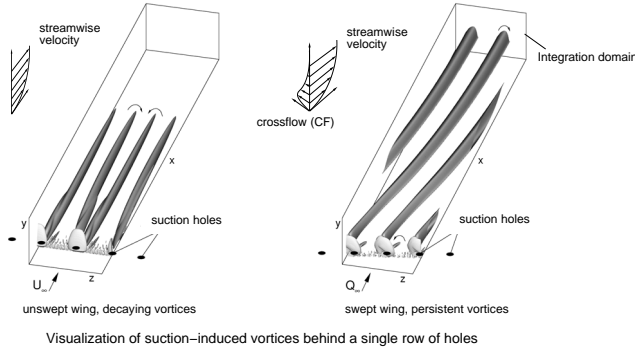


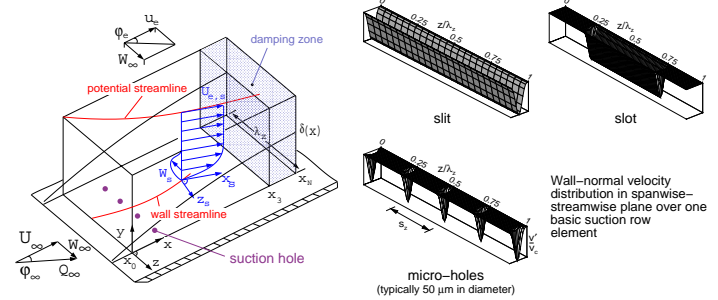
# Effects of spatial discrete suction on a 3-D boundary layer investigated by Direct Numerical Simulation (DNS)

## A Motivation

- Suction at the wall can significantly stabilize laminar boundary-layer flows but introduction of laminar flow technology in operational service of aircrafts still fails due to uncertainty resulting from an insufficient understanding of the flow phenomena inside the boundary layer.
- Discrete suction through micro-holes generates stationary disturbances which can be amplified in 3-D boundary layers like flows over swept wings of commercial airplanes, due to crossflow instability. This behaviour constitutes an essential difference to 2-D boundary-layer flows where stationary disturbances do not grow by primary instability.



## B Numerical Model for DNS

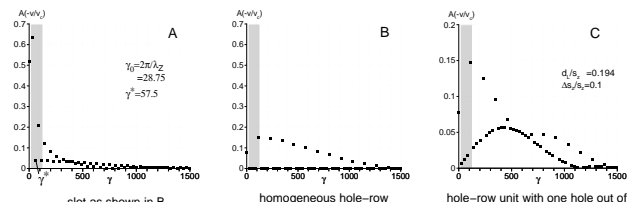


- Solution of the 3-D incompressible, unsteady Navier-Stokes equations in vorticity-velocity formulation
- Split into a steady base flow ( $\partial/\partial z=0$ ) and a disturbance flow  $u=u_b+u'$
- Time integration with 4th-order Runge-Kutta method
- Space discretization in streamwise and wall-normal direction with 6th-order compact differences on an equidistant grid with refined wall zone with halved  $\Delta y$ .
- Suction through spanwise slits, spanwise slots and holes is modeled by prescribing locally a wall-normal velocity distribution

## C Disturbance excitation by suction

### 1 Influence of shape of suction orifice and inhomogeneities

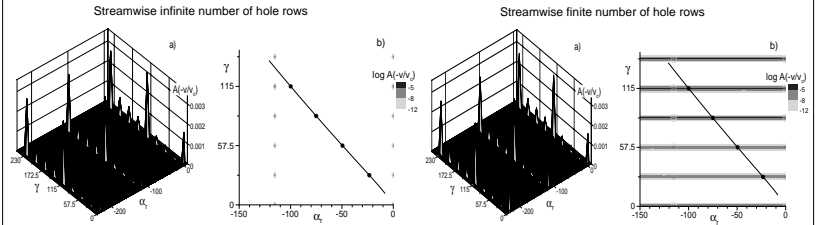
Discrete spanwise amplitude spectrum of normalized wall-normal velocity distribution in the middle of suction orifice. Shaded area indicates primarily unstable range. ( $\gamma^*$ : spanwise wavenumber of most amplified mode, see also D)



- The stronger the non-uniformity in spanwise suction-velocity distribution is, the broader is the spectrum of excited spanwise wavenumbers
- Spanwise spacing of suction orifices should be smaller than smallest wavelength of primarily amplified CF-modes
- Nevertheless, inhomogeneities like manufacturing imperfections or clogging always cause the excitation of the whole wavenumber spectrum

### 2 Hole array: Influence of streamwise extension

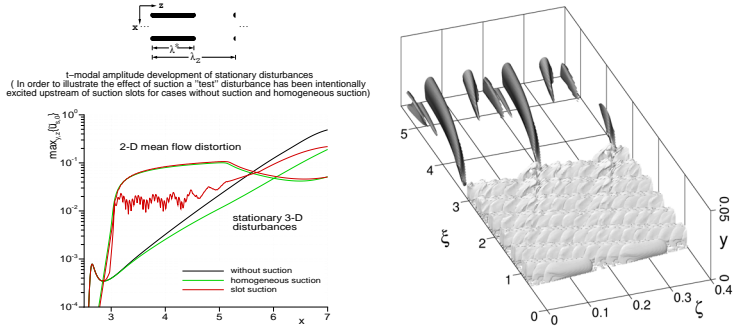
Discrete amplitude spectrum over streamwise-spanwise wavenumber plane of normalized wall-normal velocity distribution of hole array consisting of equally spaced hole rows in streamwise direction, corresponding to spectrum C1C



