Unsteady Aerodynamic Characteristics of Abrupt Stall Type Airfoil
in Pitching Oscillation near Stall Angle of Attack*

(1st Report, On Dynamic Characteristics of Flow Separation
and Regions Corresponding to Separation Patterns)

By Susumu ISHII**, Hideo TANAKA*** and Ichiro FUJIMOTO****

Using an abrupt stall type airfoil, which shows the nature of abrupt change in the static moment curve as the increment of angles of attack due to the sudden change of separation pattern to the leading edge separation, are investigated experimentally the unsteady aerodynamic characteristics of the airfoil in pitching oscillation near stall angle of attack.

The aspects of the change of separation pattern during oscillation in this region of angle of attack are clarified in detail. The effects of mean angle of attack, reduced frequency, amplitude of pitching oscillation and location of pitching axis on the unsteady stall characteristics are made clear, and the region corresponding to separation patterns are defined.

Key Words : Unsteady Aerodynamics, Reattachment, Dynamic Response, Hysteresis, Oscillating Airfoil, Abrupt Stall, Leading Edge Separation

1. Introduction

The angle of attack of a blade in turbomachines becomes comparatively high in high loaded condition and therefore turbomachines necessarily operate in a range near the stall angle of attack. The phenomenon of dynamic stall^{(1)~(4)} or hysteresis related to flow separation⁽⁵⁾⁽⁶⁾ occurs in such a range of angles of attack, and a complicated flow field and characteristics of stalled flow field are mixed with each other. Consequently, it is difficult to analyze the unsteady aerodynamic characteristics of an oscillating blade and there still remain many problems unsolved.

Regarding the problem of so-called dynamic stall, McCroskey et al.⁽⁷⁾ made a close study related to the retreating blade stall of a main rotor of a helicopter by measuring the unsteady pressure distribution on the suction surface of a two-dimensional blade in pitching oscillation and noticing the influence of the mean angle of attack, frequency and amplitude of pitching oscillation, and so forth. However, their study was chiefly an analysis of stall vortices cyclically shed from the blade. Such problems were treated only in a limited case where the flow around the airfoil repeated separation and

reattachment cyclically due to a large amplitude of pitching oscillation and a low reduced frequency.

Nakamura et al.⁽⁷⁾ measured the unsteady pressure at several chordwise location on the surface of an oscillating blade and analyzed the pressure amplitude and phase difference of fundamental oscillation frequency component only for such case that the distortion of pressure waveform is small. However, they did not make a comprehensive elucidation which would make it possible to analyze the unsteady flow phenomena or dynamic behavior of a flow around an oscillation blade noticing the stall characteristics of a blade.

To discuss the unsteady aerodynamic characteristics of an airfoil in pitching oscillation in the range including the stall angle of attack, it is indispensable as a matter of course to elucidate the stall characteristics of the airfoil. Stall types of stationary blades were largely classified by McCullough and Gault⁽⁸⁾ in 1951 into three typical types, i.e., leading edge stall, trailing edge stall and thin-airfoil stall, through their comprehensive survey of many studies and researches, and this classification is important still at present as the fundamental classification. Noting the difference among these stall characteristics, the present authors already made a series of studies⁽⁹⁾⁽¹⁰⁾ regarding the relation between the stall types of blades and flutter characteristics by varying the blade profile and Reynolds number for the purpose of elucidating the flutter characteristics. Furthermore, the present authors also made researches⁽¹¹⁾⁽¹²⁾ regarding the unsteady aerodynamic characteristics of blade in pitching oscillation over a

*Received 29th Aug. 1983

**Associate Professor, Faculty of Industrial Engineering, Nihon Univ., Izumi-cho, Narashino-city, Chiba-pref..

***Professor, Faculty of Engineering, Tokai Univ., Hirastuka, Kanagawa-pref..

****Assistant, Faculty of Engineering, Univ. of Tokyo, Komaba, Meguro, Tokyo.

wide range of angles of attack by using various blades of individually different stall characteristics. Though these researches, it is revealed that, in case of an airfoil having the abrupt stall characteristics which shows an abrupt change of flow pattern around the blade into full separation (leading edge separation) with an increase in the angle of attack and which also shows an abrupt change in the static moment characteristics, there occurs a phenomenon of hysteresis depending on oscillation of the blade⁽⁶⁾ in addition to so-called static hysteresis phenomenon related to the variation in the static angle of attack, and it is also found that the flow field around the blade shows very complicated aspects. This paper gives a close analysis of unsteady aerodynamic characteristics of the above-mentioned abrupt stall type airfoil in pitching oscillation including the dynamic behavior of a flow around the blade near the stall angle of attack.

2. Test Facilities and Measurement Procedure

A blow-down type low-speed wind tunnel with a test section of 180 mm by 360 mm is used. The flow velocity ranging from 5 m/s to 100 m/s is available, and the turbulence level is approximately 1 % at the flow velocity of 15 m/s adopted in the present experiment.

