Observation of the feedback loop associated with airfoil trailing-edge noise

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ABSTRACT

It is well known that acoustic noise emanated from an airfoil trailing edge is discrete. The mechanism on why the noise becomes discrete and how the frequency is selected remains unclear. To reveal the mechanism, the boundary layer near the trailing edge on the pressure side was artificially disturbed with the use of distributed roughness elements. As a result, the separation is swept away and an acoustic sound is suppressed. The experimental results indicate that the frequency of trailing-edge noise is determined in separation region where mean velocity distribution has an inflection point accompanying reverse flow. These are necessary conditions for absolute instability.

Key Words: trailing-edge noise, boundary layer instability, absolute instability

1. Introduction

Tonal noise is emanated from the trailing-edge (T-E) of 2-D airfoils at moderate Reynolds numbers. Most prevailing explanation is ascribed to the feedback loop between T-E noise and T-S waves growing in the boundary layer on the pressure side. Nash et al reveal that the T-S waves near the trailing edge are preferentially amplified and play an important role in frequency selection.(1) (Fig.1) But they could not explain why the discrete tone was observed and how the frequency is selected. The T-S instability is inherently unstable to broad-band disturbances, indicating that other mechanisms associated with an absolute instability(2) is required. Considering the fact that separation is observed near the trailing-edge on the pressure side when T-E noise is emanated, the experiment is performed in configuration to suppress T-E noise by manipulating the boundary layer near the trailing edge on the pressure side.

2. Experimental Setup and Procedure

The experimental set-up is shown in figure 2. The experiment is conducted in the JAXA low turbulence wind tunnel with a rectangular test-section of 550mm by 650mm in cross section. The free-stream velocity U_∞ was chosen at 14.5m/s. At this velocity, the free-stream turbulence level is less than 0.05%.

The wing model is NACA0015 cross-section whose chord length and spanwise length are 400mm and 550mm, respectively. The wing was set horizontally in order for the pressure side of the airfoil to become upper side. So that the hot-wire probe from the ceiling can be readily surveyed on the pressure side.

The streamwise velocity, whose time-mean and fluctuation components are denoted by U and u respectively, is measured with a constant temperature hot-wire anemometer. The hot-wire sensor is 5μm in diameter and 1mm in length of the tungsten. The hot-wire probe is traversed in the x- and y- directions.

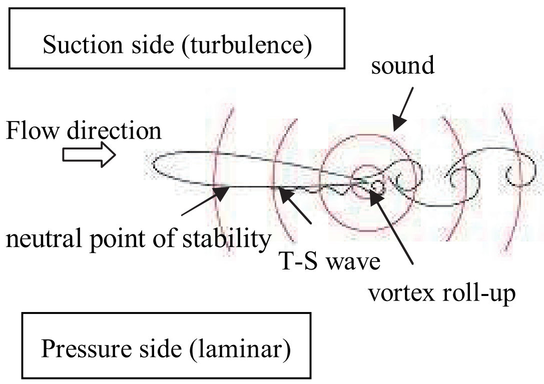

Figure 1. Diagram of the T-E. noise generation

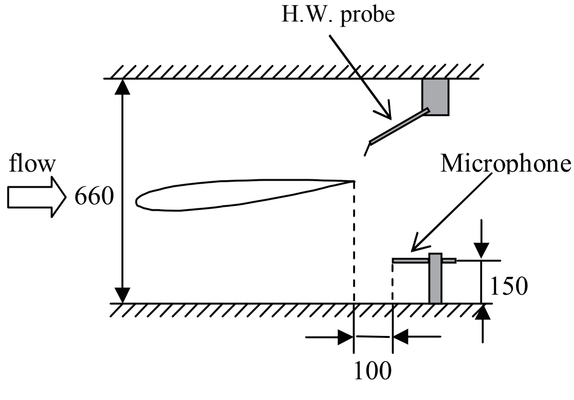

Figure 2. Experimental setup. (dimension is in mm)

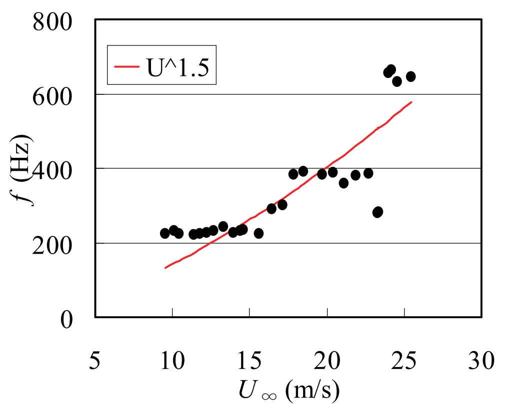

Figure 3. Sound pressure frequency VS uniform velocity. Line shows $U^{1.5}$ dependency

The acoustic sounds are measured by the microphone, B&K type 4138, which is located 100mm behind the T.E and 300mm toward the suction side of the airfoil. The velocity and acoustic sounds data are stored in personal computer with the use of an A/D converter.

