Transition to turbulence in a separated boundary layer with spanwise perturbations

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Abstract

The influence of spanwise perturbations on transition to turbulence in a separated boundary layer is studied by direct numerical simulations using a high resolution numerical scheme. The perturbations are generated by positioning a discrete roughness element that has a varying height in a periodic manner in the spanwise direction, close to the inflow. Results indicate that there are substantial differences between the dynamics of the transition to turbulence mechanism due to this varying height in comparison with the mechanism due to a discrete roughness element having a constant height in the spanwise direction.

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1. Introduction

The efficiency of low pressure turbines is influenced by the extent and size of the separation bubble that forms on the low pressure side of the turbine blade. In general the flow on the low pressure side of the turbine blade is laminar at the leading edge, decelerated due to an adverse pressure gradient, which causes the flow to separate and transition to turbulence close to the trailing edge. An increase in efficiency requires the ability to control the size of this bubble, without unduly moving the laminar-turbulent transition point upstream. Obviously a lot of study has been undertaken to understand the influence of small perturbations on the separation bubble.

Apart from time dependent fluctuations, which will not be discussed further, time independent fluctuations have been studied\textsuperscript{1}. In general these fluctuations are generated by a tripwire, with or without a spanwise (perpendicular to the flow direction) variation but roughness also falls in this category. Although these perturbations have a lower growth rate than the time dependent fluctuations, they are still important because they are easier to implement and/or they occur naturally on used turbine blades.

The work done on this subject can be broadly divided in two branches, namely a branch that concentrates on the engineering aspect of these perturbations and a branch which is more academic\textsuperscript{2}. The difference is mostly due to differences in Reynolds number (high in the first branch and relatively low in the second branch) and in the manner the
perturbations are imposed (real roughness and trip wires in the first Branch and certain blowing and suction profiles in the second).

In this article we would like to contribute in closing the gap between the engineering approach by presenting a direct numerical simulation (DNS) of a boundary layer with a turbine like pressure gradient and Reynolds number. The trip wire is implemented using an immersed boundary method, which adds additional features of a real flow configuration to the simulation.

### Nomenclature

<table>
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<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$Re$</td>
<td>Reynolds number $U_{ref} \theta/\nu$</td>
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<td>$U_{ref}$</td>
<td>Reference velocity at the inflow [m/s]</td>
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<tr>
<td>$\theta_0$</td>
<td>Momentum thickness at inlet [m]</td>
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<tr>
<td>$k_r$</td>
<td>Wavenumber of the roughness element [1/m]</td>
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<tr>
<td>$h_r$</td>
<td>Height of the roughness element [m]</td>
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2. Numerical method

The numerical code uses a relatively classical fractional-step method to solve the incompressible Navier-Stokes equations expressed in primitive variables. It is discussed in detail in $3^4$.

The model that we are using in this study is a flat plate with a streamwise pressure distribution similar to those encountered on the suction side of turbine blades. An almost constant suction velocity is imposed at the upper boundary to match a typical turbine adverse-pressure-gradient (APG). No-slip boundary condition is applied on the wall and the spanwise direction is treated as periodic. At the outflow plane a convective boundary condition is used, with minor adjustment to the exit velocity to ensure global mass conservation. The time step is adjusted to a constant $CFL = 0.6$, to preserve time accuracy. The Reynolds number based on the momentum thickness $Re_{\theta_0} \approx 110$ is low enough to be in the realm of expensive DNS $5$. The streamwise, wall-normal and spanwise directions and velocity components are $x, y, z$ and $u, v, w$, respectively.

The uncontrolled flow (without roughness) is initially laminar, separates due to strong APG, transitions within the separation bubble, reattaches as a result of the transition, and finally develops into an attached turbulent APG. The transition to turbulence scenario is altered by positioning a trip wire, with a height of $h_r = 0.7 \theta_0$, close to the inflow. The trip wire that has either a uniform height in the spanwise direction or one that has a height that is a function of the spanwise coordinate is modeled using the immersed boundary method $6^78$. Here, instead of using interpolation to impose the immersed boundary we estimate the immersed force necessary to achieve zero velocity within the roughness and then add this to the momentum equations. A similar approach was also used in $8^9$. Steady three-dimensional perturbations are also explicitly added at the inflow for transition to occur in the cases where a two-dimensional roughness is imposed, since otherwise spectral codes along the span, like the one used here, would remain strictly two-dimensional. The details of the simulations are described in $5$.

3. Results

In a recent study $5$ we systematically investigated the discrete roughness effect on a separated boundary layer development by varying the roughness type, the height, and the location. Our results indicate that the presence of discrete surface roughness increases the turbulent fluctuations in the turbulent boundary layer and it shifts the laminar-turbulent transition at some upstream position, and results in a shorter and lower separation bubble as compared to the uncontrolled flow. In that study we also found that, the spanwise varying roughness elements alter the laminar separation and turbulent transition in a different manner than the two-dimensional roughness elements. The reader is referred to that work for details of the basic flow statistics. In this study we would like to investigate in detail the transition mechanism.

Figure 1 presents the influence of the roughness on the flow velocities. The spanwise perturbations cause the flow to transition far downstream of the separation point. The most striking feature is the very ordered structure of the flow during the transition phase, in particular when $k_r \theta_0 = 0.052$, and especially considering the $v$ and $w$ velocity
Fig. 1. Effect of spanwise perturbations on transition to turbulence. (a) Two-dimensional roughness, $k_r\theta_0 = 0.0$; (b) Three-dimensional spanwise varying roughness, $k_r\theta_0 = 0.026$; (c) Three-dimensional spanwise varying roughness, $k_r\theta_0 = 0.052$. From top to bottom: instantaneous streamwise, wall-normal and spanwise velocity at $y/\theta_0 = 3.1$. --- marks the beginning of the roughness element and the end, respectively. White vertical lines mark the location of the separation bubble.

components. Although all three cases show a lot of order, the flow structures are very different between these three cases. The streamwise velocity in the case of $k_r\theta_0 = 0.052$ shows large streaky structures, extending over the whole streamwise length, whose origin can be traced back to the instability. The same is less clear for the other two cases. These differences will be discussed in detail in the final paper, along with comparisons of current numerical results with experiments and other numerical studies. Furthermore, the stability characteristics of the mean flow will be evaluated in terms of local spatial linear stability analysis based on the Orr-Sommerfeld equation.

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References