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Application of a Skewed-Slot Casing Treatment in a High-loading Axial-Centrifugal Compressor

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Abstract

A skewed-slot casing treatment (CT) was applied to a high-loading axial-centrifugal compressor, which aims at improving stall margin with little penalty in efficiency. Both steady-state numerical simulation and test methods were employed to investigate the effects of the casing treatment on the stall margin of the compressor. The numerical results show that the operating range of the compressor with casing treatment increases effectively for corrected speeds ranging from 60% to 100%, compared with the solid wall case. At the same time the penalty in adiabatic efficiency is controlled within 0.3% point at design speed. The test results verified the effects of casing treatment on the stall margin and efficiency of the compressor and show a good agreement with the computation results. The slots enable the transportation of fluid between blade passages. At the near-stall condition, some fluid is pumped from rotor outlet to rotor inlet through slots, decreasing the incidence angle, pushing the separation region rearwards, and hence delaying the onset of rotating stall.

Keywords: casing treatment, flow stability, axial-centrifugal compressor, stall margin, rotating stall

1. Introduction

In recent years, the design of the turbomachinery has a trend towards higher performance and higher reliability. How to increase the operating range of the compressor without significantly reducing the efficiency is a big challenge. To increase the operating stability margin, insight understanding of the two instability phenomenon of the compressor, surge and rotational stall, must be conducted. The study of stall in the 1980s focused on the observation and description of phenomena. During this period, Emmons et al. (1955) [1] explained the blockage caused by the flow separation of the suction surface, causing the incidence of the adjacent blades to change, which in turn caused the stall cells to propagate in the circumferential direction. Since the late 1980s, Takata and Tsukuda (1977) [2], Greitzer et al. (1979) [3] and Smith and Cumpty (1984) [4] have demonstrated the effectiveness of casing treatment on improvement of stable operating range. Since then, a large number of researchers have been involved in the research work of casing treatment. It can be found from the literature that the design and investigation of the casing treatment is mainly performed through numerical methods, such as Hathaway (2002) [5], Wilke et al. (2005) [6], Iyengar et al. (2005) [7], and Hembera et al. (2008) [8] [9]. Numerical simulations can predict comparatively accurate and reliable results of pressure ratio and efficiency characteristics, but there are still some shortcomings in the prediction of secondary flow fields. Therefore, some researchers like Voges et al. [10] [11] use PIV experiment methods together with numerical simulation to conduct the research on casing treatment.

In this paper, a skewed-slot casing treatment is applied to a high-loading axial-centrifugal compressor in order to improve the stall margin with the least efficiency penalty. The effects of the casing treatment on the stall margin and flow field are investigated using both 3D steady-state numerical simulation and experiment methods, and the results from two approached are compared to each other.

2. Research Object

The research object is an axial-centrifugal compressor consisting of an axial stage and a centrifugal stage, acting as the high-pressure compressor of a civil turboprop engine. The high-pressure compressor is required to improve the stall margin to satisfy the stability requirements of the civil turboprop engine. The 3D numerical computation shows that the stall margin is mainly limited by the leakage flow in the tip region of the first rotor. A skewed-slot casing treatment is employed in the first rotor to enhance the stall margin of this compressor. The configuration of the casing treatment is shown in Fig. 1, and there are 105 slots in total along the whole circle. The angle between the slot and the axis of rotation is about 40.5°, and the depth of the groove is about 3% of the length of the slot. The ratio of length to width for each slot is about 8. The axial length of the slots is about 50% of the axial chord length. The manufactured parts of solid wall casing and casing treatment are shown in Fig. 2.

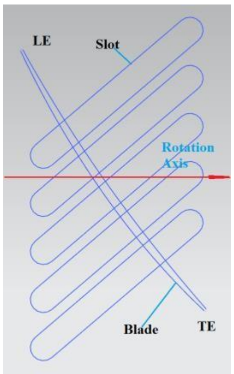


Figure 1 –Skewed-slot casing treatment.

