Experimental Study on Unsteady Aerodynamic Characteristics of an Oscillating Cascade with Tip Clearance*

Toshinori WATANABE** and Shojiro KAJI***

An experimental study was conducted for revealing unsteady aerodynamic characteristics of oscillating cascades with tip clearance. To obtain aerodynamic forces acting on blades, the surface pressure was measured in both the chordwise and spanwise directions. To evaluate the aerodynamic forces due to oscillations of arbitrary interblade phase angle, the method of influence coefficients was adopted. Tip clearances were changed from 0.056% to 2.8% of the blade span. The aerodynamic blade loading was also changed. Results show that the tip clearance has a strong influence on the distribution of unsteady aerodynamic forces along the blade span: when tip clearance exists, aerodynamic damping forces decrease considerably over a large portion of the blade span. However, when steady aerodynamic loading acts on the blades, the influence of tip clearance is suppressed. The tip vortex increases the absolute value of the unsteady aerodynamic force in the region near the blade tip.

Key Words: Unsteady Flow, Blade Oscillation, Unsteady Aerodynamic Force, Cascade Flutter, Tip Clearance, Tip Vortex

1. Introduction

Much of the investigation related to the unsteady aerodynamic characteristics of an oscillating cascade has been traditionally based on a two-dimensional analysis. In reality, however, blade vibration is strongly influenced by three-dimensional factors such as the spanwise variation of elastic characteristics and geometrical shapes, wall boundary layers, and tip leakage flows including tip vortices. Among these, the flow near the blade tip region is probably of the greatest importance because various complicated phenomena are introduced by tip clearances, wall boundary layers and consequently induced leakage vortices.

This investigation was performed for the purpose of revealing experimentally the unsteady aerodynamic characteristics of oscillating linear cas-

cades with tip clearances.

Although tip clearance is one of the most important factors which governs the flow in the blade tip region, no investigation has previously been performed on the oscillating cascade with tip clearances.

2. Test Equipment and Data Acquisition Systems

The test facility used is a blow-down type, low-speed straight cascade tunnel which is schematically shown in Fig. 1. The test section has a width of 180 mm in the spanwise direction.

Figure 2 shows the schematic view of the blade vibration system. This device gives bending oscillation to a blade with a piston-crank mechanism realized by an eccentric circular disk. Though the oscillation mode is expected to be uniform, the amplitude of the blade tip is larger than that of the hub because deformation of the cantilever blade occurs. The relative difference of amplitudes between the tip and the hub was found to be about 15% in the experimental range of frequency, given amplitude was 4.5 mm. In order to change the tip clearance, the whole vibration system can be moved in the spanwise direction.

The wall boundary layer thickness was about 20

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** Department of Mechanical Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Nakamachi, Koganei, Tokyo, 184, Japan

*** Department of Aeronautics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113, Japan

mm on the tip side wall, and about 30 mm on the hub side wall. When the wall boundary layer on the tip side was to be excluded, the boundary plate was set as shown in Fig. 2. The turbulence level in the mean flow ranged from 0.6 to 1.5%.

The test cascade was composed of flat plates, each of which had a chord length of 60 mm and a thickness of 6 mm. Their leading and trailing edges were shaped into semicircles in cross section. The blade span was 180 mm including tip clearances. The blade on which pressure was measured is shown in Fig. 3. Twenty-four aluminum pipes, each with an outer diameter of 2 mm, were embedded parallel to the blade span. Pressure holes 0.7 mm in diameter were drilled on each of these pipes at 21 spanwise locations. When pressure was measured, all pressure holes other than the specified spanwise location were covered with scotch tape. Because of the uniform oscillation mode, the spanwise distribution of the aerodynamic forces was nearly uniform. To observe the general trend, nine locations out of 21 were sufficient. These locations are also indicated in Fig. 3. However, to investigate detailed variations near the blade tip, measurements at more than nine locations were made.

