Direct Numerical Simulations of Tollmien-Schlichting Disturbances in the Presence of Surface Irregularities

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Motivation

A realistic wing is not expected to be an ideal smooth surface: the presence of junctions or wing-panels amplifies the streamwise instabilities existing on a smooth surface, potentially causing an early transition to turbulence.

Methodology

The effect of surface irregularities on the development of Tollmien-Schlichting (TS) waves in an incompressible boundary layer is investigated using direct numerical simulations (DNS). The calculations are performed with the open source spectral element code NEK5000 and consist of:

1. DNS of the steady laminar two-dimensional base flow: $\mathbf{U_1} = \mathbf{U}(x,y)$
2. DNS for the disturbance propagation: 2D TS-waves are introduced into the base flow by a periodic blowing/suction slot at the wall. The amplitude of these artificial disturbances is chosen to be small enough to grant a purely linear development. $\mathbf{U_2} = \mathbf{U}(x,y) + \mathbf{u}(x,y,t)$

After a time-periodic state is reached everywhere, the perturbation amplitudes are computed: $\mathbf{u}(x,y,t) = \mathbf{U_2} - \mathbf{U_1}$

Base Flows

The cases selected can be considered an extension of the work by Wörner, Rist and Wagner (*AIAA* J. 41 (2), 192–197, 2003) to different geometric shapes:

- **Hump**: rectangular and smooth
- **Gap**: rectangular and smooth
- **Step**: backward and forward

$Re_u = 1\ [1/m], \quad h^*/\delta_1 = 0.47$

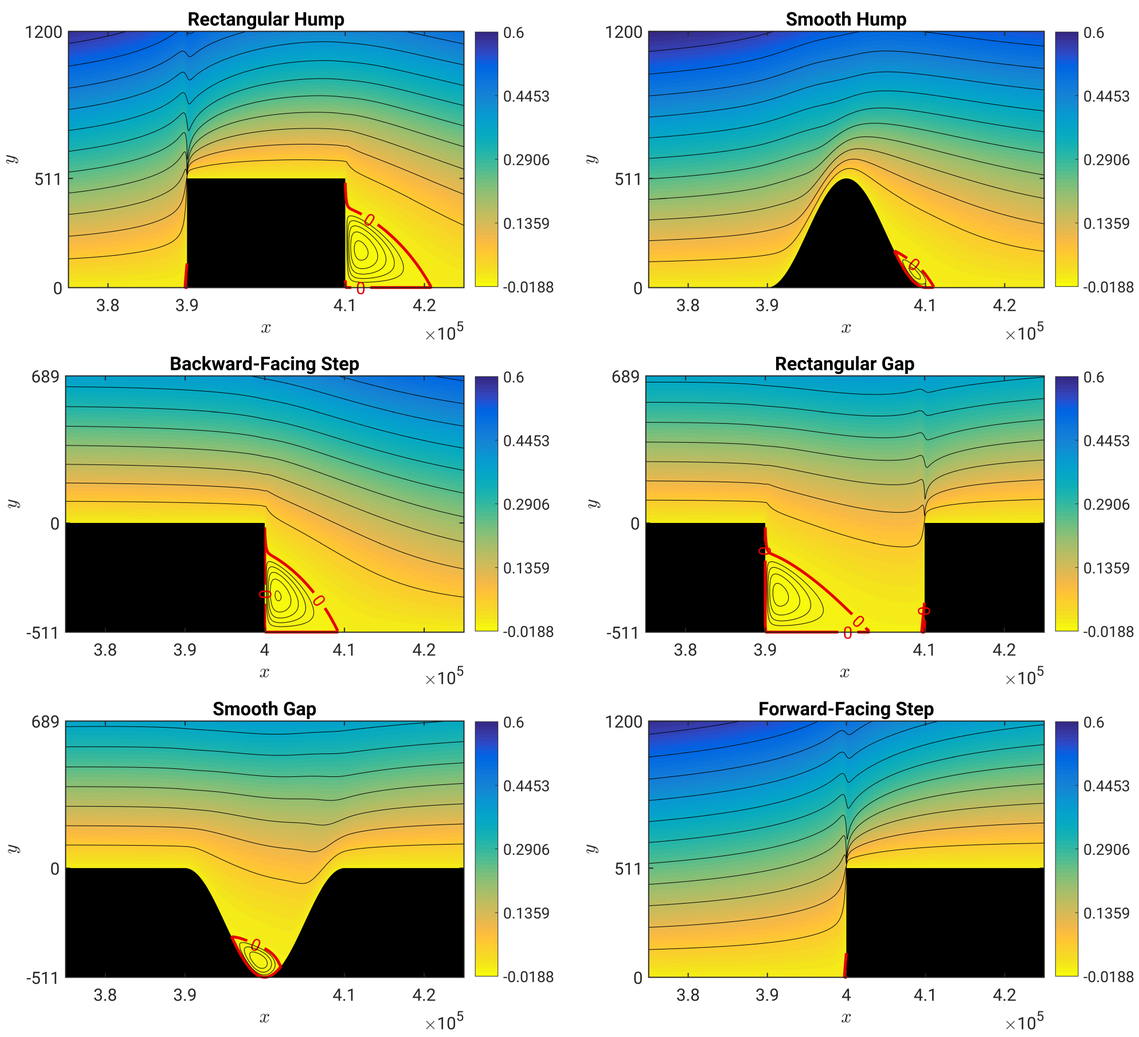
Surface irregularities parameters:

