Relationship between Aeolian tone and Wake Vortex from Inclined Flat Blade (Characteristics of Vortex Shedding in Spanwise Direction)*

Sho YOSHITAKE^{**}, Hidechito HAYASHI^{**}, Souichi SASAKI^{**}
and Tohru FUKANO^{***}

^{**}Nagasaki University, Faculty of Engineering, 1-14 Bunkyo-machi, Nagasaki, Japan
e-mail ; hidechto@nagasaki-u.ac.jp

^{***}Kyushu University, 2228-66, Kamitsu-machi, Kurume, Japan

Abstract

The three dimensional structure of the wake vortex was investigated in relating to the aeolian tone from the inclined blade. It was pointed out that the aeolian tone is largest not at zero, but at ten degree of the inclined angle. The correlation length of the wake vortex in span becomes large at small inclined angles. The large scale structures of the wake vortex are generated in zero and ten degree of inclined angle. The shape of the structure is influenced with the span-wise velocity in the dead air region. There are small scale spots of the pressure fluctuation at the trailing edge. The spots are interacted each other and make a large cluster of the pressure fluctuation. It is proposed that the scale of it is decided by the timing of the wake vortex formation. And the shape of the wake vortex structure is closely related with the scale of it. The correlation length of the wake vortex is calculated from the shape of the structure. The estimation of aeolian tone by using the length with Fukano's model is well coincided to experiments.

Key words: Aeolian Tone, Vortex Shedding, Three-dimensional Characteristics, Inclined Flat Blade, Large Structure

1. Introduction

The aeolian tone from the blunt body has been investigated for many years. In the two-dimensional cases, the characteristics between the wake vortex and the sound source is fairly cleared¹⁻⁴. The sound source concentrates near the separation point that is closely relating to the wake vortex formation. Then the level of the aeolian tone is estimated from the wake vortex characteristics^{5,6}. But the three dimensional structure of the wake vortex is not known exactly. The sound source is not cleared yet.

Some reports were presented for the inclined cylinder to make clear the effects of the three-dimensional characteristics to the wake vortex⁷⁻¹⁰. It was pointed out that the flow turned to the direction normal to the circular cylinder. This turning flow might have much influenced on the wake vortex generation³. But it is not cleared the variation of the sound pressure level with the inclined angle and the mechanism in relating to the span-wise structure of the wake vortex.

In this report, the characteristics of the span-wise structure of the wake vortex and the aeolian tone are cleared for the inclined flat blade model. That is, the variation between time-space of the three dimensional structure of the wake vortex, strength of pressure fluctuation on surface, and cross correlation coefficient of velocity fluctuation in the wake

were analysed. Moreover, the aeolian tone was estimated from these characteristics of wake vortex, with Fukano's model ⁵.

2. Nomenclature

a_0	speed of sound [m/s]
B	span length [m]
C	chord length [m]
D	blade thickness [m]
K	shape coefficient
l_c	chord correlation length [m]
l_s	span-wise correlation length [m], [mm]
p_0	minimum audible pressure [Pa]
r	distance from blade microphone [m]
R	Cross correlation coefficient
St	Strouhal number
U_0	main flow velocity [m/s]
u	downstream velocity [m/s]
u'	strength of velocity fluctuation [m/s]
w	span-wise velocity [m/s]
x	downstream coordinate [m]
y	thickness-wise coordinate [m]
z	span-wise coordinate [m]
ρ_0	density of air [kg/m ³]
τ	delay time [s]
ϕ	inclined angle [degree]