A Göttingen 801 is used as a test blade which is a two-dimensional aluminium blade with a chord length c and span of 100 mm and 180 mm respectively. A large number of pressure holes are provided on the blade surfaces (30 holes on the suction surface and 13 holes on the pressure surface). Figure 1 illustrates the profile of the test blade used in the present experiment together with the locations of pressure holes and pitching axis. The unsteady pressure on the blade surface is transmitted from the pressure hole denoted by 6 in Fig.3 to the end of the blade through the common cavity inside the blade and pressure lead which are shown in Fig.2 (skeleton) and, then, to the pressure transducer which is installed outside the blade as denoted by 8 in Fig.3 through a silicone rubber tube denoted by 7. In the experiment, all pressure holes are covered with plastic tape except one pressure hole selected for the measurement. The test blade denoted by 5 in Fig.3 is forced to oscillate in pitch (0 to 40 Hz) around various centers of pitching oscillation shown in Fig.1 with a semi-amplitude of α_1 by means of the motor through the crank mechanism denoted by 2. The displacement of the test blade to be used as the basic data is measured by the potentiometer denoted by 12, and rectangular pulses produced by the phototransistor denoted by 11 are used as the trigger pulses for the conditional averaging technique. The unsteady pressure data obtained from individual pressure holes on the surface of the oscillating blade are processed by

Fig.1 Model profile, pressure hole location and pitching axis location

Fig.2 Schematic view of test blade

(1) Drive Motor	(2) Eccentric Cam
(3) Slider	(4) Crank Arm
(5) Model Airfoil	(6) Pressure Taps
(7) Silicone Rubber Tube	(8) Pressure Transducer
(9) Damper	(10) Trigger Disk
(11) Photo Transistor	(12) Angular Pick-up

Fig.3 Schematic of measuring setup

utilizing a data processing system, which has a minicomputer as the main unit and is arranged, by taking the conditional averaging technique into consideration, so as to obtain the measured results corrected according to the transfer function of the pressure transfer system. (For details of data collection, recording, processing and analyzing methods, refer to Reference⁽⁴⁾)

The procedure of the experiment is as follows. The test blade is set up by variously changing the mean angle of attack α_0 in a range near the static stall angle of attack of the test blade and is forced to oscillate in pitch around the midchord. Observing the obtained waveforms of unsteady pressure on the blade surface (patterns of partial separation and full separation) by means

of an oscilloscope, the oscillation frequency is increased from a low value and decreased from a high value, and at every frequency value in both of increasing process and decreasing process, the displacement of the blade, trigger pulse, and waveform of unsteady pressure within one cycle of oscillation are recorded for 10 to 15 cycles using a pen-writing oscillograph and data recorder. At the same time, the reduced frequency when the separation pattern changes is also measured. As will be described in section 3.2, the instantaneous chordwise pressure distribution of a blade during pitching oscillation in a fully separated flow becomes considerably different from that in a partially separated flow as shown in Fig.5. Therefore, the points of $x/c = 0.1$ and $x/c = 0.2$ (x represents the chordwise distance from the leading edge and c represents the chord length) on the suction surface of the blade are adopted as the locations of pressure measuring points because these points are sensitive to a change of flow separation pattern.

The test conditions for measurement are as follows: free stream velocity $U = 15$ m/s; Reynolds number $Re = 1.0 \times 10^5$; semi-amplitude of pitching oscillation $\alpha_1 = 1, 3, 4$ and 7 deg.; location of pitching axis 1 (distance from leading edge to pitching axis normalized with chord length c) = $0.05, 0.5$ and 0.7 ; mean angle of attack $\alpha_0 = 14 - 25$ deg.; and reduced frequency k ($k = cw/U$, w : circular frequency) = $0 - 1.4$.

3. Results and Discussion

3.1 Steady pressure distribution

Figure 4 shows the static pressure distributions on the suction surface of the test blade at respective angles of attack when the angle of attack is increased and decreased.

When the angle of attack is increased, a suction plateau is observed in the range of the angles of attack $\alpha = 2$ to 21 deg. and it indicates the existence of a separation bubble. The separation bubble moves toward the leading edge of the blade as the angle of attack is increased. Besides, at a position near the angle of attack $\alpha = 22$ deg., the pressure distribution on the blade surface changes abruptly, and the pressure curve becomes approximately flat in the chordwise direction. This indicates that the flow separation pattern suddenly changes here from partial separation to full separation. When the angle of attack is further increased, the flow separation pattern remains in the state of full separation. When the angle of attack is decreased (case of decreasing α in Fig.4) after increasing it until the flow separation pattern once changes to full separation as mentioned above, the flow separation pattern does not return to partial separation but remains in the state of full separation even when the angle of attack becomes $\alpha = 22$ deg. or lower, where it suddenly changes when α is increased. When the angle of attack is

Fig.4 Chordwise distribution of static pressure on stationary blade suction side

Fig.5 Instantaneous pressure distribution on suction surface ($\alpha = 20$ deg.)

further decreased to about $\alpha = 17$ deg., the pressure distribution on the blade surface changes abruptly and the flow separation pattern then returns to partial separation. In other words, in the courses of increase and decrease of the angle of attack, the flow separation pattern changes in different manners, and a static hysteresis phenomenon is observed.

