IJARSCT

ISSN (Online) 2581-9429

International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

Impact Factor: 7.53

Volume 4, Issue 7, April 2024

CFD Analysis and Validation of Axial Compressor Rotor Blade

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Abstract: *This research paper employs computational simulations to investigate the consequences of inlet flow distortion, focusing specifically on inlet swirl and total pressure distortion, on the operational characteristics and robustness of an axial transonic compressor. Various permutations of inlet swirl and total pressure distortion are examined, uncovering diverse impacts on the compressor's operational robustness and efficiency. The analysis demonstrates that while co-swirl configurations marginally enhance the operational robustness of the compressor, counter-swirl configurations tend to diminish it. The combination of the effects of individual distortion patterns can provide insights into certain aspects of how a composite pattern of distortion would affect the compressor's efficiency, yet this approach falls short in accurately evaluating the compressor's operational robustness when subjected to a composite distortion pattern.*

Keywords: Axial Compressors, Total-Pressure Distortion, Inlet Swirl, Combined Distortion, Performance, Stability

I. INTRODUCTION

In the realm of compressor and fan design, the assumption of a clean flow at the inlet stands out as a particularly convenient premise. This assumption, often adopted in normal approaches, depicts the nominal inlet flow condition where flow properties are considered uniform and the flow direction is envisioned to be axial precisely at the Aerodynamic Interface Plane (AIP). Nevertheless, practical scenarios frequently unveil a different reality where the compressor grapples with distorted flow at the very inlet. Such inlet distortion can be broadly classified into three primary categories, namely total pressure distortion, total temperature distortion, and swirl distortion. These distortions play a significant role in influencing the performance metrics of the compressor, impacting parameters like pressure ratio and efficiency. However, it is noteworthy that their implications on the stability of the 2 compressor tend to carry more weight in the grand scheme of things. The patterns of inlet distortion led to a redistribution of flow parameters across the compressor blades, potentially altering the stability conditions and even instigating phenomena such as rotating stall or surge. Total pressure distortion, for instance, manifests as a non-uniform distribution of total pressure at the inlet, where the incoming flow exhibits either a radial or circumferential variation in total pressure at the AIP. A similar premise holds true for total temperature distortion, while swirl distortion, also known as flow angularity, pertains to the presence of non-axial flow at the inlet.

In this context, the incoming flow could possess both radial and circumferential components of velocity at the AIP, with a particular emphasis on the latter due to its direct impact on the incidence angle of the rotor blade. The circumferential inlet swirl can be further dissected into two primary types, namely bulk swirl and paired swirl. Bulk swirl entails the existence of a single vortex at the inlet, rotating either in the direction of compressor rotation (co-swirl) or in the opposite direction (counter-swirl). On the other hand, paired swirl involves two vortices rotating in opposite directions, encompassing both a co-swirl and a counter-swirl vortex. For a detailed exposition on the characterization of inlet swirl, interested readers are directed to the work of Sheoran et al., which delves into this aspect comprehensively. This current study focuses on the examination of radial total pressure and circumferential bulk swirl distortion patterns due to their prevalence in practical applications. It is noteworthy to highlight that total pressure distortion and swirl distortion

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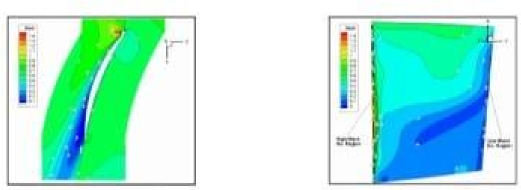
represent the more prevalent forms of inlet distortion and have consequently garnered significant attention from researchers. Numerous research endeavors have been undertaken to enhance our understanding of the characteristics and repercussions associated with these distortion patterns, employing either numerical simulations or experimental investigations. For instance, Sheoran et al. scrutinized the performance and operability of an axial compressor under swirl distortion through the utilization of 3-D flow simulations and a specifically designed distortion generator geometry. Various scenarios involving different types of inlet swirl, such as bulkswirl, paired-swirl, and offset-swirl, were meticulously studied, with ensuing shifts in compressor characteristics being duly documented. The outcomes of this study underscored that the performance and stability of the compressor could either be ameliorated or deteriorated contingent upon the type of swirl distortion in play. 3 Particularly, the study revealed that corotating bulk swirl tends to enhance the stability of the compressor, whereas counter-rotating swirl has an adverse effect. Analogous findings regarding the impact of inlet swirl have been corroborated by the works of Fredrick et al. and Davis et al. utilizing a 1-D parallel compressor model, as well as by Castaneda et al. employing 3- D simulations. Furthermore, Cameron et al. conducted a comprehensive investigation involving numerical and experimental analyses to explore stall inception in transonic axial compressors under varying conditions, encompassing both uniform inlet configurations and those featuring radial total-pressure distortion.

