UNIVERSITI PUTRA MALAYSIA

PERFORMANCE CHARACTERISTICS IN TRANSONIC AXIAL COMPRESSOR ROTOR BLADE USING CIRCULAR JETS

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By

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The reduction of the flow separation region or even eliminating it from the transonic axial flow compressor has been a motivating research area as it reduces turbulence and modifies the flow field into more desired state. Even a small performance improvement could be a big help in saving fuel cost. Several active and passive flow control options were established and one among them is synthetic jet. Synthetic jet provides unsteady momentum to the flow field without net mass injection.

Synthetic jets with slot orifice are previously investigated in transonic level study for its efficiency enhancement. Hence, a systematic numerical investigation was carried out to understand the impact of circular jets as continuous steady jet in transonic level study which is followed by time constrained synthetic jet (transient) for the analysis of flow control effectiveness. The seven and fourteen array of jet formation were placed at three positions specifically upstream, downstream and close to the flow separation point (25%, 50% and 75% of the blade span) at suction side of transonic compressor rotor blade. Two velocities such as 300m/s and 500 m/s were tested in all three jet position models to discover the superior separation control model and finally one reasonable model with better flow control effectiveness was used to run the time constrained synthetic jet approach for analyzing the flow field.

High actuation velocity provided (500m/s) shows healthier variation in flow control compared to lower velocity (300m/s) due to its low momentum coefficient. In seven array jet formations, the jet flow fixed upstream the separation point (25% of blade span) controls the separation region more effectively while in fourteen array configuration, the jet placed at the midpoint of the blade span (close to separation point) enhances the separation control showing desirable

flow control. However the vital part is that velocity distribution over the blade which reduces the flow separation in contradictory abundantly affects the total pressure ratio which also impacts adiabatic efficiency. Thus 4% of efficiency loss were calculated in seven array configuration and 13% of efficiency loss in fourteen array configuration. Comparative study over these models gives us the detailed analysis of flow field performance characteristics such as velocity variation, 3D velocity streamline, pressure distribution, Mach number distribution, efficiency and total pressure ratio.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

CIRI-CIRI PRESTASI DALAM PAKSI TRANSONIC PEMAMPAT BILAH ROTOR MENGGUNAKAN JET BERBENTUK BULATAN

Oleh

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Pengurangan kawasan pemisahan aliran atau penghapusan terus dari pemampat aliran paksi transonik telah menjadi motivasi kepada bidang penyelidikan kerana ia dapat mengurangkan gelora dan mengubah medan aliran kepada keadaan yang lebih dikehendaki. Malah peningkatan kecil dalam prestasi boleh memberi kesan yang besar dalam penjimatan kos bahan api. Beberapa pilihan aliran kawalan aktif dan pasif telah diwujudkan dan salah satu di antaranya adalah jet sintetik. Jet sintetik menyediakan momentum tidak mantap untuk medan aliran tanpa memerlukan suntikan jisim bersih.

Kajian jet sintetik dengan slot orifis sebelum ini dijalankan terhadap tahap transonik untuk meningkatkan kecekapan. Oleh itu, kajian berangka secara sistematik dijalankan untuk memahami kesan jet bulatan sebagai jet kekal berterusan dalam kajian tahap transonik yang diikuti oleh jet sintetik dengan kekangan masa (fana) untuk analisis keberkesanan kawalan aliran. Tujuh dan empat belas tatasusunan formasi jet ditempatkan di tiga kedudukan khususnya huluan, hiliran dan berdekatan titik pemisahan aliran (25%, 50% dan 75% daripada span bilah) di bahagian sedutan transonik bilah pemampat rotor. Dua halaju seperti 300m/s dan 500 m/s telah diuji dalam ketiga-tiga model kedudukan jet untuk mencari model kawalan pemisahan yang unggul dan akhirnya satu model yang bersesuaian dengan keberkesanan kawalan aliran yang lebih baik telah digunakan untuk menjalankan kajian terhadap kaedah jet sintetik dengan kekangan masa untuk menganalisis medan aliran.