Fig. 1 Test rig of linear cascade

Fig. 2 Mechanical oscillatory system and boundary plate (indicated by an arrow)

The test cascade was a linear one whose stagger angle was 45 degrees and pitch-chord ratio was 1.0. It was composed of nine blades, the central one being an oscillating blade. Unsteady surface pressure was measured on this blade as well as its two neighbouring blades. Superposition of data on these three blades provides approximately the unsteady aerodynamic force when all blades are oscillating with an arbitrary interblade phase angle.⁽¹⁾ Reference 1 indicates that 90% of the accurate aerodynamic force can be counted by the data based on these three blades.

Figure 4 shows the block diagram of the pressure-measuring system. The pressure sensed at the blade surface was transferred to the SCANIVALVE through the aluminum pipe and a vinyl tube which followed. It was then converted to an electric signal by the pressure transducer contained in the SCANIVALVE. Sampled data were processed by a minicomputer through averaging and Fourier analyses, and the component of the blade vibration frequency was derived. At the same time, the output signal of the accelerometer located on the oscillating blade was sampled and used as a reference for the phase of the blade oscillation.

Since the pressure path from holes to the transducer had frequency characteristics, sampled data had to be corrected. Frequency characteristics were calibrated using pressure signals generated by a speaker.

Fig. 3 Blade for pressure measurement

Fig. 4 Block diagram of pressure-measuring system

The unsteady aerodynamic force coefficient $C_f = C_r + iC_i$ was obtained through integration of the unsteady pressure on the blade surface in the chordwise direction after nondimensionalizing by the dynamic pressure of the main flow. As a result, the spanwise distribution of C_f on one blade was obtained. Once the distributions of C_f on three blades were determined, they were superposed in the following manner.

Let the nondimensional aerodynamic coefficient on the spanwise position z be

$$C_{f,l}(z) = C_{r,l}(z) + i \cdot C_{i,l}(z) \quad (1)$$

The subscript l denotes the blade number and $l=1$ corresponds to the oscillating blade, $l=2$ the stationary blade in the pressure side (supposing a compressor cascade) and $l=3$ to the stationary blade in the suction side. Then $C_{f,l}$ is assumed to be expanded by cosine terms in the z -direction;

$$C_{f,l}(z) = F_l^0 + \sum_{n=1}^{N-1} F_l^n \cos \frac{n\pi z}{h} \quad (2)$$

where N is number of locations for the measurement in the spanwise direction and h is distance between side walls.

Equation (2) gives coefficients $F_l^0 \sim F_l^{N-1}$ because values of $C_{f,l}$ are obtained at N locations. Data on three blades are superposed in each expansion mode and the coefficient of the n th mode F_l^n on the arbitrary interblade phase angle τ is evaluated as follows:

$$F_l^n = F_l^n + F_l^n e^{i\tau} + F_l^n e^{-i\tau} \quad (3)$$

By the reconstruction of F_l^n , the superposed aerodynamic force coefficient is obtained.

$$C_f(z) = F_r^0 + \sum_{n=1}^{N-1} F_r^n \cos \frac{n\pi z}{h} \quad (4)$$

In order to obtain information on the flow field, the steady velocity distribution in the downstream of the cascade was measured with a 5-hole pitot tube. The pitot tube was mounted on a three-dimensional automatic traversing system driven by stepping motors. Five pressure data were picked up by the SCANIVALVE system and analyzed by the minicomputer. The flow direction was also computed by the pressure difference method. The tip vortex in the steady-state condition was studied by this measurement.

3. Results and Discussions

The experiment was conducted about the isolated blade, initially, using only the central blade. Some fundamental data were obtained by this measurement. Then, the experiment for cascaded blades was made. The following discussion is based on a comparison of these two sets of data.

3.1 Isolated blade

Pressure distributions on the blade surface were measured when the tip clearance δ was 0.1, 1.0, 2.0, 3.0,

4.0, and 5.0 mm. These tip clearances correspond to 0.056, 0.56, 1.1, 1.7, 2.2 and 2.8% of the blade span, respectively. As for the angle of attack α , the results of $\alpha=0^\circ$ and 5° will be shown. The flow Reynolds number Re was 1.0×10^5 (the mean velocity was 26.5 m/s) and the reduced frequency k was 0.27 (the vibration frequency was 19 ± 0.05 Hz) in most cases, but these values were changed later. Re and k were based on the chord length of blades.