3. Experimental Apparatus and Methods

Experiments were carried out with the open type wind tunnel. Figure 1 shows the schematic diagram of the test section and the measuring apparatus. The air blows from the nozzle outlet of 230*230mm section. The oncoming velocity to the model was varied 19m/s to 40m/s. The uniformity and turbulence level at the nozzle outlet are under 0.35%. It was modelled to avoid the influence of the leading edge separation on the wake vortex formation and to clear the influence of the separation condition at the trailing edge. The shape at the leading edge is the half circular to avoid the large separation that makes the flow on the blade unstable. The trailing edge is sharply cut off normal to the model chord. The chord length C is 60mm and the thickness D is 12mm. The Reynolds number based on the blade thickness is $1.5 \times 10^4 \sim 3.0 \times 10^4$, which is varied with the main flow velocity. The model was set with the inclined angles 0 to 30 degree. The span length is varied from 230mm to 265.6mm with the inclined angle. The upper and lower end plates, which are set not to reflect the radiated sound, were set to avoid the interaction between free jet and the model. Coordinates are taken that the direction of the main flow is x axis, the direction of the blade thickness is y axis, the direction of the span is z axis.

The aeolian tone was measured at 1.5m apart from the model and normal to the main flow. In the frequency region of the aeolian tone, the level of the peak frequency was recognized to the level of aeolian tone from the blade. The correlation of the velocity fluctuations was measured in span-direction by two hot wire sensors. One hot wire sensor is fixed the position of downstream $1 D$ from the trailing edge, where the wake vortices roll up, and at the center of the span, another hot wire sensor is moved in the span direction with 1mm interval. The numerical simulation is made with the same flow conditions as

experiments. The number of mesh is about 3,000,000 the mesh. The LES model is used for the unsteady flow. The results are used in 100 times of the period of a vortex shedding.

Figure 1 Test section and model.

4. Results and Discussions

Figure 2 shows the variation of the sound pressure level (SPL) with the inclined angle, which is corresponding to the peak level of the aeolian tone in the spectrum distribution. It can be seen that the level slightly increases with the inclined angle up to 5 degree at $U_0=40.0\text{m/s}$ and 10 degree at $U_0=19.2\text{m/s}$. The maximum levels are about 2-3 dB larger than that at 0 degree. Over these angles, the levels gradually decrease with the inclined angle. It is interesting that the maximum aeolian tone generates not at the two-dimensional flow condition, zero degree, but at the three-dimensional flow condition.

Figure 2 Distribution of aeolian tone with inclined angle.

Figure 3 shows the variation of the span-wise correlation length of the wake vortex with inclined angle. It is pointed out that the scale of large structure of the Karman vortex is an important parameter to the aeolian tone. The correlation length of the wake vortex gives the scale of it¹⁰. Fukano etc. pointed out that the wake vortex generates the periodic pressure fluctuation on the blade and proposed to use the correlation length by equation (1) for the scale of the sound source^{5,6}.

$$l_s = \frac{1}{R(0)} \int_{SPAN} R(z) dz \quad (1)$$

Where $R(0)$ is the cross-correlation at the center of span, $R(z)$ is the cross-correlation at z in span. At the case of zero inclined angle, the correlation length is about two times of the blade thickness. The length rapidly increases with the inclined angle up to 10 degree. The length is about 5-6 times of the blade thickness. This indicates that the coherent structure of the wake vortex becomes maximum not at zero inclined angle, but at small inclined angles. The scale at ten degree is almost three times larger than at zero degree. Over 10 degree, the length decreases with the inclined angle. This variation of the span-wise length with the inclined angle is well coincided to the SPL variation in Fig. 2. It is confirmed that the span-wise correlation length is closely related to the aeolian tone.

Figure 3 Variation of correlation length with inclined angle.

Figure 4 (a) and (b) show the isosurfaces of the Z component of the vorticity at an instant. It can be seen in the wake that the isosurfaces stand in span. Each of the surfaces is corresponding to the wake vortex. The distance between the surfaces is hardly varied with the span-wise location. It seemed that the moving velocity of the wake vortex is almost same in span. Figure (a) is the case of zero degree. The isosurface is not parallel to the blade, but bended near the center of span. The wake vortex is appeared at $x/D = 3$ near the center of span that is already rolled up and flow downstream. At the same time, the wake vortex is rolling up at the other span locations. This is corresponding to the flow from the upper and lower side to the center of the span and the flow turned toward the downstream at the center, as shown in Fig. 5 (a). This bended vortex is seemed the large structure of the wake vortex. It can be seen the lines on the blade surface that are parallel to the flow direction. These lines show the turbulence of the boundary layer. It is seemed that the shear flow is distinguished with the lines. The distinct shear flow is rolled up at $1 D$ from the