non-dimensional height:	$h = 511$
non-dimensional width:	$l = 2 \times 10^4$
non-dimensional centre position:	$x_c = 4 \times 10^5$

shape for the smooth cases: $y = \pm\frac{h}{2}\left(cos\left(2\pi\frac{r}{l}\right)+1\right), \quad r = \sqrt{(x-x_c)^2}$

The geometric irregularities are located on a flat plate and a Blasius profile is specified at the inflow boundary.

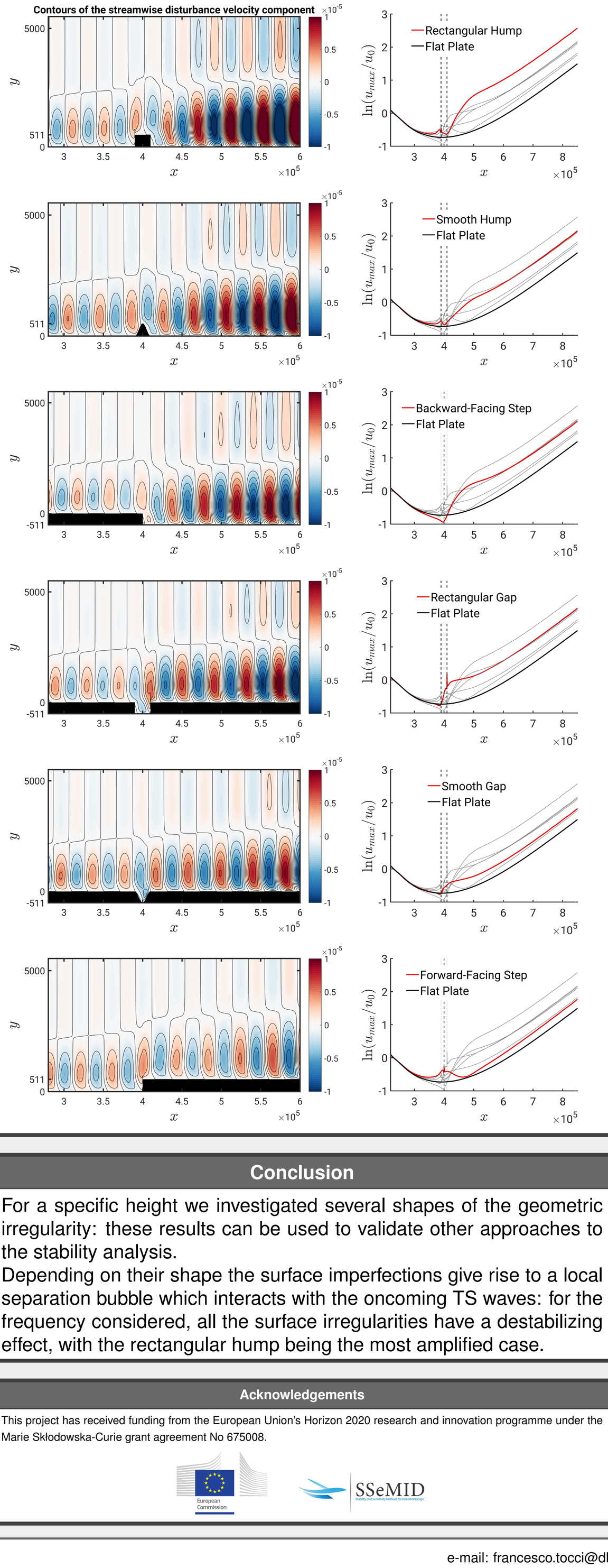
Contours of the non-dimensional streamwise velocity component for the base flows
(Note that the axes are not to scale)



Results

Development of the non-dimensional streamwise disturbance u for $\mathrm{F} = 49.34 \times 10^{-6}$ $[u_0 = u(x = 2.3 \times 10^5)]$

(Note that the axes are not to scale)



Conclusion

For a specific height we investigated several shapes of the geometric irregularity: these results can be used to validate other approaches to the stability analysis.

Depending on their shape the surface imperfections give rise to a local separation bubble which interacts with the oncoming TS waves: for the frequency considered, all the surface irregularities have a destabilizing effect, with the rectangular hump being the most amplified case.

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