Influence of a Periodical Fluctuation on a Profile Loss of a Cascade*

(Part II, Behavior of a Boundary Layer)

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Unsteady boundary layers on a cascade in a periodically fluctuating flow have been investigated using an ensemble averaging technique. Time averaged velocity profiles, ensemble averaged instantaneous velocity distributions and turbulence in boundary layers on a test cascade have been obtained. A mechanism of the change in loss characteristics due to a fluctuation has been discussed from the behavior of boundary layers.

Boundary layer thickness, 99% thickness, of a lightly loaded cascade remarkably increases with a rise in the intensity of a fluctuation, but momentum thickness is not so affected because some compensating effects occur in a change in velocity profiles. The growth in turbulence in a boundary layer is suppressed by a periodical fluctuation. In the case of a highly loaded cascade, a dynamic stall occurs during a cycle of a fluctuation, but the stall is rapidly reestablished as the intensity increases, which causes an enlargement of the unstalled range of operation. However, these effects saturate at the intensity of 8~10%.

Key Words: Fluid Machine, Cascade, Unsteady Flow, Boundary Layer, Dynamic Stall, Stall Limit, Periodical Fluctuation

1. Introduction

In a previous paper(1), total pressure loss coefficients of a cascade in a periodically fluctuating flow have been obtained from a wake survey, and the influence of a fluctuation has been discussed from a macroscopic point of view. However, in order to discuss in detail on the change in loss characteristics of a cascade, not only a measurement of wake profiles but also the behavior of boundary layers on a cascade must be determined.

Many studies concerning unsteady boundary layers on an isolated airfoil or a cascade have been made from a practical point of view. For example, Hebbel(2) and Kiock(3) have observed the details of boundary layers on a cascade in a fluctuating flow after a turbulence grid or vibrating cylinder rows. Pfeil(4) has also carried out some experiments of an unsteady boundary layer in a periodical fluctuation generated by rotating spoke cylinders, and has pointed out a fact that the feature of the transition of boundary layer is largely modified. It has been also shown that effects of an unsteady flow on a three-dimensional cascade are different from those on a two-dimensional one(5). Recently, direct measurements of boundary layers on a blade surface in an actual compressor

have been made(6).

In a test using an actual compressor blade, however, it is not so easy to change widely the test parameters such as blade loading, frequencies, intensity of a fluctuation and Reynolds numbers. Therefore, a systematical evaluation of the effect of a fluctuation on the behavior of boundary layers is rather difficult in such a experiment.

In the present paper, unsteady boundary layers on the cascade in various fluctuating flows after a rotating cylinder row are measured using an ensemble averaging technique. Some attempts to explain the results, which were obtained in the previous paper(1) from the behavior of boundary layers are made.

Symbols newly used in this paper are as follows and the others are the same as in reference(1).

U : instantaneous velocity
 $\bar{U}$; time averaged velocity
 $\bar{U}_0$; $\bar{U}$ in a main flow region
 u ; intensity of turbulence
 u_m ; maximum value of u in a boundary layer
 x ; distance in a chord-wise direction, Fig.1
 y ; distance in a direction normal to an airfoil surface
 δ ; thickness of a boundary layer (99% thickness)
 δ^* ; displacement thickness of a boundary layer
 θ ; momentum thickness of a boundary layer
 ϕ ; phase angle

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2. Experimental Apparatus and Procedure

2.1 Test installation

A test rig and a test cascade are the same as those used in the previous paper(1). The arrangement of airfoils and coordinate systems are illustrated in Fig.1. In the study we used only smoothly surfaced airfoils, of which the number is the same as in the previous study(1). The number of cylinders in the rotating cylinders is 4~72 and their rotational speed is 670~1200rpm. The axial distance z is fixed at 20 mm in all tests. In this setup we can obtain a periodically fluctuating flow with frequencies of $f=45\sim1440\text{Hz}$ and intensity of $T=4\sim16\%$. Airfoils are set in two configurations, i.e., with an incidence $i=0$ in a lightly loaded case and $i=23$ deg in a highly loaded one. Parameters of the experiments are listed in Table 1.

