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Investigation of Unsteady Tip Clearance Flow in Axial Compressor Rotor

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ABSTRACT

Tip clearance in axial compressors is known to be detrimental to the pressure rise capability, stability and efficiency of the machine. There are two aspects of the tip clearance flow; one is blockage, which is a fluid dynamic effect, and the other is loss, which is a thermodynamic effect. Compressors often operate with tip clearances that are larger than aerodynamically desirable due to changes in tip clearance during operations and limitations in manufacturing tolerances.

In this thesis investigations are done to determine the effect of unsteady tip clearance flow in axial compressor rotor used in an industrial gas turbine. CFD analysis and Structural analysis is performed for different models by changing the tip clearance 0.5mm uniformly, non-uniform tip clearance 0.5mm & 0.68mm, 0.5mm & 0.8mm and 0.5mm & 0.9mm. CFD analysis is done by using fluid air and Structural analysis is done using materials Structural Steel, Aluminum alloy and Copper alloy. 3D modeling is done in Pro/Engineer and analysis is done in Ansys.

INTRODUCTION

It is well known that the rotor tip clearance flow has profound effects on both performance and stability of axial compressor. Many researchers have devoted to the studies on tip clearance flow in the past several decades, especially the links between tip clearance flow and stall inception and its control methods to delay rotating stall. For tip critical compressors, the criteria about spike stall inception have been set up for both low speed and transonic axial compressors, which are closely related with the behavior of tip clearance flow, namely the spillage of tip clearance flow at the leading edge and backflow at the trailing edge. The results also imply that spike stall inception can be delayed by controlling tip clearance flow. Casing treatment and tip injection are most common adopted stall control measures through acting on tip clearance flow.

A variety of casing treatments have been applied to extend the compressor operating range. And several attempts have been made to study the physical mechanisms of casing treatments and their effects on compressor flow field. Comparatively, as a variation of casing treatment, tip injection received greater attention in recent years. Several experiments of active or passive air injection in the tip region of axial compressors have shown apparent stability improvement for both subsonic and transonic compressors. Suder made a thorough investigation on steady discrete tip injection to delay rotating stall in a transonic axial compressor. The results showed that tip injection increases stability by unloading the rotor tip and increasing injection velocity improves the effectiveness of tip injection. An experimental research of discrete micro tip injection with less than 0.1% of compressor flow rate has also gained good result to delay stall inception.

The mechanism of this micro injection was postulated as an unsteady response of flow in the blade tip region to the discrete micro injection by the analysis of wavelet transform and simplified three-dimensional unsteady numerical simulation. Tong conducted the micro injection experiment on the same compressor as Nie et al after adopting a new designed injector. In the experiment of Roy, for a fixed injected mass flow rate, the same control effect on stall inception can be obtained or even better by reducing injector number to increase injection velocity. Kefalakis used the injection momentum non-dimensional zed by the compressor inlet momentum to scale the improvement of stall margin for different injector numbers and rotational speeds. However the fundamental flow mechanism for discrete tip injection to improve stall margin is still unclear, especially from time-dependent aspects.

Tip clearance

Tip clearance is the distance between the tip of a rotating airfoil and a stationary part.

The inlet of an EJ200, showing rotor and stator blades. The narrow clearance between the rotor (first set of blades) and the casing is visible.

LITERATURE SURVEY

1. UNSTEADY TIP CLEARANCE FLOW PATTERN IN AN ISOLATED AXIAL COMPRESSOR ROTOR WITH MICRO TIP INJECTION By ShaojuanGeng, Hongwu Zhang, Jingyi Chen, Weiguang Huang

A numerical study of the effect of discrete micro tip injection on unsteady tip clearance flow pattern in an isolated axial compressor rotor is presented, intending to better understand the flow mechanism behind stall control measures that act on tip clearance flow. Under the influence of injection the unsteadiness of self-induced tip clearance flow could be weakened. Also the radial migration of tip clearance vortex is confined to a smaller radial extent near the rotor tip and the trajectory of tip clearance flow is pushed more downstream. So the injection is beneficial to improve compressor stability and increase static pressure rise near rotor tip region. The results of injection with different injected mass flow rates show that for the special type of injector adopted in the paper the effect of injection on tip clearance flow may be different according to the relative strength between these two streams of flow. For a fixed injected mass flow rate, reducing the injector area to increase injection velocity can improve the effect of injection on tip clearance flow and thus the compressor stability. A comparison of calculations between single blade passage and multiple blade passages validates the utility of single passage computations to investigate the tip clearance flow for the case without injection and its interaction with injected flow for the case with tip injection.