Halaju pergerakan tinggi (500m/s) menunjukkan perubahan yang sihat dalam kawalan aliran berbanding halaju rendah (300m/s) kerana pekali momentum yang rendah. Dalam formasi jet tujuh tatasusunan, aliran jet tetap hulu titik pemisahan (25% daripada span bilah) mengawal kawasan pemisahan dengan

lebih berkesan manakala di formasi jet empat belas tatasusunan, jet yang diletakkan pada titik tengah span bilah (dekat dengan titik pemisahan) meningkatkan kawalan pemisahan yang menunjukkan kawalan aliran wajar. Walau bagaimanapun, bahagian yang penting adalah bahawa taburan halaju pada bilah yang mengurangkan pemisahan aliran turut memberi kesan terhadap jumlah nisbah tekanan yang juga kesan kecekapan adiabatik. Oleh itu 4% daripada kehilangan kecekapan dikira dalam formasi jet tujuh tatasusunan dan 13% daripada kehilangan kecekapan dalam formasi jet empat belas tatasusunan. Kajian perbandingan ke atas model-model ini memberikan kita analisis terperinci ciri-ciri prestasi medan aliran seperti perubahan halaju, halaju arus 3D, taburan tekanan, pengedaran nombor Mach, kecekapan dan jumlah nisbah tekanan.

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I certify that a Thesis Examination Committee has met on 31 October 2016 to conduct the final examination of Pauline Epsipha on her thesis entitled "Performance Characteristics in Transonic Axial Compressor Rotor Blade using Circular Jets" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

SJA	Synthetic Jet Actuators
NASA	National Aeronautics and Space Administration
3D	Three Dimensional
RANS	Reynolds-Averaged Navier–Stokes
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
IGV	Inlet Guide Vane
PS	Pressure Side
SS	Suction side
FC	Flow Control
DNS	Direct Numerical Simulation
LES	Large-Eddy Simulation
NACA	National Advisory Committee for Aeronautics
URANS	Unsteady Reynolds-Averaged Navier–Stokes
AFC	Active Flow Control
ZNMF	Zero-Net-Mass-Flux
PIV	Particle Image Velocimetry
LDV	Laser Doppler Velocimetry
RNG	Re-Normalisation Group
MCA	Multiple Circular Arc
IGES	Initial Graphics Exchange Specification
ATM	Automatic Topology and Meshing
PDE	Partial-Differential Equations
SST	Shear Stress Transport
BSL	Baseline
RMS	Root mean square
RPM	Revolutions Per Minute
RAM	Random-Access Memory
AGARD	Advisory Group of Aerospace Research and Development

LIST OF NOMENCLATURES

Re	Reynolds number
L	dimensionless stroke length
Do	orifice diameter
Hz	Hertz
C_p	Specific heat at constant pressure
γ	Adiabatic coefficient
ν	Fluid kinematic viscosity
μ	Fluid dynamic viscosity
ρ	Fluid density
D_H	Hydraulic diameter
A	Cross sectional area
P	Wetted perimeter
M	Molar mass
R	Universal gas constant
P	Gas pressure
T	Absolute temperature
v	Velocity
y^+	Wall distance
y	Distance to the nearest wall
C_f	Skin friction coefficient
τ_w	Wall shear stress
U_τ	Frictional velocity
u_i	Flow velocity
τ_{ij}	Mean rate of stress tensor
f_i	Gas acceleration due to body force
$\bar{u}$	Mean variable
u'	Fluctuating variable
$\bar{\tau}_{ij}$	Fluid stress tensor
λ_{ij}	Turbulent stress tensor
P_{inlet}	Inlet pressure
T_{inlet}	Inlet temperature