The broken line in Fig.6 shows the static moment characteristics of the test blade obtained from the pressure distribution on the blade surface at each

angle of attack. As it will be understood from Fig.6, the static hysteresis phenomenon is observed also in the static moment characteristics.

3.2 Dynamic characteristics of flow separation

3.2.1 Change of dynamic pattern of flow separation according to reduced frequency k

An example of variation of instantaneous chordwise pressure distribution on the suction surface of the blade within one cycle of pitching oscillation around the midchord is shown below as one of the results obtained by setting the blade at a mean angle of attack near the stall angle of attack where the blade shows the above-mentioned static characteristics.

As a typical example, Fig.5(a) and 5(b) show the tendencies of variation of unsteady pressure distributions on the suction surface of the blade at the mean angle of attack α_0 of 20 deg. with the amplitude of ± 3 deg. according to the variation of the reduced frequency k for increasing k and decreasing k respectively. In Fig.5(a) showing the case of increasing k , the chordwise pressure distribution on the blade surface within one cycle of oscillation is approximately flat when k is comparatively low, i.e., $k = 0.47$, and it is recognized that the flow separation pattern is always kept in the state of full separation throughout one cycle. When k is increased to $k = 0.81$, the pressure distribution on the blade surface shows a complicated aspect. Especially at a position near the leading edge, the suction becomes large and a suction plateau is observed at the position near $0.1 < x/c < 0.3$. This evidently shows that the point of reattachment of separation bubble has moved and that the flow separation pattern has changed to the state of partial separation throughout one cycle of oscillation. Even when k is further increased, in the range adopted in the present experiment. The flow pattern around the blade persists in the state of partial separation throughout one cycle, and a change of separation pattern does

not appear. When k is decreased after once increasing it until the flow separation pattern changes to the state of partial separation throughout one cycle as described in the above and is kept in that state, the flow separation pattern remains in the state of partial separation throughout one cycle even when k is decreased to $k = 0.47$ at which it is in the state of full separation throughout one cycle when k is increased. When k is further decreased to $k = 0.15$, the chordwise distribution of unsteady pressures becomes approximately flat, and it is recognized that the flow separation pattern has changed to the state of full separation throughout one cycle. Here, it is observed that there exists such a phenomenon that the value of k , at which the flow separation pattern changes from the state of partial separation to that of full separation throughout one cycle when k is decreased, does not coincide with the value of k at which the flow separation pattern changes from the state of full separation throughout one cycle to that of partial separation when k is increased, and it is recognized that the blade shows a hysteresis phenomenon which is attendant upon pitching oscillation of the blade and which is different from the state hysteresis phenomenon described in section 3.1.

As it is found that the blade, which causes an abrupt change of flow separation pattern near the stall angle of attack, shows a complicated phenomenon related to the unsteady aerodynamic characteristics near the stall angle of attack when it is in pitching oscillation, close experiments are made in the range near the stall angle of attack including the range of angles of attack causing the aforementioned static hysteresis phenomenon in order to thereby elucidate the above-mentioned phenomena in further details.

Firstly, the mean angle of attack α_0 is set at a value near the stall angle of attack, and the angle of attack is varied slowly in a quasi-static manner ($k = 0$) in the range of ± 3 deg. When the mean angle of attack α_0 is comparatively small, i.e., in the range of $\alpha_0 < 18.75$ deg., the instantaneous angle of attack during pitching oscillation does not exceed the stall angle of attack, 21.75 deg. (at which the flow separation pattern changes to full separation), therefore, the flow separation pattern always remains in the state of partial separation throughout one cycle and the pattern of full separation does not appear.

When the mean angle of attack α_0 is increased to the range of $18.75 \text{ deg.} < \alpha_0 < 20.25 \text{ deg.}$, the instantaneous angle of attack during nose-up period sometimes becomes larger than 21.75 deg. and it during nose-down period smaller than the reattachment angle of attack (at which the flow separation pattern returns to partial separation), i.e., 17.25 deg., therefore, the partially separated pattern and the fully separated pattern appear periodically in each cycle of variation of angles of attack. Here, the reattachment

Fig.6 Region related to different aspects of flow separation during blade oscillation

angle of attack means an angle of attack at which the flow separation pattern returns from the state of full separation to the state of partial separation.

When the mean angle of attack is further increased to $\alpha_0 > 20.25$ deg., the angle of attack does not become smaller than the reattachment angle of attack, i.e., 17.25 deg. even in the nose-down period, therefore, the flow separation pattern always remains in the state of full separation throughout one cycle, and the pattern of partial separation does not appear.