3.1.1 Nonloaded blade Figure 5 shows the spanwise distribution of unsteady aerodynamic forces when the tip clearance changes from 0.1 mm to 5.0 mm. There is no steady loading, *i.e.*, $\alpha=0^\circ$. C_r is the real part of the nondimensional unsteady aerodynamic force coefficient which is in phase with the blade oscillation velocity and C_i is its imaginary part which is in phase with the blade acceleration. If C_r is positive, the unsteady aerodynamic force acts as an exciting force; however, C_r is always negative in Fig. 5, indicating that the oscillation is stable. When $\delta=0.1$ mm, the aerodynamic force has an almost flat distribution except in the near-wall regions. The absolute value is slightly larger in the tip side than in the hub side, because the oscillation amplitude slightly increases toward the blade tip as mentioned previously. If δ becomes larger, the distribution curve of C_r rises sharply, in other words, the damping force decreases abruptly. When $\delta=5$ mm, the change of C_r due to δ spreads widely to the midspan region. The change is greatest in the clearance range from 0.1 mm to 1.0 mm and it decreases as δ increases further. Ultimately above 3.0 mm of δ , there can be observed little change in the distribution of C_r . C_i has the same tendency as C_r . It decreases in the tip side with increasing δ and the change from $\delta=0.1$ mm to $\delta=1.0$

Fig. 5 Spanwise distributions of unsteady aerodynamic force (Isolated blade, $\alpha = 0^\circ$)

mm is the maximum.

Figure 6 shows the chordwise distribution of the unsteady pressure at locations 7, 8 and 9 (see Fig. 3) near the tip. The two cases are shown for the tip clearance of 0.1 mm and 5.0 mm. The solid line indicates the real part (in phase with the blade displacement) of the unsteady pressure and the broken line indicates its imaginary part. The center of the horizontal axis corresponds to the trailing edge, and both ends correspond to the leading edge. The left half represents the upper surface of the blade and the right half represents the lower surface. In the case of $\delta=0.1$ mm, the distributions inside the wall boundary layer (No. 8 and 9) are different from that in the main flow region (No. 7). In the wall boundary layer, the pressure distribution has a steep peak near the leading edge, but in the main flow region, this peak is gentler. When the clearance is 5 mm, this pressure peak becomes much lower and the pressure is small over whole parts compared with those cases of small clearance. This reflects a decrease in aerodynamic forces.

3.1.2 Loaded blade Figure 7 shows the spanwise distribution of C_r and C_i in the case of $\alpha=5^\circ$. The aerodynamic damping force is larger than that in the case of $\alpha=0^\circ$, and the distribution curve is

Fig. 6 Chordwise distributions of unsteady pressure (Isolated blade, $\alpha=0^\circ$, Location No. 7, 8, 9, $\delta=0.1$ mm, 5.0 mm, '5' indicates 5.0 mm of δ . Nondimensionalized by dynamic pressure of the main flow.)

flatter. The change of the distribution of C_r with the increase in tip clearance is not so abrupt as in the nonloaded case. Therefore, the steady blade loading has an effect of suppressing the influence of tip clearance. Especially at the measuring location closest to the tip, this effect is remarkable. The same effect is appreciable in C_i .

When steady loading exists, a tip vortex is formed. Figure 8 indicates steady velocity vectors downstream of the tip region in the case of $\alpha=5^\circ$. The tip clearance varies from 0.1 mm to 5.0 mm. The 5-hole pitot tube was traversed in the plane vertical to the mean flow and 20 mm downstream from the trailing edge. It is shown that a tip vortex is formed and gradually strengthened with increase in tip clearance.

With the information obtained from Fig. 8, let us once more review Fig. 7. On the distribution curve of C_r and C_i near the tip, inflections are found and the absolute values of C_r and C_i increase suddenly. This tendency emerges at $\delta=2.0$ mm, at which point the tip vortex is first clearly recognized, and becomes more and more remarkable as the clearance increases. This tendency is evidently due to the tip vortex. As a result, C_r and C_i have almost the same value at the tip, even when the tip clearance changes. This influence on C_r appears as the effect of increasing aerodynamic damping forces.

