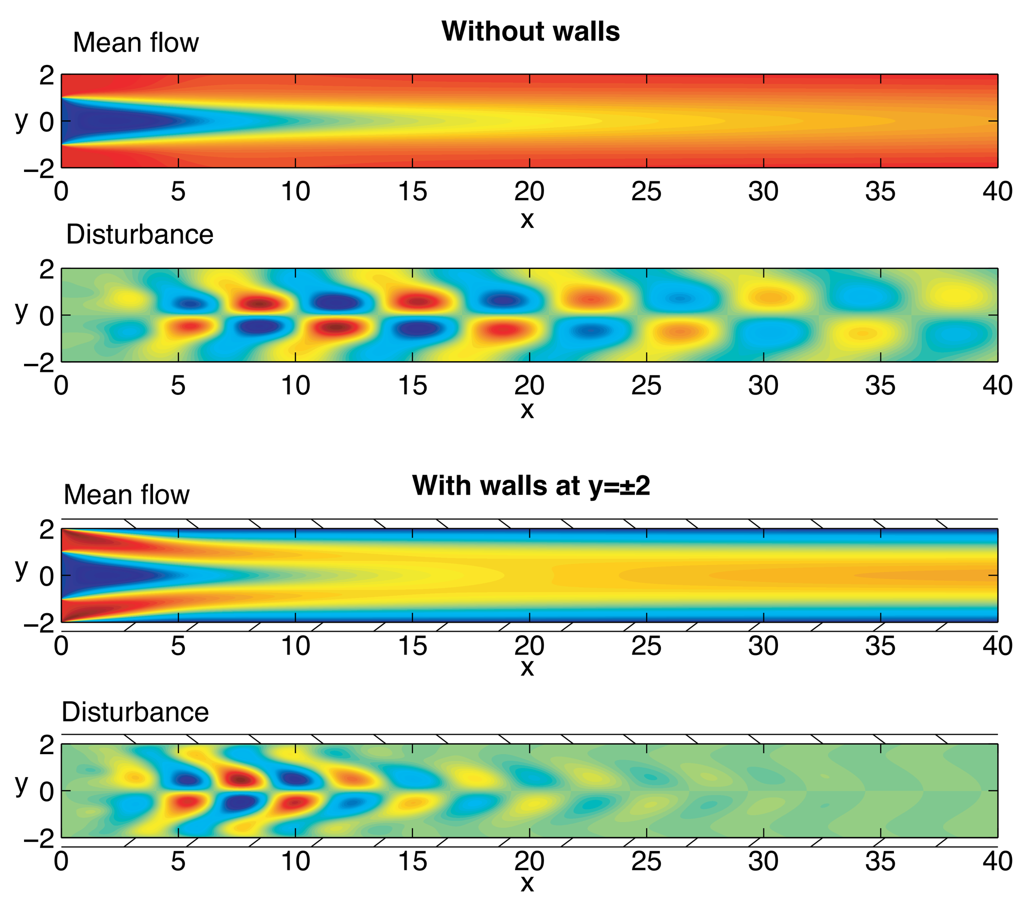
Due to the highly non-parallel nature of the flow instability mechanisms has to resort to a global formulation of the stability problem. Below the right and left eigenvectors corresponding to a globally unstable eigenvalue are depicted.

The optimal sum of global eigenmodes shows that there is a global oscillating cycle. This mechanism may be visualized in a spatio-temporal diagram of the pressure field. A wavepacket is propagating across the shear layer creating a global pressure pulse that through receptivity at the upstream cavity edge regenerates the disturbances.

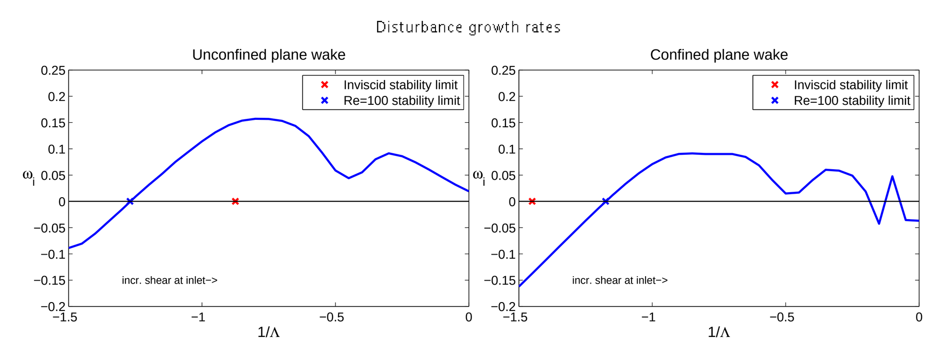


Confined plane wakes

In some applications confined plane wakes are used to enhance mixing. Inviscid analysis predicts that the confined wake is always the most globally unstable one. However, the viscous global modes with a wall boundary layer growing in the streamwise direction show that the confined wake might be more damped at least for some parameter values. Streamwise velocity for mean flow and disturbance in both cases can be seen below - the disturbance structure and wavelength are different in the two cases.