CHAPTER 1

INTRODUCTION

1.1 Overview

Transonic axial compressors are vital components in aircraft engines for their ability to produce high pressure ratios, where high pressure ratio indicates better efficiency. However, the flow field in and around the compressor is very complicated due to the rise of strong shock boundary interaction (Cumpsty, 1989)(Calvert, Emmerson, & Moore, 2003)(J. D. Denton & Xu, 1999)(Law & Wadia, 1993) and tip clearance effects(Chima, 1998)(Kenneth L. Suder & Celestina, 1996) (Chen, Greitzer, Tan, & Marble, 1991)(Yamada, Funazaki, & Sasaki, 2008). Also these complications causes aerodynamic risks such as flow separation (Simpson, 1981), surge (Rao & Ramesh, 2007)(Niazi, 2000)(Willems, 1997) and stall (E M Greitzer, 1980; Hah & Loellbach, 1999)(Masaki & Kaji, 1997)(Hah & Loellbach, 1999)(Mcdougall, 1990)which are potential threats that can cause damage to the engines. Thus significant amount of researches have been carried both numerically and experimentally to understand the flow behavior of the compressor followed by proposals for controlling it.

With a number of analysis on flow behavior , optimized compressor models with modifications in casing and hub(X. Liu, Sun, Sun, & Wang, 2012), thickness distribution (K. L. Suder, Chima, Strazisar, & Roberts, 1995) ,sweep and lean rotor blades (Benini & Biollo, 2007)(Abate, 2012) with better flow field were discovered. Hence understanding the flow and developing techniques to improve flow field to achieve good performance parameter, is considered mandatory in compressor characteristics. It includes improving the pressure ratio, efficiency and increasing stall margin.

Various active and passive methods have been established to reduce the flow separation and control the flow behavior in desired path on turbo-machinery bladings. Active techniques such as fluidic actuators (Cerretelli & Kirtley, 2009) piezo-electric actuators(Watanabe, 2014), synthetic jet actuators (SJA)(Glezer & Amitay, 2002)(B. L. Smith & Glezer, 2002)(Kral, Donovan, Cain, & Cary, 1997), controls and sensors require energy input to reduce or eliminate the flow disabilities while passive techniques involve geometrical modifications such as longitudinal/circumferential grooves, casing treatments (X. Liu et al., 2012)to achieve the desired flow. Fluidic-oriented methods were researched for a decade, for its feasibility in suction, blowing and oscillating jet movement.

Particularly, SJA have advantages in the areas of heat and mass transfer, enhancement in flow mixing, jet vectoring, control in separation and turbulence.

SJA have great efficiency to effectively delay the boundary layer separation on compressor. This characteristic feature of SJA has gained the attention of many researchers in recent years for its simple yet effective installation system. Optimal utilization of the working fluid in the flow system is one of its key characteristics. Thus, synthetic jets of active flow control technology has gained an important place in flow control process.

The idea of synthetic jets were introduced by Glezer (Barton L Smith & Glezer, 1998) and its impact is being widely explored experimentally and numerically for its vast applications such as mixing enhancement(Bae, Breuer, & Tan, 2005), boundary layer separation control (Seifert, Bachar, Koss, Shepshelovich, & Wygnanski, 1993)(Cerretelli & Kirtley, 2009),vortex shedding control and jet vectoring (B. L. Smith & Glezer, 2002). The flow mechanism of synthetic jets (zero mass-flux) works as follows. A moving device, like a slice of piston makes up and down reciprocating movement inside a cavity through external excitation, which results in periodic suction and ejection at the jet nozzle. The ambient air is pulled into the cavity when the piston moves downward; and blown out when the piston moves upward.

The working principle is very simple and the installation requires almost no pumps and pipes which makes this device very compact. Hence, many researches (Durán, López, & Ph, 2010)(Zhang & Zhong, 2010)(Matejka, Popelka, Safarik, & Nozicka, 2008)(Zaman & Culley, 2006) both numerically and experimentally were conducted to push the limitations of the application. Synthetic jets with circular orifice were widely employed as flow control applications but mostly in subsonic level. According to Biollo (Benini, Biollo, & Ponza, 2011a), circular synthetic jets have never been demonstrated experimentally in transonic axial flow compressors, because of its unfavorable pressure gradient occurrence. The presence of shock and boundary interaction make it hard to study the flow field at transonic level.