2.EXPERIMENTAL AND NUMERICAL INVESTIGATION OF UNSTEADY FLOWS IN A HIGH SPEED THREE STAGES COMPRESSOR By N. Gourdain , X. Ottavy and A. Vouillarmet

This study takes place in the frame of a research project to better understand the flow that develops in a multistage high pressure compressor. The present paper focuses on the unsteady effects induced by rotor-stator interactions. Two complementary approaches are considered to increase data reliability and investigation capacity. First the flow is computed by the mean of a numerical approach, considering a 3D unsteady RANS flow solver. Then experimental data are used to validate and enhance the database. Results show that a good estimation of the mean flow features is obtained with the numerical model, even if some discrepancies are also observed, especially when regarding the transport of information along the axial distance. Detailed investigations of the flow at design and off-design conditions are then presented with the objective to underline the role of rotor-stator interactions.

3.UNSTEADY TIP CLEARANCE FLOW PATTERN IN AN ISOLATED AXIAL COMPRESSOR ROTOR WITH MICRO TIP INJECTION BY

Shaojuan Geng, Hongwu Zhang , Jingyi Chen , Weiguang Huang

A numerical study of the effect of discrete micro tip injection on unsteady tip clearance flow pattern in an isolated axial compressor rotor is presented, intending to better understand the flow mechanism behind stall control measures that act on tip clearance flow. Under the influence of injection the unsteadiness of self-induced tip clearance flow could be weakened. Also the radial migration of tip clearance vortex is confined to a smaller radial extent near the rotor tip and the trajectory of tip clearance flow is pushed more downstream. So the injection is beneficial to improve compressor stability and increase static pressure rise near rotor tip region. The results of injection with different injected mass flow rates show that for the special type of injector adopted in the paper the effect of injection on tip clearance flow may be different according to the relative strength between these two streams of flow. For a fixed injected mass flow rate, reducing the injector area to increase injection velocity can improve the effect of injection on tip clearance flow and thus the compressor stability. A comparison of calculations between single blade passage and multiple blade passages validates the utility of single passage computations to investigate the tip clearance flow for the case without injection and its interaction with injected flow for the case with tip injection.

4. UNSTEADY SIMULATION OF AN AXIAL COMPRESSOR STAGE WITH PASSIVE CONTROL STRATEGIES BY NicolasGourdain, Francis Leboeuf

This paper deals with the numerical simulation of technologies to increase the compressor performances. The objective is to extend the stable operating range of an axial compressor stage thanks to passive control devices located in the tip region. Firstly, the behavior of the tip leakage flow is investigated in the compressor without control. The simulation shows an increase of the interaction between the tip leakage flow and the main flow when the mass flow is reduced. This phenomenon is responsible for the development of a large flow blockage region at the rotor leading edge. A separation of the rotor suction side boundary layer is also observed at near stall conditions. Then, two approaches are tested in order to control these flows in the tip region. The first one is a casing treatment with non-axisymmetric slots. The method shows a good ability to control the tip leakage flow but failed to reduce the boundary layer separation on the suction side. However, an increase of the operability is observed but with a penalty for the efficiency. The second approach is a blade treatment that consists of a longitudinal groove built in the head of each rotor blade. The simulation pointed out that the device is able to control partially all the critical flows with no penalty for the efficiency. Finally, some recommendations for the design of passive treatments are presented.

5. LARGE-EDDY SIMULATION AND ANALYSIS OF TIP-CLEARANCE FLOWS

IN TURBOMACHINERY APPLICATIONS BY Rajat Mittal, ParvizMoin

The tip-leakage flow in axial turbo machines is studied using large-eddy simulation with an emphasis on understanding the underlying mechanisms for lowpressure fluctuations and cavitation downstream of the tip-gap. Simulation results are validated against experimental measurements, and reasonable agreements are obtained. Dominant vertical structures such as the tip-leakage vortex and tip-separation vortices are examined, and their effects on the turbulent flow characteristics as well as on the low-pressure statistics are investigated. Analysis of the velocity and pressure fields suggests a high correlation between cavitation inception and the tip-leakage vortex. To suppress the tip-leakage vortex and the associated low-pressure events, the use of a grooved casing wall is explored, and preliminary simulation results show good promise. Additional simulations to investigate the effects of inflow vortices and tip-gap size are also discussed.