trailing edge. It seems that the ragged distributions of the cross correlation in Fig. 9 is corresponding to this vortex rolling up. The vortex structure is regarded the small segment of the wake vortex. The small segments are connected each other at the location of rolling up and the large-scale vortex is formed. Figure (b) is the case of ten degree. The isosurfaces of the vorticity are a little inclined compared with the blade angle. The surface is revealed the large-scale structure of the wake vortex. The upward flows exist in the wake and the flow turned to the downstream at the top of the span, as shown in Fig. 5 (b). It is revealed that the rolling up of the wake vortex occurred a little earlier at the upper side and the vortex flow downstream. The rolling up at the lower side is trailed with the upper vortex. In this case, there are the lines on the blade surface and the small segments are formed in span. The small segments are connected at the location of vortex rolling up. It seems that the large-scale structure in span is influenced to the sound source.

Figure 5 (a) and (b) show distributions of velocity vectors in the dead air region at $0.5D$ away from the trailing edge. It is seen in Fig. (a) that the upward flow from the lower end wall to the center of the span exists and the downward flow from upper wall to the center exists in the dead air region. These upward and downward flows collide at the center of the span and the flows turn to the downstream. These velocity distributions in the dead region cause the large-scale structure in Fig. 4. At the case of 10 degree in Fig. (b), It is seen that the upward flow from the lower end wall to the upper wall exists in the dead air region. This upward flow concentrate at the upper of the span and the flow turns to the downstream. These velocity distributions in the dead region also cause the large-scale structure in Fig. 4.

Figure 4 Isosurface of vorticity
(Vertical component of Vorticity=1000[1/s])

(a) Simulation results, $\phi = 0^\circ$.

(b) Simulation results, $\phi = 10^\circ$.

Figure 5 distributions of velocity vectors at ZX plane($y=0$).

Figure 6 (a) and (b) show the instantaneous distributions of the strength of the pressure fluctuation on the blade. In Fig. (a) of the zero inclined angle, there are strong and small spots at the trailing edge. The spots are generated at the several span locations. Some spots interacted each other and form a large cluster on the surface. At the case of Fig. (b), it can be also seen the small spots at several span locations. The clusters are also made from these spots. It is considered that the formation of the cluster is restricted between the spots of same timing. As the pressure fluctuation on the plate is closely related to the wake vortex^{5,9,10}, we proposed that the cluster of the pressure fluctuation is related to the formation of the wake vortex and the shape of the large structure of the wake vortex. At the case of zero, the span-wise structure is bended large in Fig. 4, the timing of the spots generation is varied in span and the scale of the cluster is relatively small. At ten degree, the span-wise structure is a little inclined in Fig. 4, the timing of the spots generation is almost same and the large scale of cluster is formed. As mention the next figure, there small spots fluctuation does not influence directly, but the large scale cluster generates the aeolian tone.

Figure 7 (a) and (b) shows the contour map of the cross correlation of the pressure fluctuation on the trailing edge in the retarded time domain. The cross correlation is taken between the center of span and each span location at the trailing edge. It emerges the span-wise lines periodically in both Figs. These are corresponding to the wake vortex. And it can be seen the strong correlation corresponding to the small spots in Figs at several locations in span. As mentioned in Fig. 6, these small spots are corresponding to small segments of wake vortices. Sound level is concerned to the strength and the area of the sound source. The sound sources of spots are strong but very small as shown in Fig. 5, then it seems that the influences of the spots on the aeolian tone is weak.

Figure 8 (a) and (b) shows the contour map of the cross correlation at $1D$ apart from surface. It is disappeared the strong correlation of the small spots. But the large-scale distributions in span remain. At the case of zero inclined angle in Fig. (a), the large correlation region is restricted around the center of the span. The distributions of cross correlation are almost parallel to the span near the center of span, and a little retarded at the upper and lower sides. At the case of 10 degree, the strong correlation is extended in span. The distributions of the large correlation are a retarded and weak at the lower side. This

distribution is corresponding to that the wake vortex formation is delayed at the lower side in Fig. 4.