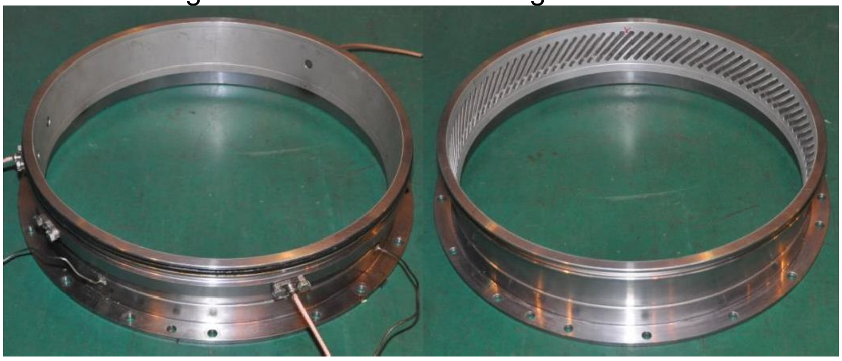


Figure 2 – The parts of solid wall (left) casing and casing treatment (right) of the first rotor.

3. Numerical Approach

The computational mesh of the compressor with skew-slot casing treatment is generated by the Autogrid 5 module of NUMECA^{TM} software. The intermediate casing and struts are also included in the computation domain. The first layer wall grid of the compressor is shown in Fig. 3. The total nodes of this grid are about 3.9 million. The width of the first layer of the grid is carefully set so that y^+ can be lower than 2 in most near-wall areas. The detailed grid for the skewed slots and the first rotor of the compressor are shown in Fig. 4. It can be seen that there are 5 slots per blade channel.

Figure 3 – Computation mesh of the compressor including the struts.

Figure 4 – Detailed grid of the skewed slot and first rotor.

The numerical computation is performed through ANSYS CFX software for 3D steady-state viscous numerical simulation. And the SST turbulence model is selected. Uniform total temperature (288.15K) and total pressure (101325Pa) are specified at the inlet, and the air flow entries into the compressor in axial direction. An average static pressure is given at the outlet of the compressor. Several points are calculated for a certain rotation speed, and the operating points are obtained by changing the outlet back pressure. The computation is considered to be converged when the global residual converges to a certain magnitude while the inlet and outlet flow, pressure ratio and efficiency remain nearly constant. The last operating point before the diverged computation is considered as the near stall point.

4. Results and Discussion

4.1 Performance Analysis

The pressure ratio and efficiency maps of the compressor are shown in Fig. 5 and Fig. 6. The pressure ratio, efficiency and mass flow rate in the figures are non-dimensionalised by dividing their reference value at the peak efficiency point of 80% rotation speed. The characteristics lines with different labels represent different results, in which SW denotes for solid wall casing, CT denotes for casing treatment, CAL stands for computation, and EXP stands for experiment.

The computation results in Fig. 5 show that the compressor with casing treatment sees an increase in the stall margin at all rotation speeds. The increase in stall margin is due to the increase of the pressure ratio and the expansion of the flow range. The test results of pressure ratio characteristics also indicate that the stall margin increases, especially at medium and low rotation speeds. At 0.8 nominal speed, experiment results indicate that the stall margin increases by 3.2% with this skewed-slot casing treatment. It also can be seen that the pressure ratio characteristic lines of test results lay lower left against the lines for the computation results, which indicates that the test results have lower mass flow rate and pressure ratio at all rotation speeds compared to the computation ones.

The computation results in Fig. 6 show that there is only 0.3% penalty in efficiency of the compressor due to the casing treatment, while the test results indicate that the adiabatic efficiency dropped by 0.8% after the employing of casing treatment. Although the test results are a little lower than the computation results, the trends of test and computation efficiency have a good agreement.

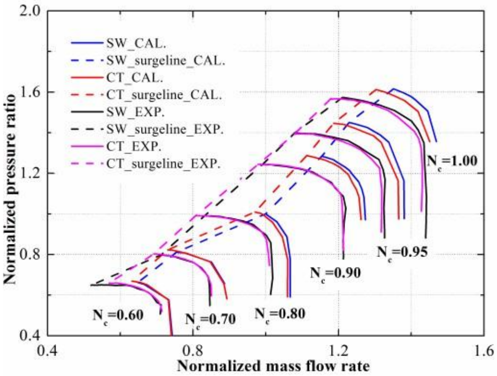


Figure 5 –Pressure ratio characteristics of the axial and centrifugal combined compressor.