OBJECTIVE

1. Blade Efficiency Enhancement: Optimize blade geometry to improve aerodynamic performance and increase efficiency.
2. Turbulence Model Comparison: Evaluate different turbulence models to identify the most accurate model for predicting rotor blade performance.
3. Validation with Experimental Data: Validate CFD results against experimental data to ensure accuracy and reliability.

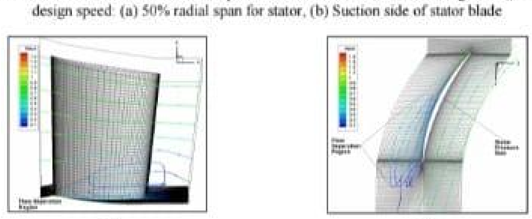
II. LITERATURE REVIEW

A] "CFD Validation and Analysis of a Single-Stage Axial Compressor" by Xiang, Jörg Uwe Schlüter, and Fei Duan (2014) provides a comprehensive overview of the existing research on computational fluid dynamics (CFD) applied to axial compressors. The review highlights the significance of axial compressors in various industrial applications, emphasizing their critical role in enhancing efficiency and performance in propulsion systems, turbomachinery, and energy conversion processes. It discusses previous studies focusing on CFD simulations of axial compressors, covering aspects such as flow dynamics, blade design, performance optimization, and validation techniques. Additionally, the review addresses the challenges associated with CFD modeling of complex flow phenomena within axial compressors, including boundary layer separation, shock interactions, and tip clearance effects.



(a) (b)

Figure 15: Ma distribution at 50% stator span and at stator suction side for designed M_{fr} at 100% design speed: (a) 50% radial span for stator, (b) Suction side of stator blade



(a) (b)

Figure 16: Streamlines in stator flow path for designed M_{fr} at 100% design speed: (a) view from Z axis, (b) view from X axis

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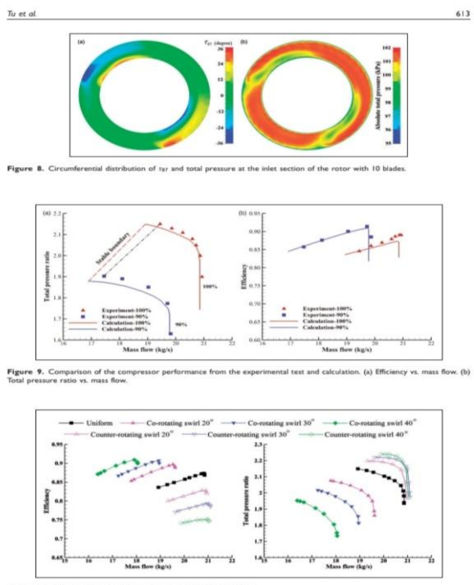
By synthesizing insights from prior research, the literature review sets the foundation for the present study, underscoring the need for rigorous validation and analysis of CFD models to ensure accuracy and reliability in predicting compressor performance.

B] "Effect of swirl on the performance and stability of transonic axial compressor" authored by Baofeng Tu, Luyao Zhang, and Jun Hu, published in November 17, offers a detailed investigation into the influence of swirl on the performance and stability of transonic axial compressors. 4 Through comprehensive experimental and computational analyses, the authors explore how varying degrees of swirl affect the aerodynamic behavior and operational characteristics of such compressors. By manipulating swirl levels, they systematically examine parameters including pressure ratio, efficiency, and surge margin, crucial for compressor performance and stability.



The study delves into the intricate flow mechanisms induced by swirl, elucidating phenomena such as shock wave interactions, boundary layer development, and stall inception. Moreover, the paper sheds light on the implications of swirl variations on compressor stability limits, providing valuable insights into surge and stall phenomena.

The findings underscore the significant impact of swirl on compressor performance, highlighting the intricate interplay between flow dynamics and operational stability in transonic axial compressors. Furthermore, the study contributes to advancing understanding in turbo machinery design and optimization, offering valuable guidelines for mitigating performance degradation, and enhancing operational robustness in compressor systems operating under varying flow conditions. Overall, the paper serves as a valuable resource for researchers and engineers engaged in the development and optimization of transonic axial compressors, providing essential insights into the role of swirl in shaping compressor performance and stability characteristics.