To confirm the effect of the tip vortex, aerodynamic forces were measured at further locations near the blade tip in the case of $\delta=5.0$ mm. Results are shown in Fig. 9. The considerable increase in the absolute values of C_r and C_i are obviously indicated in the tip region.

Figure 10 shows the distribution of the unsteady pressure at locations 7, 8 and 9 in the case of $\alpha=5^\circ$. In

Fig. 7 Spanwise distributions of unsteady aerodynamic force (Isolated blade, $\alpha=5^\circ$)

comparison with the nonloaded case, the pressure peak on the suction side moves toward the trailing edge and widens. The remarkable tendency found in the distribution, in this case, is the flat shape of negative pressures on the suction side and a small peak near the tip which is indicated clearly in the data of location No. 9. Though not shown in this figure, data from a location 2 mm from the tip have no apparent peak and have a flat distribution over almost the entire suction surface. This flatness can be attributed to the leakage flow through the tip clearance. Since leakage flow separates at the tip and forms a separate region on the blade surface, the pressure near the tip tends to be uniform.

3.2 Cascaded blades

The flow angle which corresponds to the nonloaded blade is regarded here as $\alpha=0^\circ$. At this flow angle, the incidence is 4 degrees. Results at $\alpha=0^\circ$ and $\alpha=5^\circ$ (the cascade operates as a compressor) are shown in

Fig. 8 Tip vortex
(Isolated blade, $\alpha=5^\circ$, 20 mm downstream of the trailing edge.)

Fig. 9 Spanwise distributions of unsteady aerodynamic force showing effect of tip vortex
(Isolated blade, $\alpha=5^\circ$, $\delta=5.0$ mm)

this section. Tip clearances used are 0.1, 1.0, 3.0 and 5.0 mm. The case of $Re=1.0 \times 10^5$, $k=0.27$ was studied first; then experiments on different conditions were made.

3.2.1 Nonloaded cascade Figure 11 shows the spanwise distributions of C_r and C_i for each of three measuring blades. The values of C_r and C_i on the oscillating blade are about the same as those of an isolated blade. Therefore, the unsteady aerodynamic force induced on an oscillating blade is scarcely influenced by the other blades in the cascade. The induced aerodynamic force on the stationary blade on the pressure side (No. 2 blade) is very small. The reason is that this blade is located upstream of the oscillating blade and is hardly influenced by unsteady vortices shed downstream from the vibrating blade. The suction side blade (No. 3) is located downstream of the oscillating blade so that it is strongly influenced by the wake vortices, the induced force being accordingly large. The difference in unsteady forces due to the tip clearance is large near the blade tip, as seen on the oscillating blade. The absolute value of C_r as well as C_i decreases with increasing value of δ .

Figure 12 shows the resultant unsteady aerodynamic force. Data on the three blades were super-

Fig. 10 Chordwise distributions of unsteady pressure
(Isolated blade, $\alpha=5^\circ$, Location No. 7, 8, 9, $\delta=0.1$ mm, 5.0 mm, '5' indicates 5.0 mm of δ . Nondimensionalized by dynamic pressure of the main flow.)

posed by the manner described in section 2.1. C_r and C_i are plotted with various interblade phase angles, τ . Generally speaking, the tendency of variations in the aerodynamic force due to the tip clearance follows that of the oscillating blade; however, on the resultant values of the unsteady aerodynamic force, the influence of tip clearance is based on the interblade phase angle. When $\tau=0^\circ$, that is, all blades oscillate in the same phase, both C_r and C_i are scarcely influenced by the tip clearance. The influence on C_r is the strongest at $\tau=180^\circ$ and the absolute value of C_r is large at this τ , regardless of tip clearance. On the other hand, the influence on C_i is the strongest at $\tau=270^\circ$. From these results, it is found that the influence of tip clearance is the strongest when two leakage flows of neighbouring blades simultaneously enter and leave the blade-to-blade channel.