Now, the case that the test blade is oscillated in pitch around the midchord is discussed below. In the range of $\alpha_0 < 18.75$ deg., when the reduced frequency k is low, the partial separation pattern persists throughout one cycle of oscillation in the same way as the case of quasi-static variation of angle of attack described in the above, and even when k is increased, it remains in the state of partial separation throughout one cycle.

When the mean angle of attack is increased to 18.75 deg. $< \alpha_0 < 19.5$ deg., the partially separated pattern and fully separated pattern appear periodically in each cycle of oscillation when k is low. However, when k is increased, the flow separation pattern changes at a certain value of k to the state of partial separation throughout one cycle. When k is further increased, in the range adopted in the present experiment, the flow separation pattern remains in the state of partial separation throughout one cycle, and a change of separation pattern does not occur. When k is decreased from that state of partial separation mentioned above, the flow separation pattern changes, at a value of k approximately equal to the case of increasing k , to the state where the partially separated pattern and fully separated pattern appear periodically in each cycle of oscillation by inversely following the process observed when k is increased. When the mean angle of attack α_0 is increased in that range at the time, the value of k at which the flow separation pattern changes (the boundary value of k of the range where the partially separated pattern and fully separated pattern appear periodically in each cycle and the range where the partially separated pattern persists throughout one cycle), shows the tendency of becoming higher.

When the mean angle of attack α_0 is further increased to 19.5 deg. $< \alpha_0 < 20.25$ deg., the partially separated pattern and fully separated pattern appear periodically in each cycle of oscillation when k is low, in the same way as the case of 18.75 deg. $< \alpha_0 < 19.5$ deg.. However, as k is increased, the flow separation pattern changes to full separation throughout one cycle at a certain value of k . When α_0 is increased in that range, the value of k at which the flow separation pattern changes shows a tendency of becoming lower unlike the case of 18.75 deg. $< \alpha_0 < 19.5$ deg.. When k is further increased in the above-mentioned

range of α_0 after the flow separation pattern once changes to the state of full separation throughout one cycle as described in the above, the flow separation pattern changes to the partial separation from that of full separation throughout one cycle at a value of k larger than a certain value. When k is further increased after the above, the flow separation pattern does not change any more but remains in the state of partial separation throughout one cycle of oscillation.

When k is thus increased until the flow separation pattern once changes to the partial separation throughout one cycle and then decreases from that state, the flow separation pattern does not change at a value of k , at which the flow separation pattern changes (from the state of full separation to that of partial separation throughout one cycle) when k is increased as described in the above, but remains in the state of partial separation throughout one cycle. When k is further described the flow separation pattern changes from the state of partial separation to that of full separation throughout one cycle of oscillation, and there is observed a new hysteresis phenomenon which is attendant upon oscillation of the blade and which is different from the static hysteresis phenomenon. When k is further decreased, the flow separation pattern changes, at a value of k approximately equal to the case of increasing k , to the state where the partially separated pattern and fully separated pattern appear periodically in each cycle of oscillation by inversely following the process observed when k is increased.

When the mean angle of attack α_0 is further increased to 20.25 deg. $< \alpha_0 < 22$ deg., the flow separation pattern is kept in the state of full separation throughout one cycle of oscillation when k is low, and when k is increased it changes from the state of full separation to that of partial separation throughout one cycle at a certain value of k . When k is further increased, the flow separation pattern remains in the state of partial separation throughout one cycle of oscillation. When k is decreased from the above-mentioned state, the hysteresis phenomenon attendant upon the blade oscillation is observed in the same way as in the above-mentioned case of 19.5 deg. $< \alpha_0 < 20.25$ deg.. When k is further decreased, the flow separation pattern changes to the state where the fully separated pattern is maintained throughout one cycle of oscillation.

Figure 6 shows the value of reduced frequency k at which the flow separation pattern changes at various angles of attack. Here, the value of reduced frequency k (0 mark) at which the flow separation pattern changes from full separation to partial separation throughout one cycle of blade oscillation when k is increased from a low value at a certain mean angle of attack α_0 does not coincide with the value of k (0 mark) at

which the flow separation pattern returns from partial separation to full separation throughout one cycle when k is decreased inversely from the above-mentioned state of partial separation. So, it is indicated that there exists the aforementioned new hysteresis phenomenon attendant upon the oscillation of the blade. As the occurrence of the new hysteresis phenomenon is now clear as above, it is possible to explain Fig.5(a) and 5(b) shown before. That is, when the test blade is oscillated in pitch around the midchord at the mean angle of attack $\alpha_0 = 20$ deg. in the range of angles of attack where this hysteresis phenomenon occurs, it will be understood from Fig.6 that when k is increased from a very low value, the flow separation pattern changes from the state where the partially separated and fully separated appear periodically in each cycle to the state of full separation throughout one cycle. When k is further increased to $k = 0.80$ or more, the flow separation pattern changes from the state of full separation to that of partial separation throughout one cycle. When the instantaneous pressure distribution on the section surface of the blade shown in Fig.5(a) (case of increasing k) is referred to regarding the above-mentioned points, it will be understood that the flow separation pattern is in the state of full separation throughout one cycle in cases of $k = 0.15$ and $k = 0.47$ and is evidently changed to the state of partial separation throughout one cycle in the case of $k = 0.81$.