2.2 Measuring procedure and instruments

A hot wire probe used is shown in Fig.2. The probe was inserted into the working section at the distance of x from the leading edge of a test cascade in such a manner that a sting of the probe and the airfoil surface made an angle of $20\sim30\text{deg}$, and the probe was traversed in y -direction at a pitch of 0.05 mm. The arrangement of the instruments is generally the same as in reference(1). For an ensemble averaging treatment, an electro-magnetic pickup was mounted at an end of the rotational axis and its signal was fed to a pulse generator, which was used as an interrupt signal to a micro-computer. The output from an

Fig.1 Details of a working section

anemometer was digitized with an A/D converter, and ensemble averages and fluctuating components were computed in the on-line process. The sampling frequency and data numbers are 0.9~29kHz and 300~1000, respectively.

3. Experimental Results and Discussions

3.1 Boundary layers of a lightly loaded cascade

Similarly to the previous study(1), the incidence was set at $i=0$ and velocity profiles in boundary layers were determined.

3.1.1 Time averaged properties of boundary layers

Time averaged velocity profiles are illustrated in Fig.3, where the measurements were made on only one side of an airfoil. The results shown as 'Annular duct' indicate the case in which the rotating cylinder row has been perfectly removed and the turbulence level is as high as 2 % due to inflow turbulence and boundary layers on the annular duct. The turbulence level is too high to consider the flow to be steady. But as we intend to clarify the effects of a relatively large fluctuation here, the steady case is represented by these ones. The time averaged velocity is heavily affected by a fluctuation and the boundary layer thickness, 99% thickness, increases with a rise in the intensity. The velocity distributions at the same chord-wise position but with different intensities are compared in Fig.4. Although few differences appear near the leading edge, remarkable changes can be observed after the mid-chord. The variations in velocity distributions are quite similar to those caused by the transition of a boundary layer from laminar to turbulent on a flat plate(8). The velocity defects in the vicinity of the cascade surface decrease with a rise in the intensity, while a rapid growth of boundary layer thickness, 99% thickness, occurs simultaneously.

Fig.2 Hot wire probe

Table 1 Experimental conditions

i deg	0						23					
N												
n rpm												
f Hz												
T %												
x/c

Fig.3 Time averaged velocity profiles

Fig.4 Effect of the intensity on time averaged profiles

As Evans(6) has pointed out, however, boundary layers on the blade surface in a periodical fluctuation are not necessarily turbulent even if they may look like turbulent from the time averaged flow profiles. Further discussions on the flow details will be made on the basis of a measurement of turbulence later.

The displacement thickness δ^* and momentum thickness θ obtained from these velocity profiles are shown in Fig.5. The displacement thickness in a steady or a relatively weak fluctuation rapidly grows after the mid-chord region, which suggests the transition of a boundary layer to turbulent flow, but such a remarkable growth vanishes in a high intensity fluctuation. The momentum thickness also increases after the mid-chord region, but the increase is not so remarkable as that in the displacement thickness. Therefore, the well known abrupt decrease in shape factor at the transition point cannot be detected. It can be considered that the

transition point may not appear so clearly because all of the present tests were carried out in flow fields with a relatively large intensity of 2 %.

A remarkable growth in boundary layer thickness caused by a rise in the intensity of a fluctuation is compensated by the increase in the velocity near the surface, and such a compensating effect occurs more effectively than the steady case. In this process, the increment in total pressure loss coefficients in a periodical fluctuation is suppressed to a relatively small value as described in the previous paper(1) although the velocity profile itself is widely varied as shown in Figs.3 and 4. The relation between θ and f is plotted in Fig.6. With a rise in the intensity T , θ gradually grows at all chord-wise positions, especially such a noticeable change occurs near the leading edge region. However, this change saturates at an intensity as high as 10%, which corresponds to the intensity at which

Fig.5 Variation of displacement and momentum thickness

Fig.7 Waveforms of velocity fluctuations

the changes in wake parameters saturate(1).