Figure 13 shows the superposed aerodynamic force when τ is fixed at 180 degrees. The tip clearance is changed as 0.1, 1.0, 3.0 and 5.0 mm. The absolute

Fig. 11 Spanwise distributions of unsteady aerodynamic forces
(Cascade, $\alpha=0^\circ$, Data on each blade.)

Fig. 12 Spanwise distributions of unsteady aerodynamic forces
(Cascade, $\alpha=0^\circ$, Resultant data, $\delta=0.1$ mm, 5.0 mm, $\tau=0^\circ, 90^\circ, 180^\circ, 270^\circ$)

value of C_r considerably decreases as δ changes from 0.1 mm to 3.0 mm, but hardly changes between 3.0 mm and 5.0 mm. The absolute value of C_i also decreases with increasing δ and still decreases above 3.0 mm, which is dissimilar to C_r . These results coincide with those of the isolated blade case.

3.2.2 Loaded cascade Figure 14 shows the spanwise distribution of resultant C_r and C_i in the case of $\alpha=5^\circ$. The absolute value of C_r is larger than that of the nonloaded case when $\tau=180^\circ$ because of the steady loading. The influence of δ is not obvious at $\tau=0^\circ$ and is the strongest at $\tau=180^\circ$, which is the same as the nonloaded case. In comparison with the nonloaded case, however, the difference in C_r due to tip clearance is smaller near the blade tip as a result of the influence of the steady loading. Since the steady loading is not so large as in the isolated blade, the suppressing effect on the influence of tip clearance is

Fig. 13 Spanwise distributions of unsteady aerodynamic forces
(Cascade, $\alpha=0^\circ$, Resultant data, $\delta=0.1, 1.0, 3.0, 5.0$ mm, $\tau=180^\circ$)

Fig. 14 Spanwise distributions of unsteady aerodynamic forces
(Cascade, $\alpha=5^\circ$, Resultant data, $\delta=0.1$ mm, 5.0 mm, $\tau=0^\circ, 90^\circ, 180^\circ, 270^\circ$)

not so remarkable.

The influence of tip vortices can be seen in the cascade case as well. When $\delta=5.0$ mm, absolute values of C_r and C_i greatly increase at the blade tip, although this is not as notable as in the isolated blade case because the tip vortex is weaker owing to the reduced loading.

3.3 Influence of reduced frequency and Reynolds number

Experiments were made on two other conditions in order to verify the generality of the information obtained above. Test conditions were (1) $k=0.20$, $Re=1.4 \times 10^5$ and (2) $k=0.60$, $Re=4.5 \times 10^4$. $\alpha=0^\circ$ in both cases. The frequency of oscillation was kept at 19 ± 0.05 Hz and the mean stream velocity was varied.

Figure 15 shows the spanwise distributions of C_r and C_i under condition (1) in the case of cascaded blades. With regard to the difference of aerodynamic forces due to tip clearance, the remarks mentioned in the previous section also hold true in this case. C_r is scarcely influenced by tip clearances when τ is 0° , but at $\tau=180^\circ$, its absolute value decreases considerably toward the tip in the case of $\delta=5.0$ mm. As for C_i , it is hardly influenced when $\tau=0^\circ$, and decreases remarkably toward the tip when $\tau=270^\circ$ in the large tip clearance.

Figure 16 indicates the distribution of aerodynamic forces under condition (2) for a cascade case. The influence of tip clearance is the same as mentioned for condition (1).

The information obtained in section 3.2 is verified for another conditions of k and Re . Furthermore, from experiments on an isolated blade, remarks on the case with steady loading is also proved to be applicable for different conditions.

Fig. 15 Spanwise distributions of unsteady aerodynamic forces
(Cascade, $\alpha=0^\circ$, Resultant data,
 $k=0.20$, $Re=1.4 \times 10^5$)

3.4 Influence of wall boundary layer

Since the flow field around the tip clearance is inside the wall boundary layer, it is important to investigate the influence of the boundary layer on unsteady aerodynamic characteristics.

