Inception mechanism and suppression of rotating stall in an axial-flow fan

T Nishioka
Turbomachinery R&D Center, Hitachi, Ltd., Infrastructure Systems Company, Tsuchiura, Ibaraki 300-0013, Japan
E-mail: takahiro.nishioka.sf@hitachi.com

Abstract. Inception patterns of rotating stall at two stagger-angle settings for the highly loaded rotor blades were experimentally investigated in a low-speed axial-flow fan. Rotor-tip flow fields were also numerically investigated to clarify the mechanism behind the rotating stall inception. The stall inception patterns depended on the rotor stagger-angle settings. The stall inception from a rotating instability was confirmed at the design stagger-angle settings. The stall inception from a short length-scale stall cell (spike) was also confirmed at the small stagger-angle setting. The spillage of tip-leakage flow and the tip-leakage vortex breakdown influence the rotating stall inception. An air-separator has been developed based on the clarified inception mechanism of rotating stall. The rotating stall was suppressed by the developed air-separator, and the operating range of fan was extended towards low flow rate. The effect of developed air-separator was also confirmed by application to a primary air fan used in a coal fired power plant. It is concluded from these results that the developed air-separator can provide a wide operating range for an axial-flow fan.

1. Introduction
Rotating stall is an aerodynamic instability that limits the stable operating range of axial-flow compressors and fans. Extensive studies have been carried out to clarify the mechanism responsible for stall inception. It is well known that there are two distinctive routes to rotating stall in compressors and fans. The first inception pattern begins with a short length-scale stall cell. This pattern is known as “spike stall inception” [1-2]. The second pattern begins with a long length-scale disturbance, which appears prior to the formation of a fully developed stall cell. This pattern is known as “modal stall inception” [1-2]. Another short length-scale disturbance, which does not lead directly to stall, has also been observed in low-speed compressors. This disturbance is called “rotating instability” [3-4].

Stall inception mechanism was also numerically investigated. Vo et al. [5] suggested two criteria necessary for spike-type stall-inception. Yamada et al. [6] also suggested that leading edge separation and a tornado-like separation vortex mainly influenced the spike-type stall inception. März et al. [4] found that the rotating instability was induced by the interaction between the incoming flow, the reversed tip-leakage flow, and the end wall backflow from the trailing edge of the rotor blade.

Passive suppression device for the rotating stall was extensively investigated, and two types of passive device were developed. The first device is a casing treatment [7-8]. The second device is an air-separator [9].

A variable-pitch axial-flow fan is used in a power plant to feed air and to exhaust gas. Because the stagger-angle settings for the rotor blades can be changed during operation, the fan covers a broad
range of requirements for flow rate and pressure rise with good operation efficiency. Following present trends, the fan must provide large flow rate and higher pressure rise without reducing the operating range. To meet these needs, it is important to clarify the stall inception mechanism and to suppress the rotating stall at various rotor stagger-angle settings. In the current study, the stall inception patterns at two stagger-angle settings for the highly loaded rotor blades were experimentally investigated, and the end wall flow fields at the rotor tip were numerically investigated to elucidate the mechanism of rotating stall inception. Moreover, an air-separator was developed, and its effect was experimentally investigated to expand the operating range of axial-flow fan.

2. Rotating stall inception

2.1 Facility and measurement method

A schematic diagram of the low-speed axial-flow fan is shown in Fig. 1. The design flow-rate coefficient is 0.44, and the total-to-total pressure-rise coefficient is 0.43. The tip clearance for the rotor blades is 2.0% of the rotor tip chord-length. The detail of design specifications for the test fan, the rotor blade and the stator vane are shown in Nishioka et al [10].

The stall-inception pattern was investigated at two stagger-angle settings for the rotor blades. One was the design stagger-angle setting. The other was the small stagger-angle setting that was 10 degrees smaller than the design value. The configurations of the rotor blade at the tip are shown in Fig. 2.

The fan performance was evaluated in terms of the inlet-total to exit-total pressure rise. The measurement points for the static pressure at the inlet and the outlet of the fan are shown as Ris and Ses in Fig. 1, respectively. The flow rate was measured using a flow nozzle located upstream of the bell mouth. Pressure fluctuation on the casing wall was measured using a high-response pressure transducer (Kulite XT-140). The transducer was mounted on the casing wall at the rotor leading edge (A in Fig. 1). The detail of measurement method was shown in Nishioka et al [10].

![Figure 1. Schematic diagram of test.](image1.png)

![Figure 2. Rotor blade configurations at tip.](image2.png)

2.2. Stall inception pattern

2.2.1. Pressure-rise characteristics Figure 3 plots the pressure-rise characteristics of the fan. In this paper, the flow-rate coefficients of 0.364, 0.347, and 0.319 at the design stagger-angle are designated as operating points A, B, and C, respectively. The flow-rate coefficients of 0.434, 0.401, and 0.358 at the small stagger-angle setting are designated as operating points D, E, and F, respectively.