6. ACTIVE CONTROL OF TIP CLEARANCE FLOW IN AXIAL COMPRESSORS BY JinwooBae

Control of compressor tip clearance flows is explored in a linear cascade using three types of fluidic actuators; Normal Synthetic Jet (NSJ; unsteady jet normal to the mean flow with zero net mass flux), Directed Synthetic Jet (DSJ; injection roughly aligned with the mean flow), and Steady Directed Jet (SDJ), mounted on the casing wall. The objective is to affect the following measures: (1) reduction of tip leakage flow rate, (2) mixing enhancement between tip leakage and core flow, and (3) increase in streamwise momentum of the flow in the endwall region. The measurements show that the NSJ provides mixing enhancement only, or both mixing enhancement and leakage flow reduction, depending on its pitchwise location. The DSJ and SDJ actuators provide streamwise momentum enhancement with a consequent reduction of clearance-related blockage. The blockage reduction associated with the use of NSJ is sensitive to actuator frequency, whereas that with the use of DSJ is not. For a given actuation amplitude, DSJ and SDJ are about twice as effective as NSJ in reducing clearance-related blockage. Further the DSJ and SDJ can eliminate clearance-related blockage with a time-averaged momentum flux roughly 16% of the momentum flux of the leakage flow. However, achieving overall gain in efficiency appears to be hard; the decrease in loss is only about 30% of the expended flow power from the present SDJ actuator, which is the best among the actuators considered. Guidelines for improving the efficiency of the directed jet actuation are presented. Time-resolved measurements show periodic unsteadiness of the tip clearance vortex with the peak frequency corresponding to the optimum condition for blockage reduction with the NSJ. A physical explanation of the source of the observed periodic unsteadiness is suggested based on trailing vortex instability theory. Observations of the time scale for the unsteadiness from different compressor geometries and flow conditions are shown to scale with a reduced frequency based on convective time through the blade passage.

7. UNSTEADY FULL ANNULUS SIMULATIONS OF A TRANSONIC AXIAL COMPRESSOR STAGE BY P. Herrick, D. Hathaway, Jen-Ping Chen

Two recent research endeavors in turbo machinery at NASA Glenn Research Center have focused on compression system stall inception and compression system aerothermodynamics performance. Physical experiment and computational research are ongoing in support of these research objectives. TURBO, an unsteady, three-dimensional, Navier-Stokes computational fluid dynamics code commissioned and developed by NASA, has been utilized, enhanced, and validated in support of these endeavors. In the research which follows, TURBO is shown to accurately capture compression system flow range—from choke to stall inception—and also to accurately calculate fundamental aerothermodynamic performance parameters. Rigorous full-annulus calculations are performed to validate TURBO’s ability to simulate the unstable, unsteady, chaotic stall inception process; as part of these efforts, full-annulus calculations are also performed at a condition approaching choke to further document TURBO’s capabilities to compute aerothermodynamic performance data and support a NASA code assessment effort.

8. EFFECTS OF TIP CLEARANCE ON ROTOR/STATOR INTERACTION TONAL NOISE OF AXIAL FAN By Liangfeng Wang, WeiyangQiao, Weijie Chen, Liang Ji

The tip leakage flow is crucial importance for the turbomachinery design and operation for its contribution in loss and noise production. This study is focused on the effects of tip clearance(TC) on tonal noise behavior of a single stage axial fan. The flow-field/acoustic-field hybrid model is used to evaluate the tonal noise level from a time-accurate CFD result. The hybrid model is based on the three-dimensional unsteady Reynolds-averaged Navier-Stokes (URANS) equations and the ducted blade-rows aerodynamics and aeroacoustics(DBAA) theory. The results indicate that the high amplitude areas of unsteady loading fluctuation are mainly around the leading edge of stator vane, and the effect of TC on the noise source distribution is mostly in the tip region. The varies of total acoustic power level is less than 1dB as the TC is changed from 0mm to 1mm. The effect of TC on the total acoustic power level is not same for different frequency or different propagated direction.