C] "Experimental Investigation of Rotating Instability in an Axial Compressor with a Steady Swirl Distortion Inlet" authored by Rong Xu, Jun Hu, Xuegao Wang, Chao Jiang, and Jiajia Ji, published on December 2, 2021, presents a comprehensive examination of the phenomenon of rotating instability in axial compressors under the influence of steady swirl distortion at the inlet. Through meticulous experimental investigations, the authors explore the intricate dynamics of rotating stall and surge in the compressor system subjected to swirlinduced flow distortions. By employing advanced instrumentation and measurement techniques, they analyze the spatial and temporal evolution of flow disturbances, elucidating the mechanisms governing the onset and propagation of rotating instability. The study reveals the profound impact of steady swirl distortion on compressor performance and stability, highlighting the propensity for instabilities such as rotating stall and surge to manifest under such flow conditions.

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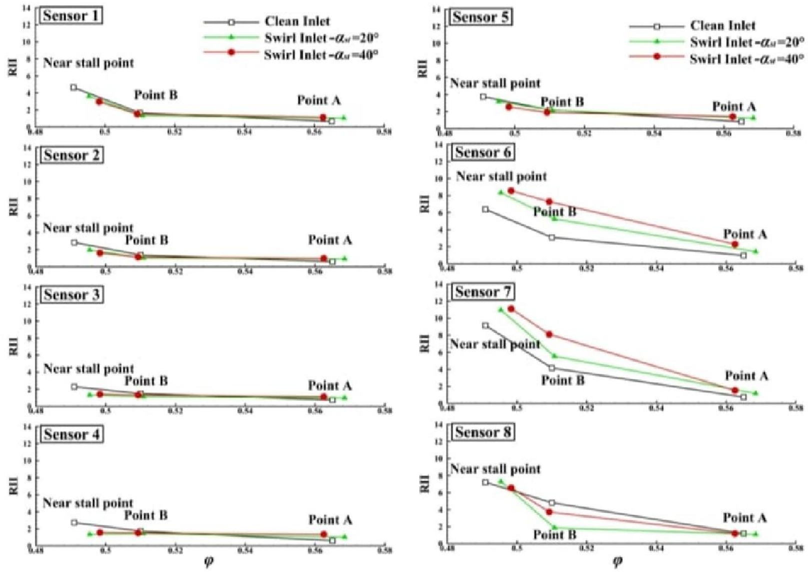

Figure 12. Effects of paired swirl distortion with two intensities on RRI at different circumferential positions, δ_r = 2 mm.

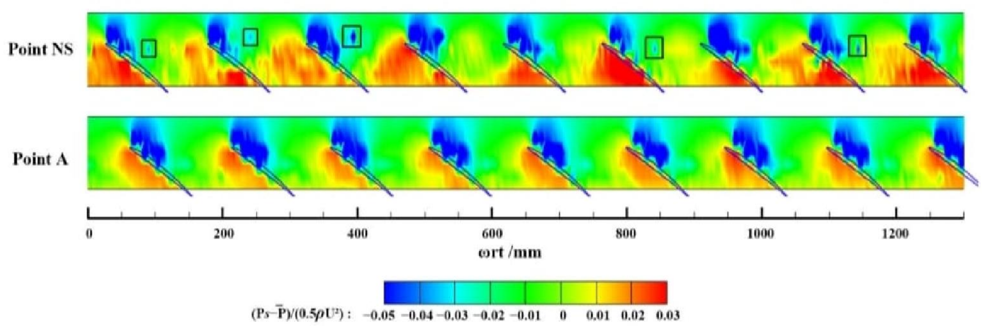

Figure 13. The dimensionless static pressure distribution diagram at the rotor tip of the operating point A and near-stall point, measured at station 7, with paired swirl distortion, α_{st} = ±20° and δ_r =2 mm.