Pressure-rise at the design stagger-angle is maximum at operating point A, and decreases through operating points A to C. At the small stagger-angle setting, the pressure-rise is maximum at operating point D, and decreases through operating points D to F.
2.2.2. Stall inception patterns  Figure 4 shows instantaneous pressure fluctuations near and at the stall condition at the design stagger-angle setting. The abscissa indicates non-dimensional time divided by the period of the rotor rotation, and the ordinate indicates pressure fluctuation coefficient ($C_p'$) divided by the rotor tip speed, respectively. The fluctuation indicating a long length-scale stall cell is observed at operating points B and C. The propagation speed of long length-scale stall cell is 45% and 42% of the rotor rotation speed at operating points B and C, respectively.

At the small stagger-angle setting shown in Fig. 5, a short length-scale stall cell first appears, and then the long length-scale stall cell develops at operating point E. The long length-scale stall cell is periodically observed at operating point F. The propagation speed of short length-scale stall cell is 58% of the rotor rotation speed, and this speed of long length-scale stall cell at operating point F is 39% of the rotor rotation speed.

Figure 6 shows the comparison of pressure fluctuation spectrum at the stall condition between the design and small stagger-angle settings. The hump indicating a rotating instability is observed around $f=9.0$ at operating point B at the design stagger-angle setting (Fig. 6 (a)). The peak indicating the long length-scale stall cell is also observed at $f=0.4$ at operating point E.

At the small stagger-angle setting shown in Fig. 6 (b), the hump indicating the rotating instability is not observed at operating point E. However, the peaks corresponding to the short length-scale stall cell are observed around $f=4.0$, and the peak corresponding to the long length-scale stall cell is also observed at $f=0.3$ at operating point E.
It is found from the experimental results at the two stagger-angle settings for the highly loaded rotor blades that the stall inception pattern depends on the rotor stagger-angle setting. It is also confirmed that the rotating stall at the design stagger-angle is induced by the rotating instability and that the rotating stall at the small stagger-angle setting initiates from the short length-scale stall cell (Spike). The change in the stall inception patterns is considered to be influenced by the end-wall flow at the rotor-tip. Therefore, the detailed flow fields at the rotor tip are numerically investigated in the next section.

3. Inception mechanisms of rotating stall

3.1. Numerical method

Only the rotor blade passage was modelled for the calculations. Moreover, the eight blade passages were modelled as the computational domain because the model of the eight blade passages yielded a better prediction for the stall inception point than that of the single passage model.

Three-dimensional compressible steady simulations were carried out using the commercial code. Averaged total pressure-rise between the inlet and the outlet boundaries was compared with the measured total pressure-rise of the fan. Moreover, the rotor tip flow fields and the behaviour of tip leakage vortex were investigated using the numerical results. The detail of the numerical model and method are shown in Nishioka et al. [10].

3.2. Calculated pressure-rise characteristics in isolated rotor

Comparison of total pressure-rise characteristics between the calculation and the measurement is shown in Fig. 7. In the following section, the flow rate coefficients of 0.353, 0.352, and 0.349 at the design stagger-angle setting used in the calculation are designated as operating points A', B', and C', respectively. The flow rate coefficients of 0.448, 0.431, and 0.426 at the small stagger-angle setting used in the calculation are designated as operating points D', E', and F', respectively.

The calculated characteristic at each stagger-angle setting is larger than the measured one, because the calculation result does not include the losses at the stator vanes (as shown in Fig.1). However, the flow rates at the maximum pressure-rise points in the calculations are almost the same as those in the measurements. Moreover, the change in calculated pressure-rise characteristic at each stagger-angle setting is similar to the measured characteristic. It is considered from the comparison of the pressure-rise characteristic that the flow fields in the rotor passage near and at the stall condition are simulated by the present calculations.
3.3. Rotor tip flow fields
Figure 8 shows relative flow vector at the 98% height from the rotor hub at the design stagger-angle setting. Backflow from the trailing edge initiates, and the tip leakage flow axially reverses at operating point A’. Moreover, the backflow develops, and the tip leakage flow spills from the leading edge of the adjacent blade at operating points B’ and C’.

Figure 9 shows relative flow vector at the rotor tip at the small stagger-angle setting. The backflow from the trailing edge also initiates at operating point D’. The interface between the incoming flow and the reversed tip-leakage flow becomes parallel to the leading edge plane at operating points E’ and F’. Moreover, the tip-leakage flow slightly spills from the leading edge of the adjacent blade at operating point F’.

It is found from the calculated rotor tip flow fields at the design stagger-angle setting that the rotating instability is induced by the interaction between the incoming flow, the reversed tip-leakage flow, and the end-wall backflow from the trailing edge. It is also found that the spillage of tip-leakage flow from the leading edge to the adjacent blade passage influences the rotating stall inception.

3.4. Behavior of tip leakage vortex
Figure 10 shows the behaviors of a tip leakage vortex at the design stagger-angle setting for the rotor blades. The tip leakage vortex is identified by a vortex core and tip leakage streamlines from the rotor leading edge. The vortex core is colored by normalized helicity [16]. The tip-leakage vortex extends to the rotor exit through operating points A’ to C’, and the tip leakage streamlines largely expand at operating points B’ and C’. The sign of the normalized helicity on the vortex core changes from negative to positive in the blade passage.