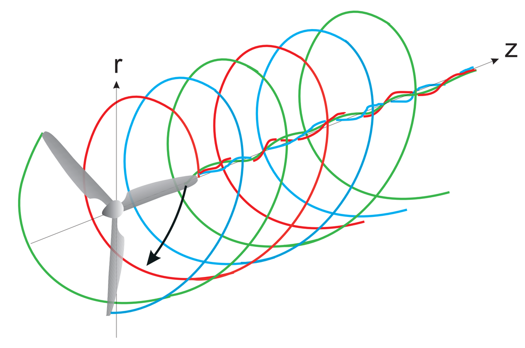


The wake confined with walls is more stable than the inviscid wake with the same inlet profile, while the opposite is true for the unconfined wake, which can be seen in the growth rate curves below.

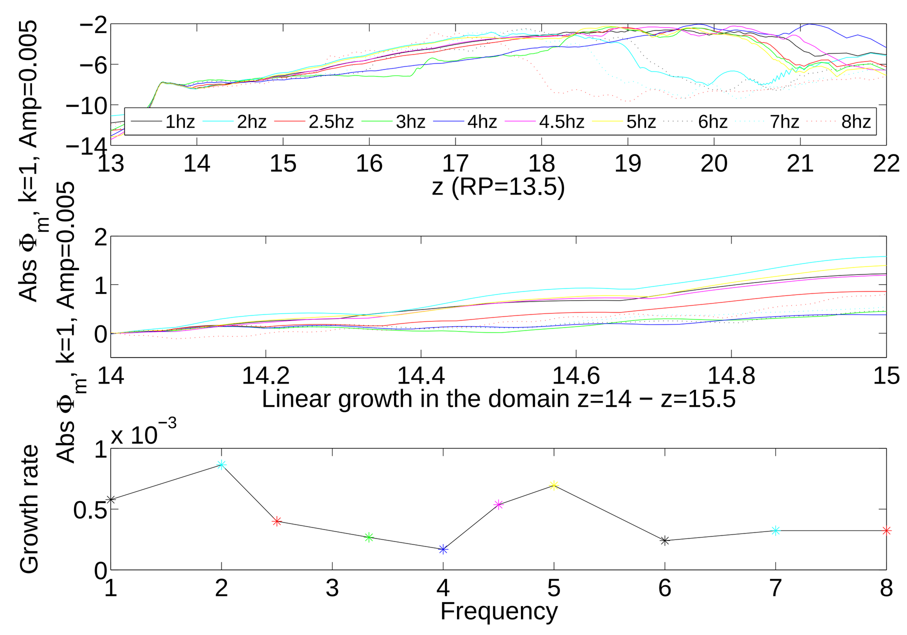


Wind Turbine Tip Vortex Stability Study

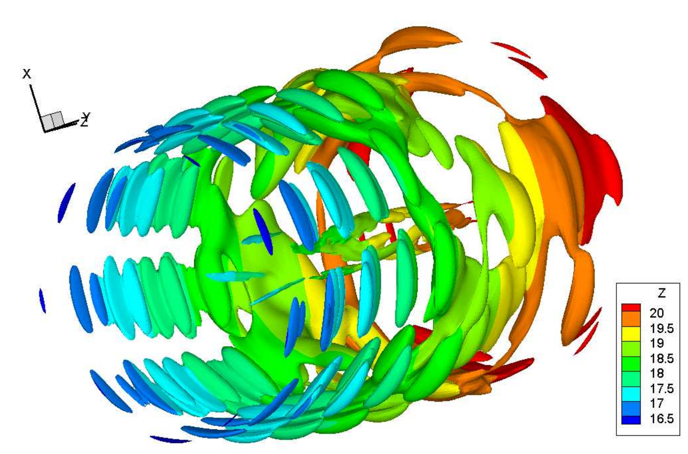
In the design of large wind farms it is essential to know the basic mechanism determening the length of the wake, closely coupled to the stability of the tip vortex. Steady simulations were performed to reach a basic steady flow field. This forms the initial condition for the subsequent stability analysis that basically consists of a time-dependent computations using large eddy simulation. To simplify the analysis only flow cases with constant axial inflow were considered. The point of onset and the growth of the instabilities were evaluated in detail. The presence of the rotor is modelled through body forces, determined from local flow and airfoil data. The aim is to study which modes that exist and to which extent they grow in order to quantify frequencies leading to vortex spiral break down. The figure shows the structure of the vortex spiral. By disturbing these vortex spirals one might trigger modes leading to instability growth and thereby vortex spiral break down.



By performing a Fourier transform on velocity field snapshots one can identify the response at different frequencies. The result shows that the maximum growth is at 2 and 5 Hz. Investigations show that this corresponds to spatial wavelength of 1.5 and 4.5 for each revolution.



The figure shows an iso-surface of the real part of the response from the perturbation with a frequency of 5 Hz. This correspond to a varicose mode with 4.5 wavelengths along the spiral in one revolution. One can identify the linear growth area up to about $z = 18.5$, i.e. 5 rotor radii behind the turbine.



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