Development of streak instability modes excited by turbulent fluctuations

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Abstract. Development of streak instability modes excited by disturbances whose frequency-spectrum was similar to that of wall turbulence was examined experimentally for a single screen-generated low-speed streak. The disturbances were introduced into the low-speed streak through two small holes made on both the sides of the low-speed streak. The result showed that even when the low-speed streak was forced by turbulent fluctuations with zero spanwise correlation, sinuous instability modes were excited with distinct frequency selectivity around the most unstable frequency of the linear streak instability and dominated streak breakdown in the downstream region. The magnitude of the sinuous modes excited was compared to the case when the anti-symmetric forcing with the same turbulence spectrum was applied.

1. Introduction
Breakdown of low-speed streak(s) into quasi-streamwise vortices, is considered to be a key event for generation and sustenance of wall turbulence structure. We have been studying the streak instability and breakdown experimentally for well-controlled low-speed streak(s) under various disturbance conditions/environments. The experiments examined the sinuous and varicose instabilities of a single low-speed streak [1] and the fundamental and subharmonic instabilities in spanwise-periodic low-speed streaks [2, 3]. In these experiments, the low-speed streak/streaks were generated artificially in a laminar boundary layer by using a small piece/pieces of screen set normal to the boundary-layer plate, and the streak instability was triggered by well-controlled sinusoidal disturbances with mono-frequency. These experiments showed that sinuous instability could continue to grow downstream and lead to breakdown of low-speed streak(s) into quasi-streamwise vortices not unlike those observed in near-wall turbulence [4, 5, 6]. Furthermore, streak instability and breakdown in a re-transition caused by suction-surviving residual turbulent fluctuations was examined [7], and streak breakdown due to growth of sinuous instability waves was observed in spite that disturbances exciting the streak instability were frequency-rich.

In experiments on bypass boundary-layer transition, laminar boundary layer was subjected to free-stream turbulence with relatively high intensity which has often been controlled by turbulent grid upstream of the boundary-layer plate [8, 9, 10]. On the other hand, in numerical computations simulating bypass boundary-layer transition under free-stream disturbance, initial disturbances were supplied using continuous-spectral modes of Orr-Sommerfeld and Squire equations [11, 12]. These experimental and computational studies showed that occurrence and growth of sinuous instability modes dominated the streak breakdown.
In the present experimental study, aiming at giving further insights on instability and breakdown of low-speed streak(s) in natural or turbulent environments, a low-speed streak is forced by disturbances with a continuous spectrum similar to that of developed wall turbulence. A particular attention is paid to how the growth of sinuous instability modes depends on nature of disturbances triggering the instability.

2. Experimental setup and procedure

The experiment was conducted in a low-turbulence wind tunnel with an exit cross-section of 400×400 mm². As illustrated in Fig. 1, a boundary-layer plate (10 mm thick and 1100 mm long) was set parallel to the oncoming uniform flow in the test section. This facility is the same as that used in experiments [1, 2, 3]. The free-stream velocity \( U_\infty \) was fixed at 4 m/s throughout the experiment. A single low-speed streak was produced in the boundary layer by using a small piece of 40-mesh screen (wire-gauze) set normal to the boundary-layer plate at a station 500 mm downstream of the leading edge. The screen height and width were both 3 mm. Note that the displacement thickness \( \delta^* \) of Blasius boundary layer was about 2.5 mm at the screen location in the absence of the screen. The coordinate system was such that \( x \) was the streamwise distance, measured from the leading edge, \( y \) the normal-to-wall distance and \( z \) the spanwise distance. The screen location (\( x = 500 \) mm) is denoted by \( x_0 \).