For this purpose, an experiment was made with setting a thin flat plate (called "boundary plate", hereafter) at the outer edge of the boundary layer parallel to the mean flow. The boundary plate is 2 mm thick, and its leading edge is acutely cut while its trailing edge is rounded. It covers about 4 times the chord length in the chordwise direction and the whole range of the wind tunnel in the pitchwise direction. The boundary layer thickness on the plate is about 1.5 mm at a point 10 mm upstream of the blade leading edge and about 2.0 mm at a point 20 mm downstream of the blade trailing edge. The distance between the plate surface and the wall is 22 mm, so the span length is 158 mm including the tip clearance. In Fig. 2, the schematic view of the test section with the boundary plate is shown.

Experimental results on an isolated blade are presented here for both loaded and nonloaded cases. Figure 17 shows the distribution of C_r and C_i when $\alpha=0^\circ$ and Fig. 18 shows the case $\alpha=5^\circ$. Referring to Fig. 5 and 7, where the results with the wall boundary layers are presented, we do not find so much influence of the wall boundary layer on the variation of aerodynamic forces due to tip clearance. The influence of the wall boundary layer is seen in the shape of distribution curves of C_r and C_i at $\delta=0.1$ mm. If a wall boundary layer exists, absolute values of C_r and C_i decrease inside the boundary layer; if it does not

Fig. 16 Spanwise distributions of unsteady aerodynamic forces
(Cascade, $\alpha=0^\circ$, Resultant data,
 $k=0.60$, $Re=4.5 \times 10^4$)

Fig. 17 Spanwise distributions of unsteady aerodynamic forces
(Isolated blade with boundary plate, $\alpha=0^\circ$)

Fig. 18 Spanwise distributions of unsteady aerodynamic forces
(Isolated blade with boundary plate, $\alpha=5^\circ$)

exist, C_r and C_i in the tip region have the same values as in the main flow region, so that the distribution curve is flattened toward the blade tip. The effect of the steady blade loading found in Fig. 7 can also be seen here. Furthermore, experiments on the cascaded blades provided almost the same results as presented here.

4. Conclusions

The unsteady aerodynamic characteristics of the oscillating linear cascade with tip clearance was studied experimentally.

From the experiment on an isolated blade, the following conclusions were derived.

(1) The spanwise distribution of unsteady aerodynamic forces remarkably changes with the variation of tip clearance. The real part of the aerodynamic force, i. e., the aerodynamic damping force, considerably decreases with increasing tip clearances. The absolute value of the imaginary part also decreases. This change is most remarkable at the blade tip, and if the tip clearance is large, the change extends as far as the midspan region.

(2) The distribution of unsteady aerodynamic forces changes steeply up to about 1.7% of the blade span, but beyond this value, it changes very little.

Next, from the experiments on the cascaded blades, the following conclusions were obtained.

(3) Conclusions (1) and (2) also hold about the cascade.

(4) When the interblade phase angle τ is 0 degrees, unsteady aerodynamic forces are hardly influenced by tip clearance. The real part is most strongly influenced when τ is 180 degrees and the imaginary part when τ is 270 degrees.

If the steady aerodynamic loading acts on blades, the following characteristics are found for both an isolated blade and cascaded blades.

(5) The change of unsteady aerodynamic forces due to tip clearance is considerably suppressed by the steady blade loading.

(6) Once a tip vortex is generated, unsteady aerodynamic forces abruptly increase at the blade tip. The decreased aerodynamic damping force due to the tip clearance is recovered by this effect.

(7) When there is a tip vortex, the distribution of the unsteady pressure near the tip on the blade suction surface is flattened in the chordwise direction.

Finally, from the measurements with a very thin wall boundary layer, the following was found.

(8) The wall boundary layer has no serious influence on the change of unsteady aerodynamic forces due to tip clearance.

References

- (1) Hanamura, Y., Tanaka, H. and Yamaguchi, K., A New Experimental Method to Measure the Unsteady Forces of Vibrating Cascade. Trans. Jpn. Soc. Mech. Eng., (in Japanese) Vol. 45, No. 398, B (1979), p. 1399.