Investigation of tip-leakage-vortex breakdown and its role in rotating stall in a 1.5-stage low-speed axial-compressor

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Long Abstract

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Introduction

Compressor stall/surge usually leads to significant loss in performance, engine flameout, even serious mechanical failure. Therefore, many efforts were devoted to reveal the mechanisms of compressor stall and then the designers develop effective stall/surge control method to extend the stable operating range of compressor.

It is well known that the rotating stall is usually triggered by the flow disturbances, usually named by stall inception. In the past two decades, two distinct stall-inception patterns had been identified. The first one refers to modal wave [1,2,3], which belongs to a long-length-scale/modal disturbance. The second one is usually called spike inception or theshort length-scale disturbance, which was observed initially by Day [4].

Many research works indicate that the spike inception may be linked to thephenomena of unsteady tip flow which usually happen at the near-stall operating condition. Variety of unsteady-tip-flowphenomena was discovered in the low-speed axial compressor, including tip separation vortex[5,6], tip-leakage-vortex breakdown[7,8], tornado-likeseparation vortex[9] and tip-leakage-vortex oscillation[10,11]. Actually, the phenomenon of the unsteady tip flow is more complicatedin a transonic axial-compressor because of the existence of the shockwave boundary-layer interaction, which can refer to [12-14].All these results cannot clarify the relationship between the unsteady tip flow and the spike inception. However, Vo et al.[15] answered this question and believed that the criteria of spikes include two aspects which are tip clearance flow spilling over the adjacent blade leading-edge and the impingement of the tip clearance backflow on the pressure surface below blade tip, which built a relationship between the tip clearance flow and stall inception.

Due to therapid advance of high-performance computing in the past ten years, the full-annulus 3D unsteadycomputation can be used to simulate thephenomena of compressor rotating stall. Gourdian et al.[16] and Chen et al.[17] carried out a full-annulus 3D numerical simulation respectively in low and high speed compressor and the results support the Vo'sspike stall criteria, but their discussion don't reveal the mechanism of the tip clearance flow spillage. Pullan et al.[18] investigate the origins and structure of spike rotating stall in multiple axial-compressors. High incidenceresults in a separation vortex shedding from the leading edge in the tip region and the separation vortex belongs to a tornado-likeseparation vortex as was suggested by Inoueet al. The upper end of the tornado-vortex moves circumferentially along the casing and leads to a new separation on the next blade. This flow features describe the process of the spike formation and propagation and reveal the mechanism of the unsteady tip flow spillage. Moreover, Wu et al.[6] also carried a 3D full-annulus numerical simulation in a low-speed axial-compressor and expose that the spillage of the unsteady tip separation vortex is another mechanism of the spike stall inception.

In recent years, more and more experimental and numerical results focus on studying the role of the unsteady tip flow in spike inception to reveal its mechanism. Current work also focuses on this issue and attempts to provide some results to improve understanding of the relationship between unsteady tip

leakage flow and spike inception in a low-speed axial-compressor.
The organization and scope of the paper is as follows. Firstly, the compressor facility and numerical method are introduced and the simulation results are validated. Secondly, the features of the leakage vortex breakdown areinvestigated through comparative analysis of the numerical and experimental results and the relationship between leakage vortex breakdown and the stall inception is revealed. At last, the transit process of rotating stall is described and discussed in detailed.

Experimental and numerical method

The Low-speed Large-scale Axial Compressor(LLAC) test rig is a single-stage axial compressor with inlet guide vanes (IGV). The rotor and stator blades with C4-series airfoil are designed in terms of the free vortex law. The past measurements show that the typical rotor speed is 75% corrected rotor speed, the discussions in this paper are focus on the condition of n=900rpm.
The whole-annulus steady and unsteady numerical simulations were carried out in this 1.5-stage low-speed axial-compressor. The length of the inlet and outlet computational domains is respectively 0.5 and 1 times of the casing diameter. The mesh was generated with the Turbogrid software and the grid topology is HOH as shown in Figure 1. The number of mesh points for one passage is about 200 000 for the rotor channel, 90 000 and 170 000 for one IGV and stator channel. The rotor tip clearance is taken into account with the H-mesh of 10 points in radial direction. Total mesh number is 10 000 000.
The unsteady flow-field is simulated using the CFX code to solve the viscous Reynolds-averaged Navier-Stokes equations with the time pursuing finite volume method. The space discretization is made by the second order upwind scheme. Theturbulence model was chosen in the numerical simulation, coupled with a scalable wall functions ($y+\approx 20$). For this application, 340 iterations are required to simulate one revolution of the rotor, 20 iterations for one channel. Each physic time step includes 10 virtual time steps which can make sure the simulation convergence.
The rotor speed is fixed at the nominal rotor speed of 900rpm. Uniform stagnation pressure and temperature are respectively 101325Pa and 288.15K given as the inlet boundary conditions. The inlet flow angle and turbulence intensity is respectively 0° and 5%. The outlet boundary condition is imposed as the average static pressure at the stable operating points, which meet the radial equilibrium condition. In order to simulate the process of compressor stall, a throttle model is applied at the outlet.

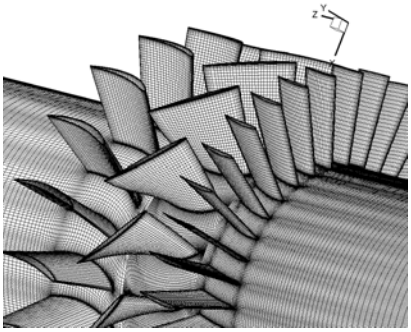

Figure 1 Partial view of the 3D mesh#

Conclusions

A whole-annulus unsteady numerical simulation is carried out to investigate the rotating stall process in a 1.5-stage low-speed axial-compressor. Some conclusions are summarized as following:
By comparing the measured and monitored pressure signals in experiments and simulations respectively, it clearly demonstrates that current numerical results capture the most features of the rotating stall process of the 1.5-stage compressor.
A modal wave was measuredat the near stall operating condition. It was also captured by numerical simulation, though its intensity is slightly lower than the measured one.
Unsteady tip-leakage-vortex breakdown occurs in the rotor blade tip region at the near stall condition. Once the unsteady tip leakage flow is spilled over the adjacent blade leading-edge, the spike inception is triggered.

Many small-scale disturbances are induced by the modal wave in the frequency mixing region and the numerical results verify that these small disturbances are actually the spikes.
These spikesemerge around the rotor annulus almost at the same time and the intensity and size of the spikes is increased rapidly during the inception period.
At last, the spikes are merged into a large stall cell, which propagates around the annulus with 30% rotor speed. The number and propagation speed of the stall cell is well predicted by the simulation.

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