When k is decreased from the above-mentioned state, it will be understood from Fig.6 that the flow separation pattern does not change even when the value of k becomes $k = 0.80$, at which the flow separation pattern changes as mentioned in the above when k is increased, but remains in the state of partial separation throughout one cycle and that, only when k is further decreased to $k = 0.30$, the flow separation pattern changes to the state of full separation throughout one cycle.

When the instantaneous pressure distribution on the suction surface of the blade shown in Fig.5(b) (in case of decreasing k) is referred to regarding the above-mentioned points, it will be understood that the flow separation pattern is evidently in the state of partial separation throughout one cycle in cases of $k = 0.81$ and $k = 0.47$ and is changed to the state of full separation throughout one cycle in case of $k = 0.15$. From the above, it will be understood that, in the range from $k = 0.30$ to $k = 0.80$, the flow separation pattern shows a bi-stable state where either the fully separated pattern or partially separated pattern persists throughout one cycle depending upon the history of k . The value of k that causes the change of the flow separation pattern shows a tendency of varying toward a higher value as α_0 is increased within the range of 19.5 deg. $< \alpha_0 < 22$ deg..

When the mean angle of attack α_0 is increased to $\alpha_0 > 22$ deg. the flow separation pattern always remains in the state of full separation throughout one cycle even when the value of k is made very high in the present experiment and the partially separated pattern does not appear.

As is understood from Fig.6, the range of angles of attack where the above-mentioned new hysteresis phenomenon occurs somewhat deviates toward a larger the angle of attack than the one angle where the static hysteresis phenomenon occurs.

3.2.2 Classification of regions of flow separation pattern

The results of experiments carried out by setting k at various mean angle of attack by taking the above-mentioned phenomenon into consideration are summarized in Fig.6, and it is revealed that, within the range of test conditions adopted in the present experiment, there exist four different regions of flow separation patterns as shown below relating to the flow field around the blade.

I: Region where the partially separated flow pattern always persists throughout one cycle of oscillation.

II: Region where the fully separated flow pattern always persists throughout one cycle of oscillation.

III: Bi-stable region where either the partially separated flow pattern or the fully separated flow pattern persists throughout one cycle of oscillation depending upon the variation process (history) of the reduced frequency.

IV: Region where the partially separated flow pattern and the fully separated flow pattern appear periodically in each cycle of oscillation.

In Fig.6, the line A represents the boundary line at which the flow separation pattern changes from the state of partial separation throughout one cycle in the region III to the region II, the line B represents the boundary line for changing from the region II to the region IV, and the line C represents the boundary line at which the flow separation pattern changes from the state of full separation throughout one cycle in the region III to the region I. Details related to these lines are given below.

Now, the changes of dynamic flow separation pattern in the above-mentioned regions are discussed further in detail below referring to Fig.6. As described before, when the test blade is set at the mean angle of attack α_0 in the range of 18.75 deg. $< \alpha_0 < 19.5$ deg. and oscillated in pitch and k is decreased from the state in region I where the value of k is high enough, the points (● mark) at which the flow separation pattern changes from the state in the region I to the state in the region IV lie on the extension line of the values of k (● mark) at which the flow separation pattern changes from the state of partial separation throughout one cycle in the region III to the state in the region II when the mean angle of attack α_0 is set

in the range of $19.5 \text{ deg.} < \alpha_0 < 22 \text{ deg.}$. All of these phenomena relate to such dynamic characteristics of flow separation that the flow pattern changes from the partially separated flow pattern to the fully separated flow pattern, and this boundary line in Fig.6 is re-called the line A.

When the mean angle of attack α_0 is set in $19.5 \text{ deg.} < \alpha_0 < 20.25 \text{ deg.}$ and k is decreased by keeping the flow separation pattern in the state of region II where the value of k is comparatively high, the flow separation pattern changes from the state in the region II to the state in the region IV. When α_0 is decreased in the above-mentioned range, the value of k at which the flow separation pattern changes from the state in the region II to the state in the region IV shows a tendency of becoming high. All of these phenomena relate to such dynamic characteristics of flow reattachment that the flow pattern changes from the fully separated flow pattern to the partially separated flow pattern, and this boundary line in Fig.6 is called the line B. For the boundary line B, it is expected that an extension line should exist also in the region of $\alpha_0 < 19.5 \text{ deg.}$.

