NUMERICAL STUDY ON THE KEY MECHANISM OF BYPASS TRANSITION

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Abstract The scenario of bypass transition is generally described theoretically as follows: the low-frequency disturbances in the free-stream generate long stream-wise streaks in the boundary layer, which later would trigger secondary instability, leading to rapid increase of high-frequency disturbances, then possibly turbulent spots emerge, and through their merging, fully developed turbulence appears. This description, however, is insufficient in the sense that it does not provide the inherent mechanism of transition that during the breakdown stage, why a large number of waves with different frequencies and wave numbers would appear almost simultaneously, leading to a swift change of the mean flow profile. In this paper, the mechanism is found to be the swift change of the stability characteristics of mean flow, which has a positive feedback effect on the change of mean flow profile. And another interesting finding is that, during the transition, the unstable disturbance waves which appear first belong to a branch of inviscid modes, while following the change of the stability characteristics of the mean flow profile, disturbance waves belong to another branch of inviscid modes, which play the key role in bypass transition.

INTRODUCTION

So far, the whole scenario of bypass transition is described as consists of several stages: the generation of streaks by FST; the evolution of streaks; the secondary instability and the growing and merging of turbulent spots. However, there is no explanation in regard with how secondary instability leads to turbulent spot, and how turbulent spots merge, etc. Hence, there is actually no clear description about the inherent mechanism of breakdown. The aim of the present paper is to build this missing link in the process of bypass transition.

In this paper, temporal mode direct numerical simulation (DNS) for the bypass transition of an incompressible boundary layer on a flat plate is performed, from which the inherent mechanism of the breakdown process is to be sought out. Our DNS starts from an instant that longitudinal streaks have already been triggered by free-stream turbulence, and the flow field of that instant was provided by Zhang from their computation [1]. Our computation ends up when the breakdown process is fully accomplished, i.e. fully developed turbulent flow appears.

TEMPORAL DNS METHOD AND RESULTS

We use temporal mode DNS. The initial flow field in our DNS is a Blasius profile plus a flow field representing a group of longitudinal streaks, which is kindly provided by Zhang et al.[1]. Based on the 2-D basic flow, the secondary instability disturbance is also introduced as the initial disturbance with amplitude of 0.005.

In the simulation, no free stream turbulence is introduced at the upper boundary of the computational domain, or at the inviscid region of the initial flow, the streak would die out quickly without a forcing, so we imposed a body force to maintain the streaky profile. Considering the streaks only exist in the laminar stage, we only imposed the body force from t=0 up to t=48.8, after that, the body force term is set to be zero, which makes sure the transition and turbulent stage are not influent by the body force imposed.

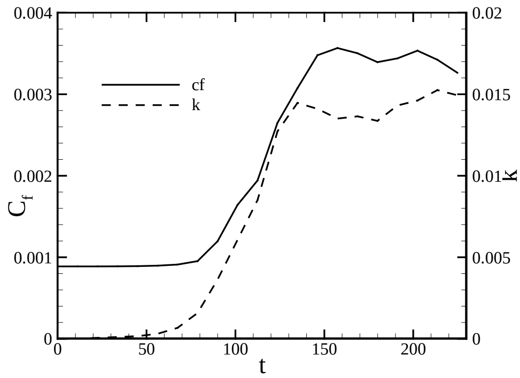


Figure 1. Cf curves vs. t.

