EXPERIMENTAL INVESTIGATION ON LATER TRANSITION STAGE OF LAMINAR STREAK

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Summary The present experiment is devoted to study the laminar streak dynamics exposed to the wake of an interference wire which can be regarded as the quasi-antisymmetric disturbance source. It is observed that one low-speed streak is initially formed inside the laminar boundary layer through leading-edge receptivity, and it fulfills a spanwise reproduction process through streak instability mainly characterized as sinuous mode. However, Proper Orthogonal Decomposition analysis shows the existence of varicose mode, which competes with sinuous mode throughout the whole streamwise extend. These two modes have almost the same convection velocity, and both contributes to the streak breakdown which provides inertial feedback to the near wall fluid to induce additional low-speed streaks.

INTRODUCTION

It is widely accepted that the later transition stage of laminar boundary layer is mainly characterized by nonlinear evolution of coherent structures and their subsequent interaction. Low-speed streaks, as one of the universal structures in later transition stage, contribute a lot to the final 'breakdown' to turbulence and the underlying self-sustaining mechanisms[1].

A lot of work has been done dealing with streak formation and streak instability. It is believed that the streak formation stage, in the sense of bypass transition subject to free-stream disturbance, can be more or less predicted by transient growth theory[2, 3] and the related optimal disturbance analysis[4, 5]. Previous work on streak instability mainly use localized wave disturbance to trigger secondary instability, revealing the existence of two types of streak instability[6-10]: sinuous mode and varicose mode. These works promote the understanding of later-transition dynamics to the level of structure interaction; however, difference still exists between the well-controlled disturbances used to trigger localized secondary instability of a single streak and the distributed disturbances in reality which has broad range of frequency and wavelength and convected downstream within the boundary layer.

The present work is devoted to study the laminar streak dynamics subjected to a distributed disturbance environment. Inspired by the work of Kogan[13], we use the wake of an interference wire as the disturbance source. With the wire Reynolds number Re_D=220, the wire wake contains transitional eddies, thus triggers the boundary layer with distributed disturbance which gradually lose its periodicity and anti-symmetry as convecting downstream. The experiment is conducted in a water channel with low level of background noise (free-stream turbulence intensity Tu<0.8%) at U_∞=87mms^{-1}. Both Hydrogen bubble visualization and two-dimensional time-resolved PIV measurement are used to investigate the whole flow field. Fig.1 illustrates the model arrangement and the coordinate definition.

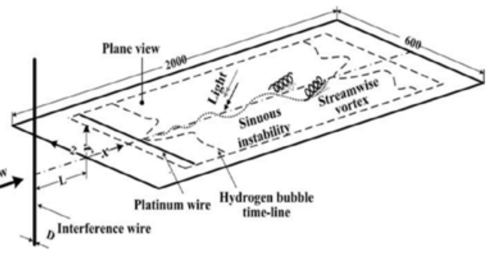

Fig.1 Illustration of the experimental arrangement.

RESULTS AND CONCLUSION

It is found that the wire wake generates one low-speed streak inside the boundary layer through leading-edge receptivity process similar to what has been predicted by rapid distortion theory[14]. The downstream evolution of this single streak presents a re-growth trend in streak strength statistics. The first growth stage is dominated by the streak instability, while the secondary growth stage might be associated with the unsteady breakdown of the streak. Two additional low-speed streaks begin to appear on either side of the original streak both in mean velocity field and in instantaneous flow pattern in the second growth stage (as shown in Fig.2).

The streak instability mainly presents a sinuous mode, whose qualitative representation is the spanwise-wavy motion of the streak, which can be observed from Hydrogen bubble visualized flow pattern (as shown in Fig.2a and Fig.2b). Using Proper Orthogonal Decomposition (POD), the sinuous mode and varicose mode can be both observed in the mode space. To do this, the PIV-measured velocity filed in (x, z) plane is decomposed into sets of orthogonal modes, which are ranked in the order of their contribution to the total energy. Typical sinuous mode presents an odd distribution of u component and an even distribution of v component in (x, z) plane (as shown in Fig.3a), *e.g.* in sinuous mode the low speed streak has anti-symmetric velocity fluctuation of u component and symmetric v fluctuation along its center. On the other hand, typical varicose mode presents an

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opposite shape: even distribution of u and odd distribution of v along streak center. Using this criteria, we can classify all the POD modes into three groups: sinuous type, varicose type and else. By summarizing the corresponding energy value of each sinuous/varicose POD mode, the total energy contribution of each instability type can be estimated. Table.1 shows the relative energy portion at 3 different streamwise position. It is again evidenced that sinuous mode is the dominant streak instability throughout the whole streamwise span; however, the competition from varicose mode is significant: at the streamwise station of x=1150mm, the energy contribution of varicose mode is three times larger than the value at x=400mm.