Previous experimental observations showed that the T-S wave is abruptly amplified in separation region near the trailing edge and then discrete sound is emitted when the amplified T-S wave is shed from the trailing edge. Therefore, acoustic sound should be weakened or suppressed, if the separation structure can be destroyed. According to this speculation, isolated roughness elements with 3mm in diameter and 4mm in height were distributed in staggered formation at 92.5% of the chord length on the pressure side.

3. Results and Discussion

Some fundamental results are shown in Figs.3 and 4. Figure 3 shows the frequency dependency of the sound against the uniform velocity. As numerous researchers observed [(3)], a ladder-like structure with $U^{1.5}$ is observed. But each step does not fit to $U^{0.8}$ but rather fit to constant. This behavior is identical to the result observed by Nash et al. before the anechoic test section is used, which allows the reflections of the sound at a hard wall. The step-like structure in Fig. 3 seems to be due to the test section without anechoic treatment. We do not discuss any more about this constant behavior, because this point is away from the present subject on the frequency-selection mechanism of the T-E noise.

Figures 4 (a) and (b) show typical frequency spectra of the sound pressure for the free stream velocity of 14.5m/s with and without the distributed roughness, respectively. Also the background noise spectrum in the empty test section is superimposed in black line. In natural case, the tonal noise is clearly

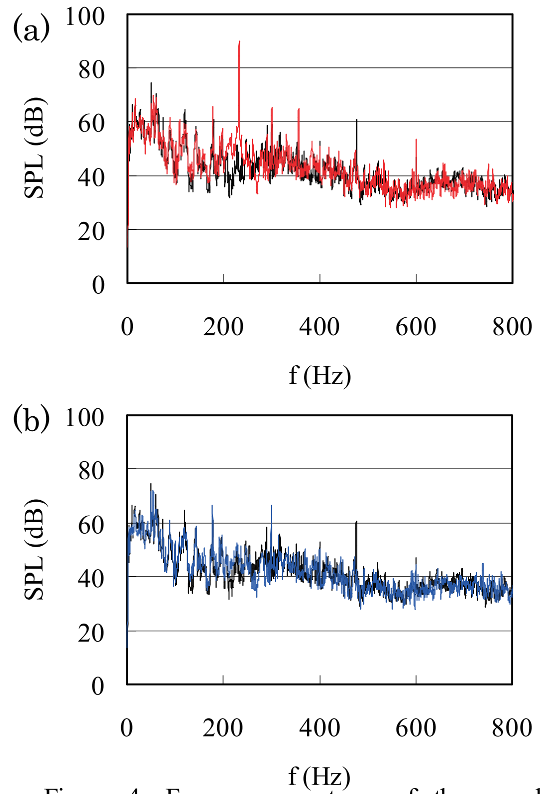

Figure 4. Frequency spectrum of the sound pressure.

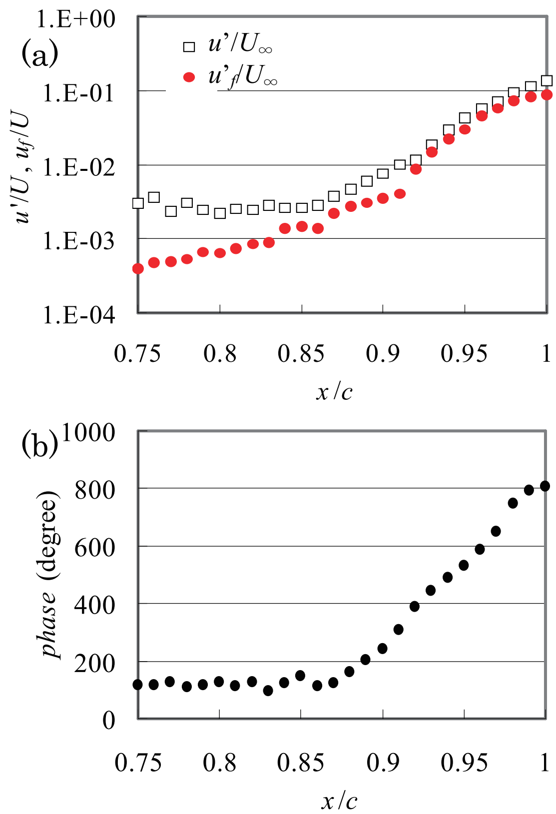

Figure 5. Disturbance development and its phase distribution in the chordwise direction on the pressure side. Phase shifts are obtained from using the microphone as a reference signal.