3.1.2 Turbulence in the boundary layer
Waveforms of velocity fluctuations are given in Fig.7. In the case of steady flow, random turbulence near the mid-chord rapidly increases, which indicates the transition of a boundary layer. On the other hand, in the case of a periodically fluctuating flow the waveforms consist of a cyclic fluctuation and random turbulence. Therefore, rms values of these waveforms do not indicate the true turbulence level. In the present study, the turbulence level in boundary layers is calculated from deviative components of the velocity from an ensemble averaged one. Fig.8 illustrates the turbulence distributions in boundary layers. In the case of steady flow, a turbulence with very high intensity, which is characterized by the turbulent boundary layer, appears in a region after $x/c=0.6$. For a periodically fluctuating flow, such a remarkable increase in turbulence disappears although only a little increase occurs near the surface.

Fig.6 Influence of f and T on momentum thickness

Fig.8 Turbulence in a boundary layer

The maximum turbulence level in boundary layers near the trailing edge, where an effect of a fluctuation clearly appears, is shown in Fig.9. The turbulence level gradually decreases with a rise in T , but the variation saturates at $T=(8\sim 10)\%$. From these results, it can be concluded that a periodical fluctuation has an effect to suppress the growth of a turbulence in boundary layers, and the boundary layers are gradually laminized with an increase in

Fig.9 Maximum turbulence in a boundary layer

the intensity.

From measurements of boundary layers in a two-dimensional cascade, Klock(3) has shown the fact that the region covered by a laminar boundary layer gradually enlarges with a rise in the turbulence level but at the specific turbulence level called critical turbulence, the transition of boundary layers takes place from the leading edge.

In the present experiment, an apparent decrease in turbulence in boundary layers due to a periodical fluctuation is observed, but a critical turbulence cannot be recognized.

3.1.3 Instantaneous velocity profiles

Fig.10 illustrates ensemble averaged instantaneous velocity profiles at four phase angles, where the reference phase angle is an angle at the moment when the velocity in the main flow indicates a maximum. Upper figures show the results in a relatively weak fluctuation. Judging from the variation in boundary layer thickness, Fig.5, the structure seems to be similar to that in a steady flow, but the actual velocity profiles remarkably vary with time. Although

Fig.10 Ensemble averaged instantaneous velocity profiles

instantaneous velocity profiles near the leading edge vary in phase with the main flow, those at the mid-chord vary out of phase as described in reference(6), i.e., the velocity near the surface indicates a minimum when the main flow becomes a maximum. Near the trailing edge, the boundary layer thickness varies more heavily and the flow reaches a near-separation at $\phi = 0$, but it is perfectly reestablished at the opposite phase. In the case of relatively high intensity, the variation in velocities at all chord-wise positions is small and a reversal of the phase of the profile variation appears only in a limited region. Even near the trailing edge, an instantaneous separation is not witnessed at all.

From a measurement in an axial-flow compressor, Evans(6) has indicated that in a boundary layer on a stator blade a relatively wide intermittent region in which laminar and turbulent flows alternate during a cycle of a fluctuation exists, and a reversal of the phase takes place in such a

Fig.11 Time averaged velocity profiles

region. However, we cannot detect any intermittent region from the waveforms of a velocity fluctuation or a distribution of turbulence.

3.2 Boundary layers of a highly loaded cascade

The behavior of boundary layers on a cascade with an incidence of 23 deg is discussed in this section.

3.2.1 Time averaged properties of a boundary layers

Time averaged velocity profiles on the suction surface are illustrated in Fig.11. It must be noticed that the ordinate of the figures is five times larger than that in Fig.3. The influence of a periodical fluctuation appears more clearly than that for the lightly loaded cascade. The velocity profiles near the mid-chord and the trailing edge are plotted in Fig.12. A boundary layer in a steady flow grows thick and the velocity defect near the surface becomes quite large, but it rapidly decreases with a rise in T . Unlike in a lightly loaded cascade, however, the boundary layer thickness also decreases, which indicates that the flow is rapidly reestablished with a rise in T .