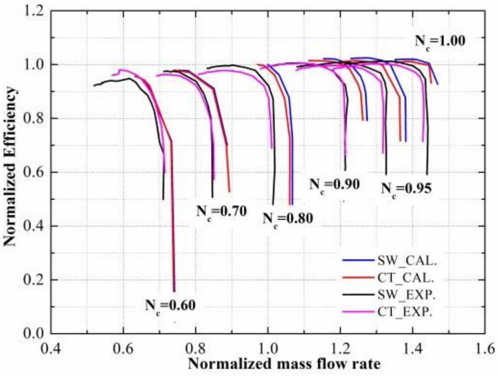


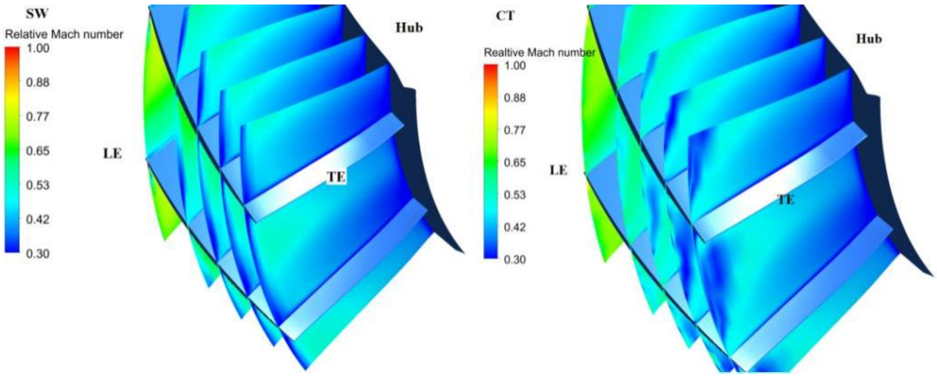
Figure 6 –Efficiency characteristics of the axial and centrifugal combined compressor.

4.2 Analysis of Internal Flow Field of Compressor

The stall margin expansion mechanism of the casing treatment is given by analyzing the flow field of the compressors with and without casing treatment. The near-stall point at 80% nominal speed is selected and the flow fields for both compressors are compared. Figure 7 shows the relative Mach number contours of the first rotor at 80% nominal speed for the casing treatment and solid-wall compressor.

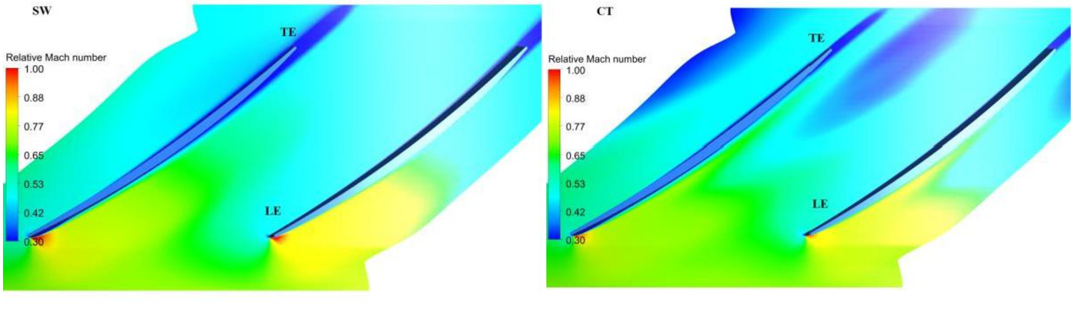
The comparison of the relative Mach number contours at the tip regions of the two compressors shows that the low-speed region at the front of the tip region is significantly reduced by the skewed- slot casing treatment. The stall which firstly occurs at the first rotor tip region is suppressed a lot by the skewed slots, which contributes to the stall margin expansion of the compressor.