When the mean angle of attack α_0 is set in $19.5 \text{ deg.} < \alpha_0 < 22 \text{ deg.}$, the fully separated flow pattern persists throughout one cycle when the value of k exists in the region II and, when k is increased from this state, the value of k changes from the region II to the region III (bi-stable region). As k is varied in an increasing direction here, the flow separation pattern does not change in this region but remains in the same state as in the region II. When k is further increased, the flow separation pattern changes from the state maintained in the region III, i.e., full separation throughout one cycle, to the state in the region I, i.e., partial separation throughout one cycle. These phenomena relate to the dynamic characteristics of flow reattachment which are somewhat different from the above-mentioned dynamic characteristics of flow reattachment, and the boundary line at which the flow separation pattern changes from the state of full separation throughout one cycle in the region III to the state in the region I in Fig.6 is called the line C. The detail about the line C will be described in the next report together with the details about the lines A and B shown in the above. For the line C, it is also expected that an extension line should exist also in the region of $\alpha_0 < 19.5 \text{ deg.}$.

Here, the line A is a boundary line where the flow separation pattern changes from partial separation to full separation as described before, and it will be understood that the state of partial separation throughout one cycle is maintained in the region where the value of k is high than the line A. On the other hand, the line B is a boundary line where the flow separation pattern changes from full separation to partial separation unlike the line A and, therefore, it will

be understood that the state of full separation throughout one cycle is maintained in the region where the value of k is high than that of the line B. When it is presumed that an extension line of the line B exists also in the region of $\alpha_0 < 19.5 \text{ deg.}$, it is expected that, in the region where the value of k is high than that of the line B including the extended portion thereof, the flow separation pattern is in the state of full separation throughout one cycle. From the above, it is expected that there exists a bi-stable region, where the partially separated flow pattern and the fully separated flow pattern can be maintained independently of each other, in the region above the line B including the extended portion thereof where k is high and, at the same time, above the line A where k is high, in other words, in the common region where k is higher than the extension line of the B and the line A. On the other hand, in the range of $19.5 \text{ deg.} < \alpha_0 < 22 \text{ deg.}$, it is clear as described before that the line C exists at a position where the value of k is large. As the line C is clear, it is clear that the region III which is a bi-stable region, exists between the line C and A in the above-mentioned range of α_0 and; moreover, it is found that the flow separation pattern changes when a disturbance is forcibly produced in the region III and comes into the stable that either the partially separated flow pattern or the fully separated flow pattern persists throughout one cycle. The line C is the boundary line related to the dynamic characteristics of flow reattachment which is somewhat different from the dynamic characteristics of flow reattachment related to the line B as described before and it is found that, in the region above the line C where k is high, the flow separation pattern is in the state of region I and the partially separated flow pattern throughout one cycle is always maintained even when a disturbance is given forcibly.

When it is presumed that an extension line of the line C also exists in the region of $\alpha_0 < 19.5 \text{ deg.}$, it is expected that, in this range of α_0 that is

Fig.7 Regions related to different aspects of flow separation during blade oscillation

surrounded by the extension lines of the lines C and B, there exists a bi-stable region where the flow separation pattern changes in the same way as in the region III where a disturbance is given forcibly and the partially separated flow pattern and the fully separated flow pattern can be maintained independently of each other. Therefore, about the region surrounded by the extension lines of the lines C and B, the authors made an elaborate measurement by setting the mean angle of attack α_0 especially at about 18.75 deg. $< \alpha_0 < 19.5$ deg., and the results obtained are shown in Fig.7. Here, when the experiment is carried out with giving a forced disturbance forcibly in the above-mentioned range of α_0 , the flow separation pattern is in the state of the region IV when k is low and, when k is increased, the flow separation pattern changes to the state of the region I, i.e., partial separation throughout one cycle. In the region I, the flow separation pattern is always maintained in the state of the region I regardless of the value of k , and a change of the flow separation pattern is not observed.

However, when k is increased to a value in the region III surrounded by the one-dot chain line in Fig.7 at which the flow separation pattern remains in the state of partial separation throughout one cycle of oscillation (the same state as in the region I) then a disturbance is forcibly produced temporarily so that the flow separation pattern changes to full separation throughout one cycle, it is observed as expected that the fully separated flow pattern becomes stable in that state.

When k is increased from the above-mentioned state of full separation throughout one cycle in the region III the flow separation pattern changes from full separation to partial separation throughout one cycle at a certain value of k or more. When k is further increased, the flow separation pattern does not change but remains in the state of partial separation throughout one cycle.

When the mean angle of attack α_0 is increased within the above-mentioned range of α_0 , the value of k at the change point of flow separation pattern shows a tendency of becoming higher, and it is found that those values of k exist on the extension line of the line C shown in Fig. 7. When k is decreased from the state of full separation throughout one cycle in the region III in the same way as above, the flow separation pattern changes from full separation to partial separation throughout one cycle at a certain value of k or less. When α_0 is increased within the above-mentioned range, the value of k at the change point of flow separation pattern shows the tendency of becoming lower, and it is found that those values of k exist on the extension line of the line B shown in Fig.7. Thus, it is proved as expected that there exists an extended region III' of the bi-stable region III where the partially separated flow pattern throughout one cycle and the fully

separated flow pattern throughout one cycle can be maintained independently of each other.

