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

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Abstract 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, using very large-scale direct numerical simulation with 4 billion grid points, that bypass 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 simulation, the boundary layer growes from momentum thickness Reynolds 80 to 3000, and the mesh is 16384 x 500 x 512. Accuracy of hte results is established by verifying the statistics agree with analytic laminar solution over an extended region prior to breakdown, follows the trend of the well-known T3A bypass transition experiment, and agrees with the Melbourne wind tunnel data after the completion of transition. Causality embedded in the transition process is revealed by sequencing high-resolution images during the dynamic transition process..

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