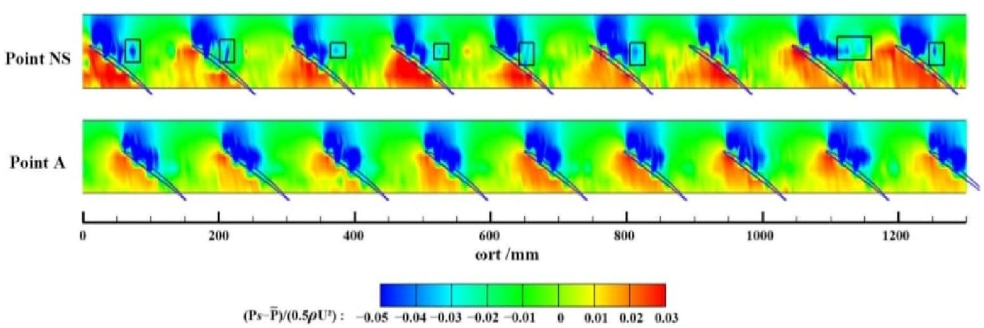

Figure 14. The dimensionless static pressure distribution diagram at the rotor tip of the operating point A and near the stall point, measured at station 7, with paired swirl distortion, α_{st} = ±40° and δ_r = 2 mm.

Additionally, the paper discusses the implications of rotating instability on compressor operation and efficiency, emphasizing the importance of mitigating adverse effects associated with swirl-induced flow distortions. The findings contribute valuable insights to the understanding of 5 compressor aerodynamics and operational characteristics, providing essential knowledge for the design and optimization of axial compressor systems subjected to inlet flow

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distortions. Moreover, the study offers practical guidance for engineers and researchers in identifying and addressing rotating instability issues in real-world compressor applications, thus advancing the state-of-the-art in turbomachinery design and performance enhancement. Overall, the paper represents a significant contribution to the field of compressor aerodynamics, offering valuable insights into the complex interactions between flow distortion, rotating instability, and compressor performance.

D] "An experimental investigation on the interaction between inlet swirl distortion and a low-speed axial compressor," authored by Xuegao Wang, Jun Hu, Jin Guo, Baofeng Tu, and Zhiqiang Wang, published in 2020, presents a comprehensive examination of the intricate interaction between inlet swirl distortion and a low-speed axial compressor. Through a series of carefully designed experiments, the authors investigate the effects of varying levels of inlet swirl distortion on the performance and aerodynamic stability of the compressor. Employing advanced measurement techniques and instrumentation, the study systematically analyzes the spatial and temporal distribution of flow distortions within the compressor, elucidating the mechanisms underlying the interaction between inlet swirl and compressor operation.

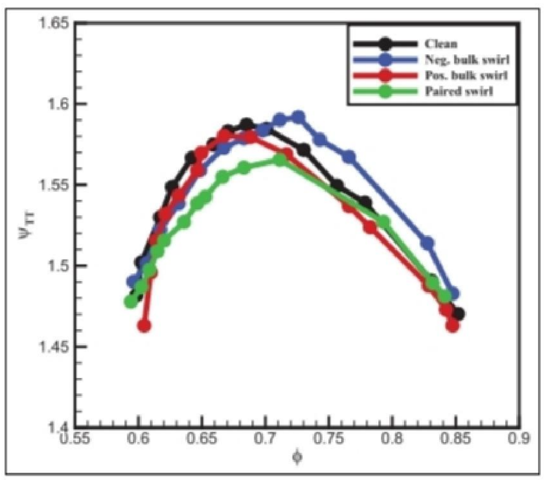

Figure 17. Overall performance map of the compressor under different inlet flow conditions.

The findings of the research shed light on the influence of swirl distortion on key performance parameters such as pressure ratio, efficiency, and surge margin, providing valuable insights into the behavior of the compressor under non uniform inlet flow conditions.

Additionally, the paper discusses the implications of the observed interaction between swirl distortion and compressor performance for practical applications in turbomachinery design and operation. By elucidating the complex interplay between inlet flow characteristics and compressor behavior, the study contributes to a deeper understanding of the factors influencing compressor performance and stability. Furthermore, the research offers practical guidance for engineers and researchers in the development and optimization of axial compressor systems subjected to inlet swirl distortion, thus advancing the stateof-the-art in compressor design and performance enhancement. Overall, the paper represents a significant contribution to the field of turbomachinery aerodynamics, providing valuable insights into the effects of inlet swirl distortion on low-speed axial compressor performance and stability.

III. CONCLUSION

After reviewing existing literature and research papers, it was noted that simulations of the rotor blade under consideration had been conducted using ANSYS software but polytrophic efficiency of rotor blade can be increased. In response, this project aimed to fill this gap by simulating the rotor blade in ANSYS and optimizing it to enhance efficiency. Through comprehensive analysis and comparison with experimental data, it was demonstrated that ANSYS simulations can provide valuable insights into rotor blade performance, leading to potential improvements in aerodynamic efficiency and overall functionality.

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