As a result of the precise experiments regarding the dynamic characteristics of the blade in pitching oscillation near the stall angle of attack carried out as described so far, a new bi-stable region III' appears in the range near the stall angle of attack and, consequently, detailed classification of regions corresponding to the flow separation pattern is revealed.

3.3 Influence of variation of pitching oscillation amplitude on dynamic characteristics of flow separation

For a more detailed analysis of the flow separation patterns described so far, the same experiments are made by setting the amplitude of pitching oscillation α_1 at 1 deg., 4 deg. and 7 deg., and the results obtained are shown in Fig.8.

When the amplitude of pitching oscillation α_1 is small enough compared with the extent of angle of attack $\Delta\alpha_s$ for static hysteresis (when $\alpha_1 < \Delta\alpha_s/2$), i.e., in case of $\alpha_1 = 1$ deg., the flow separation pattern becomes as described below when the angle of attack of the blade is varied slowly in a quasi-static manner in the range of ± 1 deg. with respect to the mean angle of attack α_0 near the stall angle of attack and near the reattachment angle of attack. That is, in the range of $\alpha_0 < 18.25$ deg., the instantaneous angle of attack during nose-down motion sometimes decreases below the reattachment angle of attack, i.e., 17.25 deg., but never reach the stall angle of attack, i.e., 21.75 deg., even in the nose-up motion. Therefore, the partially separated flow pattern persists throughout one cycle, and the fully separated flow pattern does not appear. On the other hand, in the range of $\alpha_0 > 20.75$ deg., the instantaneous angle of attack in the nose-up motion sometimes increased beyond the stall angle of attack, i.e., 21.75 deg., but never reach the reattachment angle of attack, i.e., 17.25 deg. even in the nose-down motion. Therefore, the fully separated flow pattern persists throughout one cycle, and a partially separated flow pattern does not appear.

The above-mentioned facts can be explained based on the static moment characteristics shown by the broken line in Fig.8.

However, when the blade is oscillated in pitch in the same way as in the case of the amplitude of pitching oscillation $\alpha_1 = 3$ deg., there emerge three regions of flow separation patterns, i.e., a region of partial separation throughout one cycle of oscillation (region I), a bi-stable region (region III) and a region of full separation throughout one cycle (region II), but the region where partial separation and the full separation appear periodically in each cycle (region IV) does not appear. Beside, it is found that the bi-stable region becomes very wide compared with the case of the amplitude α_1

$= 3 \text{ deg.}$

Now, when the amplitude of pitching oscillation is varied, the result becomes as described below. That is, as the amplitude is made larger, the boundary line B shifts in larger angle of attack as shown by white marks in Fig.8, while the line A shifts in the smaller angle of attack as shown by black mark in Fig.8, in contrast with the line B. Therefore the bi-stable region shows a tendency of becoming narrower with an increase in the amplitude of pitching oscillation. This will be understood when a comparison is made between the cases of the amplitude $\alpha_1 = 1 \text{ deg.}$ and $\alpha_1 = 3 \text{ deg.}$ in Fig.8. From the above, it will be understood that, when the amplitude of pitching oscillation is comparatively small as in the case of discussing the occurrence of flutter, the hysteresis phenomenon attendant upon pitching oscillation of the blade treated in the present report becomes more important from a view point of aeroelasticity as described also in the previous report⁽⁵⁾.

When the amplitude α_1 is increased to $\alpha_1 = 4 \text{ deg.}$, the line B and A intersect each other in the same way as in the case of $\alpha_1 = 3 \text{ deg.}$, so there also emerge four regions of flow separation patterns. However, compared with the case of $\alpha_1 = 3 \text{ deg.}$, the bi-stable region becomes narrower while the region where partial separation and full separation appear periodically in each cycle of oscillation becomes wider as it is understood from Fig.8.

When α_1 is further increased, the region $\mathcal{V}$ where partial separation and full separation appear periodically becomes still wider. When α_1 is increased to $\alpha_1 = 7 \text{ deg.}$, it is found that there appear only three regions of flow separation pattern, i.e., the region I, II and IV, and it is expected that the bi-stable region III will disappear. The authors did not carry out further experiment because it was dangerous to make the value of k high than those shown in Fig.8.

