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Bypass transition in the narrow sense revisited using very-large-scale direct numerical simulation

Xiaohua Wu* **and Parviz Moin**†

* Mechanical and Aerospace Engineering Department, Royal Military College of Canada
†Center for Turbulence Research, Stanford University

Flat-plate boundary layer, an idealization of the flow over an aircraft wing, may transition from laminar to turbulent under infinitesimal disturbance (natural transition), or under weak yet finite amplitude disturbance (bypass transition). We define bypass transition in the narrow sense as the zero-pressure-gradient boundary layer beneath a continuous free-stream flow of grid turbulence decaying from an initial intensity between 1 to 4 percent. It has been widely believed in the literature that this type of transition always develops its own distinct primary instability in the form of streaks, as well as its own secondary instability. We show that bypass pass transition in the narrow sense may also proceed through the natural and sequential formation of quasi-spanwise structure, Lambda vortex, hairpin packet, infant turbulent spot, and hairpin forest.

In our most recent very-large-scale direct numerical simulation of the incompressible flat-plate boundary layer, the boundary layer grows from $Re_\theta = 80$ to $Re_\theta = 3018$. The grid size is $16384 \times 500 \times 512$, yielding a total mesh points of 4.2 billion. Accuracy of the results is established by verifying the statistics agree with analytic laminar solution over an extended range prior to breakdown, and agree with accepted data in the fully-turbulent region after the completion of transition. Specifically, we compared our DNS results with the experimental data of DeGraaff & Eaton (2000) at $Re_\theta = 2900$. The agreement is excellent. We also compared the present results with the DNS of Schlatter & Orlu (2010) at $Re_\theta = 2536$. Predicted skin friction falls almost exactly on to the Blasius solution prior to breakdown, follows the trend of the well-known T3A bypass transition experiment, and agrees very well with Melbourne wind tunnel data after the completion of transition. Causality embedded in the present transition process is revealed by sequencing images similar to Fig.1. We found that bypass transition in the narrow sense can occur along a route analogous to the secondary instability and breakdown process of boundary layer natural transition. Streaks are present, but they are not dynamically important in our flow because they occur downstream of the Lambda vortices.