Another interesting phenomena depicted by Table.1 is that the energy contribution of sinuous mode is not monotonically increasing with streamwise position. After x=750mm, the energy portion contributed from sinuous mode gradually decreases, this is consistent with the Hydrogen bubble visualization: streak sinusoidal oscillation becomes more and more irregular, suggesting that nonlinearity effect develops quickly to deviate the regular sinuous instability. It can be observed that sometimes the low-speed streak may oscillates with very large amplitude in several cycles, in which significant energy growth up to tenfold can be achieved; once the streak reaches a local maximum of oscillation amplitude, generation of streamwise vortices can be observed, which leads to the formation of a train of streamwise vortices with alternating sign. The vortex generation scenario is consistent with that in both the 'controlled' streak breakdown triggered by localized wall-introduced disturbances[6] and the 'natural' breakdown exposed to FST[11, 12]. We argue that this sinuous-typed 'streak breakdown' provides inertial feedback to the near wall fluid to induce additional low-speed streaks. Therefore, the single streak fulfils the spanwise reproduction process in the same sense of what the self sustaining mechanisms depict. Moreover, the characteristic frequency and the corresponding streamwise/spanwise wavelength will be discussed with the help of POD analysis.

Table.1 Comparison of energy contribution between sinuous mode and varicose mode at different streamwise station

	sinuous mode	varicose mode
x=400mm~500mm	32.8%	3.4%
x=750mm~850mm	57.5%	6.7%
x=1150mm~1250mm	40%	9%

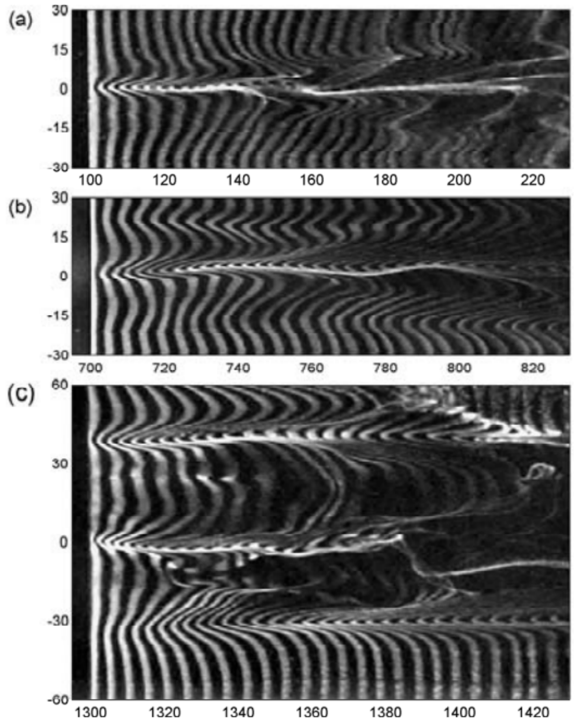

Fig.2 Typical (x, z)-plane visualization at y/δ=0.4 with different streamwise position. Free-stream flows from left to right, and platinum wire is horizontally positioned at (a) x_w=100 mm; (b) x_w=700 mm; (c) x_w=1300 mm. (Unit: mm)

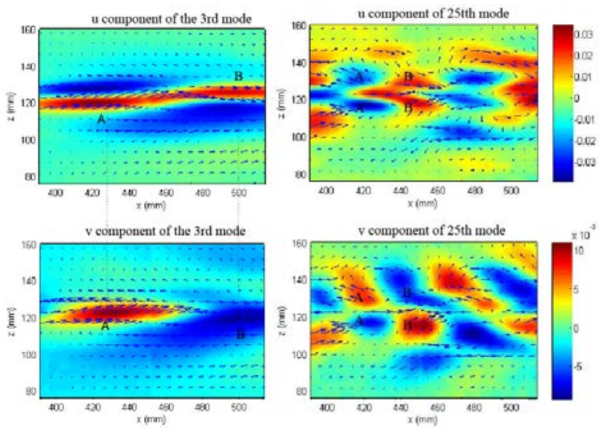

Fig.3 Sinuous mode and varicose mode represented by the u/v component of POD mode shape. Noting that time averaged velocity field has been subtracted from the mode, where the mean low-speed streak centers at around z=120mm.

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