The laminar streak flow was forced by external disturbances which were introduced through two small holes which are drilled on the wall 6 mm downstream of the screen, with a spanwise interval of 6 mm and were connected to two loudspeakers as has been done in [1] where the streak instability was excited at a single frequency. In the present experiment, the instability was excited by a turbulent fluctuation signal which was deduced by a hot-wire measurement in a buffer region (\( y^+ = 23 \)) of turbulent boundary layer generated by gluing cylinder roughness elements on the boundary layer plate, at an upstream location (\( x = 100 \) mm) under the same free-stream condition. The screen width (3 mm) was about 50\( \nu/u_t \), where \( u_t \) was the friction velocity of the turbulent boundary layer and \( \nu \) was the kinematic viscosity. We applied two kinds of forcing to excite streak instability. One was an anti-symmetric forcing (Case 1) in which two loudspeakers were driven with turbulent signals that were 180° out of phase, and the other was a forcing due to two turbulent signals with zero correlation (Case 2). We of course expected that the anti-symmetric forcing was the most effective for excitation of sinuous instability modes. A constant temperature hot-wire anemometer was used to measure time-mean and fluctuating velocities in the streamwise direction, \( U \) and \( u \).
3. Result and discussion
Figs. 2(a) and (b) illustrate distributions of the mean velocity $U/U_\infty$ in the $(y, z)$ plane at $x-x_0 = 60$ mm and 140 mm, respectively. A laminar low-speed streak developed downstream of the screen. The velocity difference across the low-speed streak was about 35% and 20%, at $x-x_0 = 60$ mm and 140 mm, respectively. In the absence of any artificial disturbances, the low-speed streak maintained laminar completely in the observation region up to $x-x_0 = 300$ mm.

Before examining frequency-selective growth of disturbances initially consisting of turbulent spectral components, we examined the instability characteristics of the present low-speed streak by driving the loudspeakers at a single frequency. By introducing symmetric and anti-symmetric disturbances, we could easily excite varicose and sinuous instability modes as shown in Figs. 3(a) and (b), respectively, which illustrate the amplitude distributions of $u$-fluctuation (of the forcing frequency).

Figure 2. Contours of mean velocity $(U/U_\infty)$ in the $(y, z)$ plane. (a) $x-x_0 = 60$ mm, (b) $x-x_0 = 140$ mm. Contour levels range from 0.1 to 0.9.

Figure 3. Amplitude distributions of $u$-fluctuations $(u'/U_\infty)$ in the $(y, z)$ plane. (a) Varicose mode of $f = 110$ Hz at $x-x_0 = 50$ mm. Contour levels range from 0.002 to 0.018. (b) Sinuous mode of $f = 90$ Hz at $x-x_0 = 100$ mm. Contour levels range from 0.005 to 0.035.

Figure 4. Amplification of sinuous mode from $x-x_0 = 40$ mm to 180 mm. $N$ vs. $f$. 

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in the (y, z) plane. The symmetric varicose modes could not continue to grow downstream in the present low-speed streak because the span width of the horizontal (∂U/∂y) shear layer away from the wall in the low-speed streak was too small compared to the shear-layer thickness: Varicose modes decay downstream beyond x - x₀ = 60 mm. Whereas the anti-symmetric sinuous modes could continue to grow downstream almost exponentially. Fig. 4 illustrates the frequency selective growth of sinuous disturbances in terms of N-value defined as N = ln[ u'² / u'₀²] where u'₀ is the maximum rms value of u-fluctuation component at x - x₀ = 40 mm. The maximum amplification of the sinuous mode occurred at and around 100 Hz in the present streak flow condition. Then we examine the response of the low-speed streak to disturbance with turbulence spectrum mentioned above.

**Figure 5.** Waveform and power spectrum of the forcing signal. (a) Waveform, (b) power spectrum.

**Figure 6.** Power spectra of u at x - x₀ = 10 mm, 60 mm, 100 mm, 140 mm and 180 mm for anti-symmetric excitation (Case 1).