- Suction panels having a finite extension in streamwise direction always excite exponentially growing eigenmodes since the full spectrum of streamwise wavenumbers is excited
- As a first guideline for design streamwise and spanwise spacing of suction orifices should not coincide with  $\alpha_1-\gamma$  combinations of amplified eigenmodes of base flow

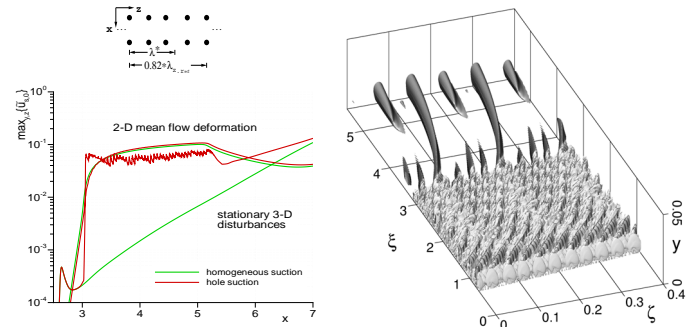
## D Disturbance development for subcritical suction

Slot array of 33 slot rows with spanwise slot spacing  $s_z = 2\lambda^*$ , where  $\lambda^*$  denotes wavelength of most amplified primary CF-mode



Suction excites damped modes of continuous eigenmode spectrum as well as exponentially growing modes of the discrete spectrum. In general, the meanflow effect of suction damps the growth of discrete eigenmodes. In case of slot array suction 3-D disturbances are only moderately excited and their amplitudes are only slightly higher than the test-disturbance amplitude in case of homogeneous suction. Each slot generates a streamwise vortex, thus the array creates a spanwise regular vortex pattern.

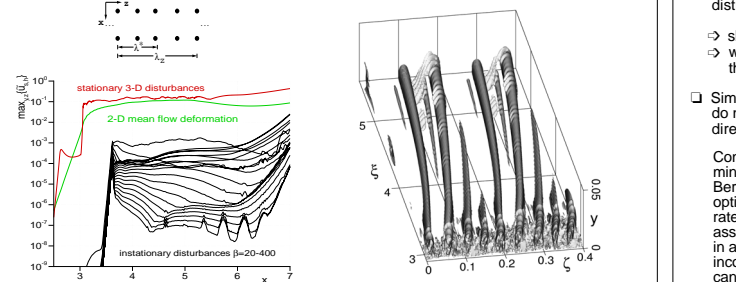
Hole array of 33 hole rows with basic spanwise hole spacing  $s_z = 0.41\lambda^*$ , but one hole out of order (see C1C, but  $\lambda_z = 0.82\lambda_{z,ref}$ ).  $s_z$  is smaller than smallest amplified wavelength.



Despite the basic hole spacing is smaller than the smallest amplified wavelength amplified wavenumbers are also excited due to one-hole disorder. Again the amplitude is only slightly higher than in case of homogeneous suction downstream of the hole array. At each hole a vortex emerges leading to complex vortex interactions over the suction array. Note that  $v_c$  is by a factor of 6.7 higher than in left case for equal suction rate.

## E Supercritical suction

Hole array of 33 hole rows with basic spanwise hole spacing  $s_z = 0.5\lambda^*$ , but one hole out of order (see C1C)



- Oversuction denoting premature transition triggered by too strong suction is caused by convective secondary instability triggered by large-amplitude crossflow vortices.
- Secondary instability theory can be used to forecast whether a suction configuration and its generated steady vortex pattern causes laminar breakdown.

## F Conclusions and Outlook

- Non-uniformity in spanwise suction distribution results in excitation of amplified stationary 3-D disturbances in 3-D boundary-layer flows
  - slits or at least spanwise slots are preferable
  - when using holes, the porosity of the panel should be high and spanwise hole spacing should be smaller than smallest wavelength of amplified crossflow modes
- Simple strategies like staggered hole orders which have been successfully applied in 2-D boundary layers do not work in 3-D base flows. One has to take into account the varying dispersion relation in streamwise direction.
  - Consequently, an optimization algorithm can be devised to minimize the excitation of discrete eigenmodes (see F. P. Bertolotti, NFMF 86, Springer, 2003). A sketch of such an optimized slot array is shown to the right. For strong suction rates stabilizing the boundary layer this approach fails as it assumes unaltered receptivity properties, as our DNS revealed in a joint project. An extension of such a concept has to incorporate the altered receptivity of the modified base flow but can be done.
- Besides the application on aircrafts, it is conceivable to laminarize the flow over rotorblades of modern wind turbines. First experiments have been undertaken by Waidmann (FH Aalen) showing a promising performance increase. Picture on the right shows the experimental set-up with a continuous suction slit in spanwise direction.