The result described above fairly corresponds to the fact that the total pressure loss coefficient of a highly loaded cascade decreases and the unstalled range of operation enlarges with a rise in the intensity of a fluctuation(1). The momentum thickness is given against f and T in Fig.13. In contrast to the case of a lightly loaded cascade, the momentum thickness abruptly decreases with rises in f and T , but these changes in the momentum thickness saturate at $T=8\sim 10\%$, which corresponds to the intensity at which the enlargement of an unstalled range of operation saturates(1).

As described above, the influence of a periodical fluctuation on a highly loaded cascade is more remarkable than that on a lightly loaded one. In the calculation of a stall limit of a compressor cascade, the limit of aerodynamic loading is usually estimated from cascade data obtained in the steady flow(9), but the procedure often leads to poor agreement with an experiment in many cases. The results demonstrated here suggest that the limit of the aerodynamic loading must be determined by taking account of the effect of a fluctuation.

3.2.2 Turbulence in boundary layers

The waveforms of a velocity fluctuation for a highly loaded cascade are shown in Fig.14. High turbulence which appears near the leading edge suggests the leading edge separation. In the mid-chord region the flow is fully separated and periodicity perfectly vanishes. However, a periodical fluctuation clearly appears again near

Fig.12 Influence of T on momentum thickness

Fig.13 Influence of f and T on momentum thickness

Fig.14 Waveforms of velocity fluctuations

Fig.15 Maximum turbulence in a boundary layer

the trailing edge, i.e., the flow is reattached. The maximum intensity of turbulence is given in Fig.15. The high turbulence due to the flow separation rapidly diminishes with a rise in T but such a variation saturates at the intensity at which the change in momentum thickness saturates as described above.

3.2.3 Instantaneous velocity profiles

Fig.16 illustrates the ensemble averaged instantaneous velocity profiles. The upper figures show the case of a weak fluctuation and the velocity near the leading edge varies with a large amplitude, and the variation is out of phase to the main flow. That is, a leading edge separation takes place at $\phi=0$ and the flow is perfectly reestablished at the opposite phase. In the mid-chord region, almost similar variation appears. The fact shows that an unsteady separation occurs widely at the forehead of an airfoil. However, the flow near the trailing edge is perfectly established in all phases. In the case of high intensity shown in the bottom of Fig.16., the amplitude of a velocity fluctuation near the leading edge is the largest and a few signs of flow separation remain, but an apparent separation is not recognized at all. From these results, we can conclude that the dynamic stall, which is characterized by an alternation in flow conditions from separated to reattached occurs in a highly loaded cascade, but the unsteady separation is suppressed gradually with a rise of intensity, and it perfectly disappears when T reaches a specific value.

It must be emphasized that the foregoing discussion holds only for a cascade operating near its stall limit. Since the effect of a fluctuation to suppress the flow separation is naturally limited, an onset of the separation at too large incidence is inevitable even though the intensity of a fluctuation is quite large.

Fig.16 Ensemble averaged instantaneous velocity profiles

4. Conclusions

The influences of a periodical fluctuation on the time averaged velocity profiles, wake parameters, ensemble averaged instantaneous velocity distributions and turbulence in boundary layers on a cascade are investigated. The results can be summarized as follows.

(1) Although the velocity profiles are heavily affected by a periodical fluctuation, an increase in the momentum thickness becomes relatively small because an increment of the boundary layer thickness is compensated by a decrement of the velocity defect near the surface.

(2) A periodical fluctuation has an effect to suppress the growth of turbulence in boundary layers, but the effect saturates when the intensity reaches 8~10 %.

(3) A dynamic stall occurs in a cascade in a periodical fluctuation with relatively low intensity. Since a fluctuation has an effect to suppress the onset of separation, the unstalled range of operation enlarges with an increase in the intensity.

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