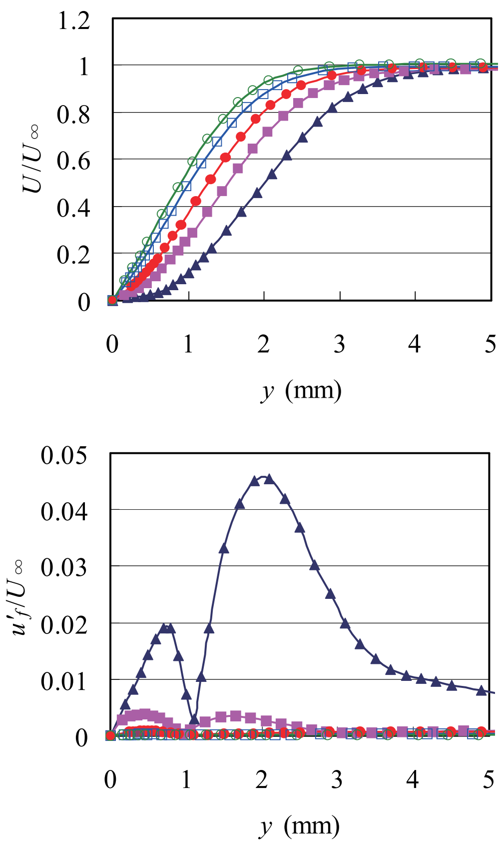

Figure 6. Velocity distribution and RMS distribution of the T-E. noise component. ○:x/c=0.75, □:x/c=0.8, ●:x/c=0.85, ■:x/c=0.9, ▲: x/c=0.95.

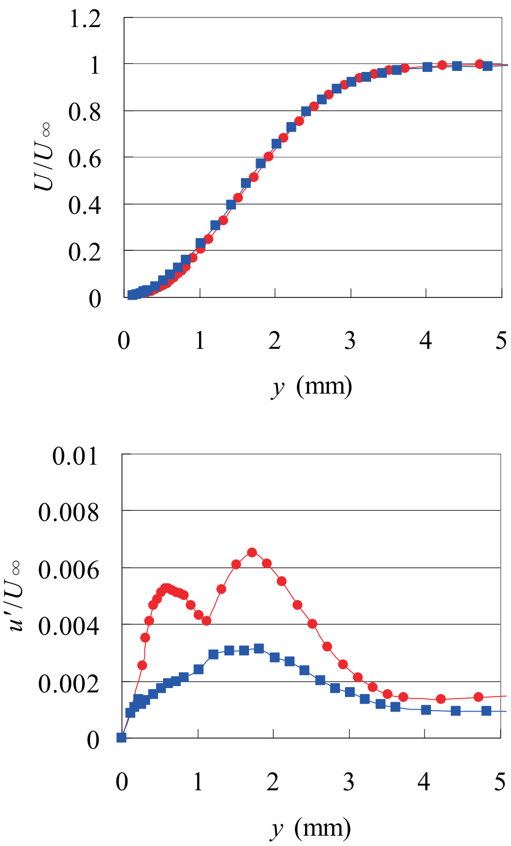

Figure 7. Mean velocity distribution and RMS(O.A) distribution at x/c=0.9 just upstream of the distributed roughness. ●: natural case, ■: artificially disturbed case.

observed at 232 Hz. Once the boundary layer on the pressure side is artificially disturbed, this tonal noise disappeared, suggesting that the distributed roughness elements prevent the 2-D vortex shedding, which generates strong acoustic emission.

Figure 5 (a) shows disturbance growth against the chordwise direction on the pressure side, where u' and u'_f denote the total RMS value and the RMS value of the discrete frequency component. The discrete frequency coincides with the tonal noise frequency in the sound pressure. As can be seen from the total RMS value, the disturbances start exponen- tially to grow downstream of x/c=0.875. The discrete frequency component and its higher harmonics contributes in the exponential growth. Therefore, the flow is highly periodic. Since the magnitude of the overall disturbance exceeds 10% of the free stream velocity U_∞ at the verge of the airfoil, significantly strong vortex should be shed from the trailing edge.