It can also be seen from Fig. 7 that a distinct low speed region occurs at the rear of the tip blade passage. This low-speed region can be more pronounced in the relative Mach number contour at 90% span section of the first rotor in Fig. 8. The low-speed region could probably be the main reason for the reduction in efficiency after the use of casing treatment. Figure 8 also indicates that the wake at 90% span of the first rotor is significantly reduced in the casing treatment compressor, which could be related to the smaller incidence in the first rotor tip region after utilizing the casing treatment.



(a) Solid wall (b) Casing treatment

Figure 7 – Rotor relative Mach number contours at circumferential surfaces.



(a) Solid wall (b) Casing treatment

Figure 8 – Rotor relative Mach number contours at 90% span.

The comparison of non-dimensional static pressure distributions at 90% span of the first rotor between the solid wall and casing treatment are shown in Fig. 9. It can be seen that the incidence of the first rotor is reduced by the application of the casing treatment. It also can be seen that the capability of pressure rise is enhanced at the rear part region, which mainly contributes to the increase of the pressure ratio of the casing treatment compressor.

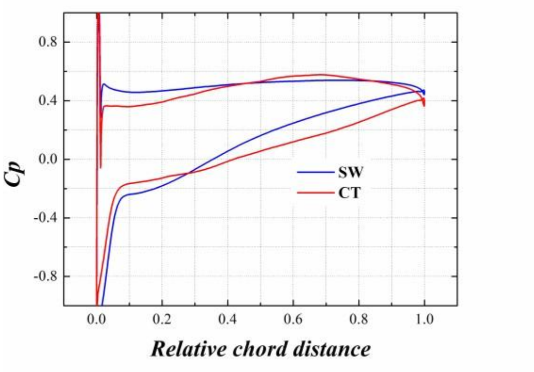


Figure 9 – Non-dimensional static pressure distributions at 90% span of the first rotor.

The differences in the flow capability of the first rotor between the casing treatment and solid-wall compressors can be obtained by comparing the spanwise distributions of axial velocity ratio of the first rotor in Fig. 10. It can be seen that the axial velocity of the first rotor with the casing treatment decreases above 75% span whereas increases below 75% span, compared with the solid-wall case. The reduction of axial velocity is mainly caused by the low-speed flow at the tip region of the first rotor with casing treatment as shown in Fig. 8 (b). The increase of axial velocity below 75% span of the rotor is due to the fact that the casing treatment reduces the flow capability in the tip region and redistributes the mass flow rate along the span.

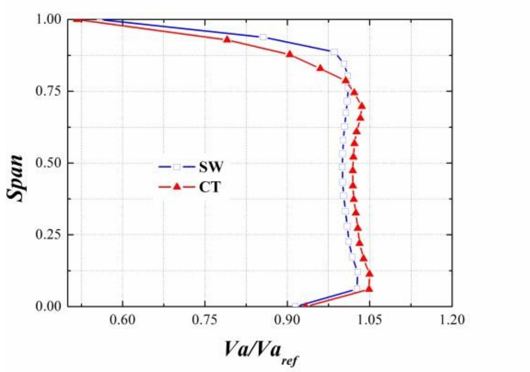


Figure 10 – Comparison of axial velocity distribution along the span of the first rotor outlet.

5. Conclusions

The application of a skewed-slot casing treatment in a high-loading axial-centrifugal compressor is investigated using both 3D steady-state numerical simulation and test methods in this paper. The effects of the casing treatment on the expansion of flow stability of the compressor are analyzed. The main conclusions are as follows:

(1) The stall margin of the high-loading axial-centrifugal compressor can be expanded effectively by the skewed-slot casing treatment, especially at medium and low rotation speeds.

(2) The reason for the expansion of stall margin by the skewed-slot casing treatment is related to the decrease of incidence and enhancement of increasing pressure capability at the tip region of the first rotor.

(3) The skewed-slot casing treatment did not lead to a significant reduction of the efficiency while expanding the stall margin of the axial-centrifugal compressor.

6. Acknowledgement

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7. Copyright Statement

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