(a) $\phi = 0 \text{ deg.}$

(b) $\phi = 10 \text{ deg.}$

Figure 6 Strength of pressure fluctuation on surface(simulation results).

(a) 0 deg.

(b) 10 deg.

Figure 7 Contour map of the cross correlation coefficient in time domain.
(Pressure fluctuation on the trailing edge, simulation results)

Figure 8 Contour map of the cross correlation coefficient in time domain.
(Pressure fluctuation on $1D$ apart from the surface, simulation results)

Figure 9 shows the distributions of the cross-correlation coefficient of the velocity fluctuation in the wake. The cross correlation is taken between the center and each span location. The one sensor is fixed at the center of a rolling up vortex at the center of span and another is traveled in span at the center of another rolling up vortex. The left hand distributions are the experimental results and the right hand ones are the simulation results. The level at $z=0$ is not equal to the unity because the cross-correlation are not obtained at the same location. At the case of simulation, the sampling data is a few compared to the experiments and the influence of the unperiodic data is large. The level is rapidly decreased with span at zero inclined angle and gradually decreased at ten degree. The correlation length is very large at the 10degree of inclined angle compared with the zero case. The numerical results are relatively coincided with the experiments. At zero angle, both correlation becomes zero near $z=25\text{mm}$. At 10 degree, the correlation becomes zero at 40-50mm. There are a little rugged distributions. It is considered that these rugged distributions are corresponding to the existence of the small segments. Then the influences of the small segments are fairly small compared to the large scale structure.

Figure 10 shows the comparison of the sound pressure level between the experiments and estimation with the Fukano's method that the correlation length and the velocity fluctuation are used by the results of the numerical simulation. The SPL is obtained by Fukano⁹ with below

$$SPL = 10 \log \left\{ \frac{1}{4} \left(\frac{\rho_0}{a_0 p_0 r} \right)^2 \bar{U}_0^6 St^2 K \left(\frac{l_c}{C} \right) \left(\frac{u'}{\bar{U}_0} \right)^2 l_s B \right\} \quad (2)$$

ρ_0 is density of air, a_0 is speed of sound, p_0 is minimum audible pressure, r is distance from blade to measuring point, $\bar{U}_0$ is velocity of main flow, St is Strouhal number, K is shape coefficient, l_c is chord-wise correlation length, C is chord length, u' is strength of velocity fluctuation, l_s is span-wise correlation length, B is span length.

The span-wise correlation length l_s is estimated from the large scale structure of the wake vortex. The experiments and the estimations are well coincided within 2 dB. The slightly differences are caused by the error of velocity fluctuation u' . The correlation length by the large scale structure is well revealed to the scale of sound source.

Figure 9 Distributions of the cross-correlation coefficient of the velocity fluctuation in the wake.

Figure 10 Comparison of the SPL of the experiments to the estimation.

5. Conclusions

We investigate the characteristics of the aeolian tone and the fluctuating flow of the inclined blade. The following results are obtained.

- (1) The aeolian tone becomes large not at the two-dimensional flow condition, zero inclined angle, but at the slightly inclined condition, 5 degree at $U_0=40.0\text{m/s}$ and 10 degree at $U_0=19.2\text{m/s}$.
- (2) When the aeolian tone becomes large, the span-wise correlation length becomes large. The increment of the length is about 3 times from zero to 10 degree of the inclined angle.
- (3) There exist the two types structure in the wake vortex. The one is small segment and another one is a large structure over the span.
- (4) The three-dimensional wake vortex formation is occurred even at the 2D flow condition.
- (5) The small spots of the strong pressure fluctuations are distributed at several locations in the span direction that are influenced by the small segments of wake vortices. There exist the small spots of pressure fluctuation at the trailing edge. But these small spots are interfered and denied each other, and then do not influence the aeolian tone directly.
- (6) Aeolian tone is not relating to the small segment of wake vortex, but to the large structure of the vortex.

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