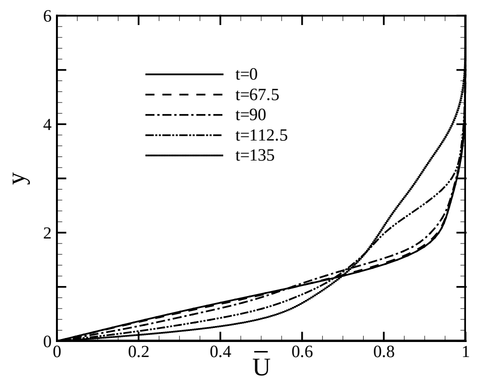
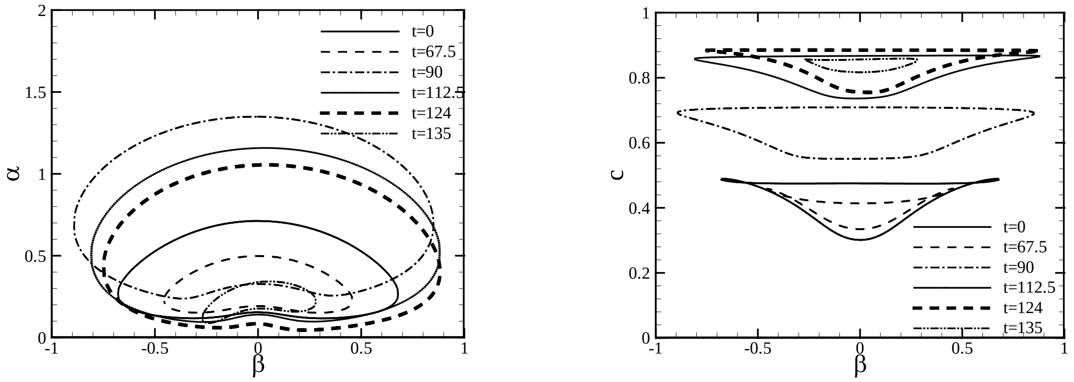


Figure 2. Mean flow profile

Fig. 1 shows the temporal evolution the friction coefficient at the wall (Cf curve) and the turbulent kinetic energy. They all start to rise sharply at about t=75, indicating that laminar flow breakdown process starts. Actually, the turbulent kinetic energy curve rises a little earlier than Cf curve does, but the difference is not big.

Fig. 2 shows the span-wisely averaged mean velocity profiles at different time. The initial mean profile keeps almost unchanged up to t=67.5. At t=90, the modification is more visible, there appear two inflection points, the upper one, which causes invicid instability, is located at y≈1.35, and at this moment, $\overline{U}_0(1.35) \approx 0.72$. At t=112.5, the upper inflection point moves to a higher location, i.e. y≈2.36, and at this moment, $\overline{U}_0(2.36) \approx 0.86$. The change of the location of the inflection point may lead to different branches of instability waves.



a) Neutral curves

b) Phase speeds of the neutral curves

Figure 3. Neutral curves and the corresponding phase speed based on mean profiles at different time instants

Fig. 3-a) shows the neutral curves for the mean flow profiles at different time instants. For the initial mean flow profile, linear stability analysis shows that there is already an unstable zone in α-β plane. Actually, the mean flow profile is already modified by then due to the existence of streaks, guaranteeing that the initial unstable wave can further extract energy from the mean flow through linear instability mechanism, and it in turn modifies further the mean flow profile. However, as time goes on, this unstable zone becomes smaller and smaller, and even disappears before t=80. On the other hand, before t=90, there appears another new unstable zone, and becomes a larger one at t=90, with a higher phase speed, around 0.6, for the unstable waves. Further later, for example, from t=112.5 up to t=124, the phase speed of the unstable waves become even larger, around 0.8, and the unstable zone remains large. The largest growth rates of unstable waves corresponding to these several time instants are of order 0.01, much larger than traditional viscous T-S waves, i.e. O(0.001). The implication is, during the breakdown process, unstable waves would be amplified very rapidly. Besides, larger phase speed implies that the peak location of their disturbance velocity is further away from the wall, so the modification of the mean flow profile is now mainly in the outer region. Further downstream, the unstable zone becomes smaller, and vanishes at turbulent stage.

A short summary is, in the breakdown process, as the unstable zone enlarges, more unstable waves would appear and be amplified, and the amplified waves in turn would generate larger Reynolds stress, modifies the mean flow profile more effectively, thus further influence the unstable zone. This certainly is a sort of positive feedback effect, is the inherent mechanism of the breakdown process.

As for the unstable waves, there is a switch from the lower phase speed mode to higher phase speed mode, or we call a switch from the inner mode to the outer mode, so in the breakdown process, the outer mode eventually plays the key role

References

[1] Y. Zhang, T. Zaki, S. Sherwin and X. Wu. Nonlinear response of a laminar boundary layer to isotropic and spanwise localized free-stream turbulence. AIAA-2011-3292. 2011.