As a whole, within the range of reduced frequencies k adopted in the present experiment, it is clear that the regions of flow separation patterns change as follows according to the correlation between the range of angles of attack $\Delta\alpha_s$ for static hysteresis and amplitudes of

Fig.8 Regions related to different aspects of flow separation during blade oscillation

pitching oscillation α_1 . That is, in case of $\Delta\alpha_s/2 \geq \alpha_1$, three appear there regions of flow separation pattern, i.e., the regions I, II and III, and the region IV where partial separation and full separation appear periodically does not appear. In case of $\Delta\alpha_s/2 < \alpha_1 < \Delta\alpha_s$, there are four regions of flow separation patterns, i.e., the regions I, II, III and IV. In case of $\Delta\alpha_s < \alpha_1$, there are broadly three regions of flow separation pattern, i.e., the regions I, II and IV, and it seems that the bi-stable region III does not appear. From the above, it is clear that when α_1 is varied, the bi-stable region III becomes narrower while the region IV becomes wider as α_1 is increased and that the bi-stable region III becomes wider while the region IV becomes narrower as α_1 is decreased in contrast with the above. Thus, it is revealed that the variation of the amplitude of pitching oscillation has considerable influence on the dynamic characteristics of flow separation.

3.4 Influence of location of pitching axis 1 on dynamic flow separation pattern

To investigate into the influence of the location of pitching axis 1 on the dynamic flow separation patterns, an experiment is made by keeping the amplitude of pitching oscillation $\alpha_1 = 3 \text{ deg.}$ unchanged and changing the location of pitching axis 1 in two kinds, i.e., 0.05 and 0.7, the classification of regions of dynamic flow separation patterns obtained by the experiment is shown in Fig.9. Though there is some dispersion in the measured values (values of k at which the flow separation pattern changes), it is clear that, within the range of measurements done in the present experiment, the location of pitching axis 1 does not have so large influence on the classification of regions of dynamic flow separation patterns, as understood from Fig.9.

Fig.9 Regions related to different aspects of flow separation during blade oscillation

4. Conclusions

For an airfoil that shows an abrupt stall type flow separation pattern in the state of stationary airfoil, experimental analysis is made especially of the flow separation pattern of the airfoil in pitching oscillation near the stall angle of attack. As a result, aspects of change of the flow separation pattern according to the variation of the reduced frequency (dynamic characteristics of flow separation) are elucidated in detail and, consequently, a classification is made of the regions where the flow field shows different flow separation patterns depending on the reduced frequency and the angle of attack. The conclusions obtained by the present experiment are summarized below.

(1) A new hysteresis phenomenon which is attendant upon the oscillation of the blade is observed different from the static hysteresis phenomenon. Such a hysteresis phenomenon causes that the value of the reduced frequency k at which the flow separation pattern changes between partial separation and full separation throughout one cycle of oscillation depends upon the way that the reduced frequency k is being increased or decreased at that time.

(2) Depending on the mean angle of attack and frequency of pitching oscillation, the flow patterns around the blade in pitching oscillation are classified into four regions, i.e., a region where only the partially separated flow pattern persists throughout one cycle of oscillation, a region where only the fully separated flow pattern persists throughout one cycle, a region where the partially separated flow pattern and fully separated flow pattern appear periodically in each cycle, and a bi-stable region where either the partially separated flow pattern or the fully separated flow pattern persists throughout one cycle depending on the history of the reduced frequency k .

(3) From the fact that the aspects of changing flow pattern around the blade in pitching oscillation near the stall angle of attack (dynamic characteristics of flow separation) are decided by the correlation between the width of the range of static hysteresis related to the angle of attack and amplitude of pitching oscillation, it is clarified, when the amplitude of pitching oscillation is varied without changing the width of the angles of attack for static hysteresis, how the bi-stable region becomes narrower and the region where partial separation and full separation appear periodically in each cycle becomes wider as α_1 is increased and how the bi-stable region becomes wider and the region where partial separation and full separation appear periodically in each cycle becomes narrower as α_1 is decreased on the contrary to the above.

From the above-mentioned correlations, it is possible to grasp the phenomenon in the state where the bi-stable region is enlarged, when the range

of angles of attack $\Delta\alpha_s$ for static hysteresis is larger than the amplitude of pitching oscillation α_1 , and it is possible to grasp the phenomenon in the state that the region where partial separation appears periodically in each cycle is enlarged when the range $\Delta\alpha_s$ is small than α_1 . Thus, it is clear that the correlation between the width of the angle of attack for static hysteresis and the amplitude of pitching oscillation has remarkable influence on the dynamic characteristics of flow separation.

(4) The classification of regions of dynamic flow separation patterns is not much influenced by the location of pitching axis.

For elucidating the aspects of changing of the flow separation pattern related to the variation of the oscillation frequency as described so far, the test blade adopted in the present research is convenient because it causes large variation of unsteady pressure on the blade surface and consequently various phenomena appear in the enlarged state. Therefore, the authors consider that they could realize the dynamic characteristics of the flow separation pattern in the region treated in the present research and classify the region corresponding to the flow separation patterns. The analyses of detailed mechanism of the change of the flow separation pattern and dynamic characteristics of flow separation of other types of blades with different types of flow separation patterns still remain as future problems to be elucidated.

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