At the small stagger-angle setting shown in Fig. 11, the tip-leakage vortex also extends to the rotor exit at operating point D’. Another vortex core is observed near the rotor exit. The tip leakage streamlines spirals along the vortex core at operating point D’ and expands in the blade passage at operating point E’. These streamlines do not roll up at operating point F. The sign of the normalized helicity changes from negative to positive near the leading edge at operating point E’.

It is also confirmed from the behaviour of tip leakage flow that the tip-leakage vortex breakdown occurs at the stall condition at both design and small stagger-angle settings. It is also found that the tip-leakage vortex break down influences the rotating stall inception.
Figure 8. Pressure fluctuation on casing wall at design stagger-angle setting.

Figure 9. Pressure-rise characteristics at two rotor stagger-angle setting.

Figure 10. Pressure fluctuation on casing wall at design stagger-angle setting.

Figure 11. Pressure-rise characteristics at two rotor stagger-angle setting.

4. Suppression of rotating stall by air-separator

4.1. Design of air-separator

Figure 12 shows a schematic diagram of the air-separator. The air-separator consists of circular-arc outer walls, side walls, and an airfoil-shape connecting part. The outer wall is made by connecting a part of a pipe to reduce the manufacturing cost, and a part of the outer wall forms a skewed guide vane in the air-separator.
The developed air-separator was experimentally optimized to remove low energy fluid near the rotor tip and to suppress the spillage of tip leakage flow. The detail of design specifications for air-separator were shown in Nishioka et al. [11].

4.2. Effect of air-separator
Figure 13 shows a comparison of pressure-rise characteristic with and without the air-separator. The abscissa and the ordinate indicate the flow rate coefficient and the total to static pressure-rise coefficient based on the rotor speed at the mean radius, respectively. In the case with air-separator, the operating limit, which is defined as the maximum pressure-rise point, moves to higher pressure rise and lower flow rate region than that without air-separator at each design and small stagger-angle setting. The minimum flow rate with the air-separator is 17% lower than that without air-separator at both design and small stagger-angle settings.

Figure 14 show the pressure fluctuation on the casing wall at the rotor outlet with and without the air-separator at the design stagger-angle setting for the rotor blade. In the case without air-separator, the fluctuations indicating the rotating stall are confirmed at operating points B and C (shown in Fig. 13). In contrast, in the case with air-separator, No fluctuation indicating the rotating stall is confirmed at operating points A’, B’, and C’.

It is found from the experimental results that the developed air-separator can suppress the rotating stall and expand the operating range of fan.

4.3. Application of air-separator to primary air fan used in power plant
The air-separator was applied to a primary air fan (PAF) used in a coal fired power plant after verification of its effects in the test fan. A schematic diagram of the PAF is shown in Fig. 15. This fan is a two-stage variable-pitch axial-flow fan. Its main components are the rotor blades, stator vanes, suction casing, and diffuser. The air-separators are mounted upstream of the first rotor and the second rotor shown in Fig. 15. Figure 16 shows a photograph of the air-separator. The air-separator applied in PAF is similar to that applied in the test fan. The details of design specifications for the PAF and the air-separator were shown in Nishioka et al. [11].

The performance of the fan equipped with the air-separator was compared with that of a non-air-separator fan. The design flow rate and pressure-rise coefficient of both fans are the same. Figure 17 compares the pressure-rise characteristics of the two fans. At each stagger-angle setting for the rotor blade, the operating limit for the air-separator moves toward the lower flow-rate and higher pressure-rise region. The surge line therefore moves toward the higher pressure-rise region.

It is confirmed from the test results in the PAF that the developed air-separator provide the wide operating range.

Figure 15. Schematic diagram of primary air fan

Figure 16. Air-separator applied to primary air fan

Figure 17. Pressure-rise characteristics of primary air fan with and without air-separator

5. Summary

Inception patterns of rotating stall at two stagger-angle settings for the highly loaded rotor blades were experimentally investigated in a low-speed axial-flow fan. Rotor-tip flow fields were also numerically investigated to clarify the mechanism behind the rotating stall inception. The stall inception patterns depended on the rotor stagger-angle settings. The stall inception from rotating instability was confirmed at the design stagger-angle settings. The stall inception from a short length-scale stall cell (spike) was also confirmed at the small stagger-angle setting. The rotating instability was induced by
an interaction between the incoming flow, the reversed tip-leakage flow, and the end-wall backflow from the trailing edge. The Spillage of tip leakage flow was confirmed near and at the stall condition, and the tip leakage vortex breakdown was also confirmed at the stall condition at both design and small stagger-angle settings. The spillage of tip-leakage flow and the tip-leakage vortex breakdown influenced the rotating stall inception.

An air-separator developed based on the clarified inception mechanism of rotating stall to extend the operating range of a variable-pitch axial-flow fan. The rotating stall was suppressed by the developed air-separator, and the operating range was expanded towards low flow rate. The effect of developed air-separator was also confirmed by application to a primary-air fan used in a coal fired power plant. It was concluded from these results that the developed air-separator can provide a wide operating range for an axial-flow fan.

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