Figure 5 (b) shows the phase differences between velocity fluctuation u and sound pressure measured by the microphone against the chordwise direction. Because of a limited range of the measurement area, the delay of sound pressure at each measurement position is not considered. Upstream of x/c=0.875, no phase change is observed, indicating that the discrete component fore of this location in Fig.5 (a) is not the velocity fluctuation but the sound pressure radiated from the trailing edge. This is the reason why the hot-wire anemometer is sensitive to the acoustic fluctuations as well as the velocity components. The phase velocity of the growing discrete disturbance is about 40% of the free-stream velocity U_∞ deduced from the wave length. This observed value is identical to the phase velocity of T-S waves.

Figure 6 (a) and (b) show distributions of the mean velocity and RMS value of the tonal noise component in y direction at various x locations. It is clearly visible that the velocity profile is inflectional, which destabilizes the flow leading to rapid growth of the disturbance.

Figure 7 shows distributions of the mean velocity and the overall RMS value of velocity fluctuation just upstream of the roughness elements, where no tonal noise is perceptible. No effect of the roughness is visible in the mean velocity distribution even though the flow downstream of the roughness is drastically changed from laminar to turbulent state, although the

RMS profile is definitely altered. This alteration suggests that without acoustic forcing there is no massive amplification of disturbance fore of this *x*-position. Thus, the condition that the mean velocity profile has an inflectional profile is not a sufficient condition of the amplification of the disturbances.

Figure 8 shows the frequency spectra of the *u*-component at x/c = 0.9. Discrete *u*-component disappeared in the presence of distributed roughness even if the mean velocity profile is still inflectional. Instead of discrete *u*-component, a moderate broad-band bump is observed in slightly higher frequency region than that of the discrete *u*-component. This is due to the fact that naturally growing instability waves consist of broad-band components. Also, there is another difference in spectra that the lower frequency components than that of the discrete *u*-component are attenuated. This indicates that the mean flow of the boundary layer in no roughness case is fluctuating at low frequency associated with the fact that the separation point on the pressure side is unsteady.

This disappearance of the discrete component documents that there obviously exists an acoustic feedback loop between tonal noise and *u*-component. Also, the result suggests that the disturbance rapidly grows when the mean velocity profile instantaneously contains a reverse flow in a laminar separation bubble.

4. Conclusion

In order to reveal the frequency-selection mechanism of the 2-D airfoil trailing-edge noise, we focused on the relation between tonal noise and flow separation near the trailing-edge region. To remove the separation, the distributed roughness elements were adhered on the airfoil near its trailing edge and eventually sound emission was suppressed.

For the case with no roughness elements, the discrete disturbance, the so-called T-S wave, grows in the boundary layer where an inflectional point accompanying reverse flow was observed on the mean velocity profile.

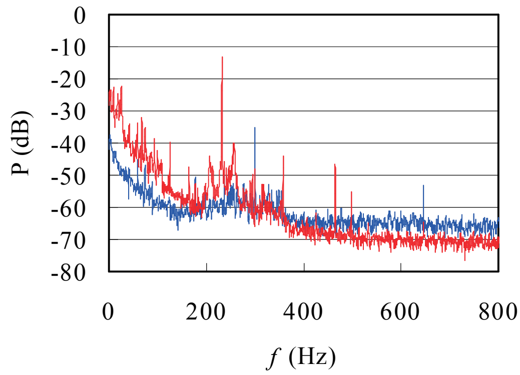

Figure 8. Frequency spectra of the velocity fluctuations at x/c=0.9. Red line: natural case, blue line: artificially disturbed case.

When the boundary layer near the trailing edge on the pressure side was disturbed, a tonal noise disappeared. This is because the boundary layer near the trailing edge becomes turbulence and reverse flow was removed. The mean velocity profile does not change upstream of the roughness and an inflection point still exists. However, no rapid growth of disturbances is observed. These results represent that in addition to an inflection point on the profile a recirculation near the trailing-edge is essentially necessary for the noise generation.

It can be finally concluded that the frequency of the trailing-edge noise is selected in the laminar separation region, where the mean velocity distribution in the normal-to-wall direction has an inflection point and reverse flow, both of which are necessary conditions for absolute instability [3].

References

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