**Figure 7.** Amplitude distribution of u (u' over 30-120 Hz) in the (y, z) plane for anti-symmetric excitation (Case 1). (a) x - x₀ = 60 mm. Contour levels range from 0.0015 to 0.009. (b) x - x₀ = 140 mm. Contour levels range from 0.003 to 0.03.
Figure 8. Power spectra of $u$ at $x - x_0 = 10$ mm, 60 mm, 100 mm, 140 mm and 180 mm for Case 2.

Figure 9. Amplitude distribution of $u$ ($u'$) over 30-120 Hz in the $(y, z)$ plane for anti-symmetric excitation (Case 2). (a) $x - x_0 = 60$ mm. Contour levels range from 0.0015 to 0.009. (b) $x - x_0 = 100$ mm. Contour levels range from 0.002 to 0.014. (c) $x - x_0 = 140$ mm. Contour levels range from 0.003 to 0.021. (d) $x - x_0 = 180$ mm. Contour levels range from 0.003 to 0.027.

Figs. 5(a) and (b) display the waveform and power spectrum of turbulent signals supplied to the two loudspeakers, where the spectral components below 5 Hz were filtered out for the input signals to the loudspeakers. Fig. 6 illustrates power spectra of $u$ at $x - x_0 = 10$ mm, 60 mm, 100 mm, 140 mm and 180 mm for the anti-symmetric excitation (Case 1); they were measured at a vertical shear-layer ($\partial U/\partial z$) position where the disturbance took a maximum in amplitude at each $x$ station. At the initial stage, at $x - x_0 = 10$ mm, the spectra were close to those of the input signals to the loudspeakers, and the rms value of $u$-fluctuations were calculated from the spectra to be about 1.3% of $U_\infty$. In the downstream stations, we can see disturbances are amplified over the frequency range of 30-120 Hz. The growing disturbance over the frequency range of 30-120 Hz was of course a sinuous instability mode as shown in Fig. 7 which illustrates amplitude distributions of $u$ in the $(y, z)$ plane at $x - x_0 = 60$ mm and 140 mm.

Next we examined the disturbance development when the streak flow was excited by the zero-correlation fluctuation signals (Case 2). Fig. 8 illustrates power spectra of $u$ at $x - x_0 = 10$ mm, 60 mm, 100 mm, 140 mm and 180 mm for Case 2; they were measured at a vertical shear-layer similarly to Case

\[ P(f) \]

\[ f (\text{Hz}) \]

\[ x - x_0 = 10 \text{ mm} \]

\[ 60 \text{ mm} \]

\[ 100 \text{ mm} \]

\[ 140 \text{ mm} \]

\[ 180 \text{ mm} \]
1. At the downstream locations, we can see disturbances are amplified over the frequency range of 30-120 Hz in this case, too, suggesting that the sinuous instability mode was also amplified. Fig. 9 shows the disturbance development in terms of the amplitude distributions in the (y, z) plane at four x stations: \( x - x_0 = 60 \text{ mm}, 100 \text{ mm}, 140 \text{ mm} \) and \( 180 \text{ mm} \). The structure of the disturbance excited was like that of the varicose mode at \( x - x_0 = 60 \text{ mm} \) and gradually changed to be that of sinuous instability mode beyond \( x - x_0 = 100 \text{ mm} \).

4. Conclusions

Growth of streak instability mode excited by initial disturbances whose frequency-spectrum was similar to that of wall turbulence was examined experimentally for a single low-speed streak. Two kinds of driving signals were used for the excitation of streak instability. One was a forcing using a pair of turbulent signals with zero correlation and the other was an anti-symmetric forcing which was the most effective for anti-symmetric sinuous modes. Even when the low-speed streak was forced by turbulent signals with zero spanwise correlation, the sinuous instability mode occurred dominantly in the downstream region around the most amplified frequency of the linear instability. The amplitude of the excited sinuous mode was found to be only by 25% smaller than that in the case of the anti-symmetric forcing.

Acknowledgments

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