CFD ANALYSIS OF AXIAL COMPRESSOR

FLUID – AIR

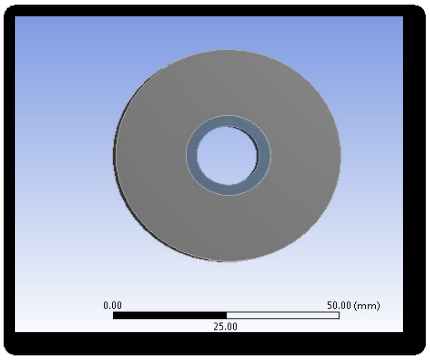
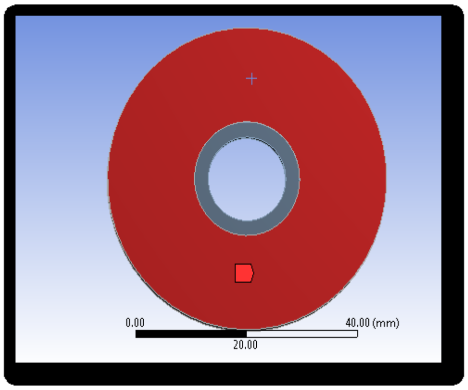
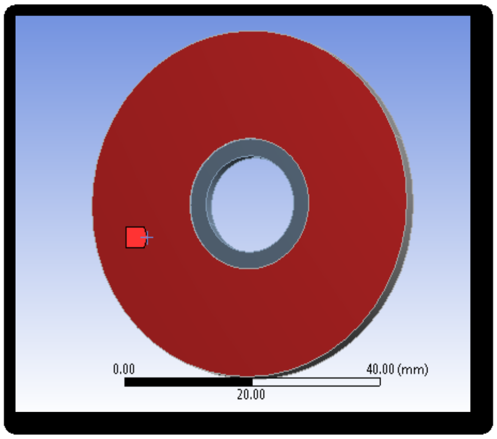


Fig – Imported model from Creo with fluid boundary

Inlet

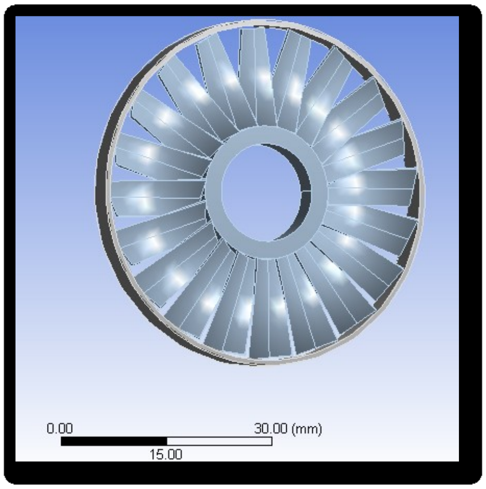


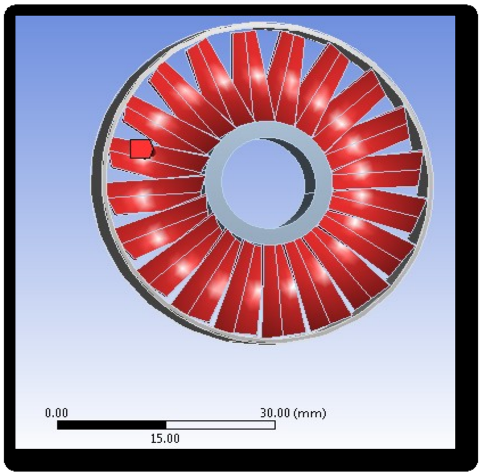
Outlet



STRUCTURAL ANALYSIS OF AXIAL COMPRESSOR

IMPORTED MODEL





RESULTS TABLE

CFD ANALYSIS

TIP CLEARENCE: 0.5mm

Inputs (kg/s)	Pressure (Pascal)	Velocity (m/s)	Reynolds number	Mass Flow Rate (kg/s)
0.0222222	2.27E+02	1.79E+01	1.86E+02	6.583132E-06
0.025	2.53E+02	1.93E+01	1.74E+02	7.2289258E-06
0.0277778	2.91E+02	2.09E+01	1.65E+02	9.1306865E-06
0.0305556	3.36E+02	2.26E+01	1.59E+02	1.0712072E-05