1.2 Problem statement

When dealing with the transonic level axial flow compressor, the formation of aerodynamic threats are inevitable around the compressor rotor blades. The flow separation region created due to the shock and boundary layer interaction can especially cause an immense deal in performance of the engine. Its disadvantages include energy loss, efficiency reduction, engine instability, blockage formation, stall and surge conditions. Thus various experimental and numerical research were concentrated on suppressing or eliminating flow separation region.

Considerable amount of new active and passive techniques were developed for flow control effects and synthetic jets are significant among them due to its simple installation and effective results. Synthetic jets with slot orifice are previously investigated in transonic level study for its efficiency enhancement by

Biollo (Benini et al., 2011a). However, synthetic jets with circular orifice have never been demonstrated in transonic level for its effectiveness. The author of this study intends to discover the effect of an array of circular orifice synthetic jet into the transonic level flow field.

In this present study, a numerical investigation was carried out to understand the interaction of continuous steady jet with circular orifice into transonic flow field. Followed by time constrained synthetic jet for the analysis of aerodynamic behavior. The seven and fourteen array of jet formation were placed at three positions specifically upstream, downstream and close to the flow separation point (25%, 50% and 75% of the blade span) at suction side of transonic compressor rotor blade for its response. Two velocities such as 300m/s and 500 m/s were tested in all three jet position models to discover the superior separation control model. One such model with better flow control result was used to run the time constrained synthetic jet approach to seek the performance parameters like total pressure ratio and adiabatic efficiency.

1.3 Aims and Objectives

The aim of this thesis is to study the resulting aerodynamic flow field behavior, when the transonic axial compressor rotor blade is equipped with seven and fourteen array of circular orifice jet. The two configurations to compare is baseline (no jet) rotor and rotor with circular orifice jets. The primary objectives are

a) Develop and assess the baseline rotor blade model.
b) Furnish it with array of circular orifice jet and conduct parametric study as continuous steady jet for jet position, total number of array and velocity study.
c) Compare and analyze all the results for superior separation control model and conduct the synthetic jet injection (transient approach) to one better model for the flow behavior analysis.

1.4 Scope and limitations

This study intends to give the initial knowledge through computational investigation regarding the aerodynamic flow field behavior around the transonic axial compressor rotor blade, when it is equipped with circular orifice jet excitations. The effectiveness of circular orifice jets in the suction side of the compressor blade to reduce the flow separation region will be evaluated separately and compared for both steady and transient case. Some limitations needed to be considered such as,

a) Due to time restriction, the analysis will be carried out with one rotor blade passage and the results were considered periodic.

b) Due to shock presence and unfavorable pressure gradients, the use of synthetic jet with circular orifice in transonic level axial compressors are not demonstrated experimentally before. Therefore this study is only a preliminary step taken through simulation to learn the flow control effect created by continuous steady jet and synthetic jet.
c) The real time synthetic jets can produce velocity from 80m/s upto 120m/s (Gilarranz, Traub, & Rediniotis, 2005), however this study intends to produce effective results rather delivering accurate values.

1.5 Thesis layout

This thesis is presented in five chapters including conclusion.

- Chapter 1 introduces the introduction and motivation behind the thesis and points out the objectives of the research along with the research scope.
- Chapter 2 provides detailed information regarding the theory and relevant literature review are discussed. The thesis starts with a discussion of transonic axial compressor and its flow disabilities which is followed by the factors governing these disabilities. Topics further include flow control concepts with emphasis on active flow control devices. Finally, introducing synthetic jets are introduced in detail along with its application which are also examined.
- Chapter 3 reviews the numerical methodology exercised in the thesis. It starts with the modelling approach handled for the baseline model followed by the mesh generation. At the end, the steady and transient simulation approach is discussed with pre-setup and post processing selections along with calculated data's.
- Chapter 4 deals with the numerical results obtained and their detailed discussion. At first, the validation of the baseline model with the documented experimental results were carried out. Next, the results of steady circular jet are discussed along with various parameters which were carried out following by the comparison of the synthetic jet characterization results. Analysis of the optimal control parameters followed by the effect of synthetic jets on the flow are discussed at the end of the chapter.
- Finally, Chapter 5 is summarized by conclusions and contributions of the thesis, as well as introduces ideas for future researches.

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