TIP CLEARENCE: 0.5&0.68mm

Inputs (kg/s)	Pressure (Pascal)	Velocity (m/s)	Reynolds number	Mass Flow Rate (kg/s)
0.0222222	2.33E+02	1.67E+01	1.85E+02	2.8572977E-06
0.025	2.87E+02	1.85E+01	1.80E+02	4.2393804E-06
0.0277778	3.61E+02	2.07E+01	1.75E+02	5.4296160E-06

0.0305556	4.31E+02	2.29E+01	1.65E+02	6.9029629E-06

TIP CLEARENCE: 0.5&0.8mm

Inputs (kg/s)	Pressure (Pascal)	Velocity (m/s)	Reynolds number	Mass Flow Rate (kg/s)
0.0222222	2.46E+02	1.67E+01	1.81E+02	2.3897737E-06
0.025	3.02E+02	1.81E+01	1.73E+02	2.5965273E-06
0.0277778	3.64E+02	2.02E+01	1.70E+02	3.779307E-06
0.0305556	4.44E+02	2.23E+01	1.68E+02	4.6882778E-06

TIP CLEARENCE: 0.5&0.9mm

Inputs (kg/s)	Pressure (Pascal)	Velocity (m/s)	Reynolds number	Mass Flow Rate (kg/s)
0.0222222	2.78E+02	1.67E+01	1.81E+02	1.8440187E-07
0.025	3.37E+02	1.79E+01	1.79E+02	1.790002E-06
0.0277778	4.06E+02	1.98E+01	1.70E+02	2.3320317E-06
0.0305556	4.75E+02	2.18E+01	1.66E+02	3.6433339E-06

STRUCTURAL ANALYSIS

TIP CLEARANCE: 0.5&0.9mm
MATERIAL: STRUCTURAL STEEL

PRESSURE (Pa)	DEFORMATION(mm)	STRAIN	STRESS (MPa)
2.78E+02	2.3081	0.033373	5403.1
3.37E+02	2.7979	0.040456	6549.8
4.06E+02	3.3708	0.048739	7890.9
4.47E+02	3.9437	0.057022	9231.9

MATERIAL: ALUMINUM ALLOY

PRESSURE (Pa)	DEFORMATION(mm)	STRAIN	STRESS (MPa)
2.78E+02	6.5005	0.093201	5382.9
3.37E+02	7.8802	0.11298	6525.4
4.06E+02	9.4936	0.13611	7861.4
4.47E+02	11.107	0.15925	9197.5

MATERIAL: COPPER ALLOY

PRESSURE (Pa)	DEFORMATION(mm)	STRAIN	STRESS (MPa)
2.78E+02	4.1938	0.059961	5377.6
3.37E+02	5.0838	0.072686	6518.9
4.06E+02	6.1248	0.087569	7853.7
4.47E+02	7.1657	0.10245	9188.4

CONCLUSION

In this thesis investigations are done to determine the effect of unsteady tip clearance flow in axial compressor rotor used in an industrial gas turbine. CFD analysis and Structural analysis is performed for different models by changing the tip clearance 0.5mm uniformly, non-uniform tip clearance 0.5mm & 0.68mm, 0.5mm & 0.8mm and 0.5mm & 0.9mm. CFD analysis is done by using fluid air and Structural analysis is done using materials Structural Steel, Aluminum alloy and Copper alloy.

By observing the CFD analysis results, the pressure is more at the vertex of the rotor and is decreasing by increasing the clearance ratio. The mass flow rate also decreases, as the mass flow decreases, the intensity of the tip clearance vortex, shock and interactionbetween them strengthens, which makes induces the interface between the incoming flowand tip clearance flow shift forward after the balance of them.

By observing the structural analysis results, the deformations and stresses are increasing by increasing the tip clearance values. The deformation and strain values are more for Aluminum alloy than Structural Steel and Copper alloy. The stresses are almost equal for all materials. by considering strength to weight ratio, Aluminum alloy is better.

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