

Summary of Research Progress in Supersonic Compressor Cascade

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Abstract. In compressors, supersonic/transonic flow is a hot topic in today's research. Its development directly affects the performance and function of compressors. The main purpose of supersonic cascade research is to increase its tip velocity, so as to improve its power capacity and boost ratio. In this paper, important research achievements since 2017 are summarized in the following aspects: the working principle of ultrasonic elements, unique intake Angle, shock wave structure and boundary layer interference. At the same time, the most widely used design blade shapes are introduced. Finally, the future development is prospected.

Keywords: ultrasonic cascade, ultrasonic element, transonic /supersonic compressor, Unique intake Angle, Shock wave structure Shock wave/boundary layer interference.

1. Introduction

In aero-engine research, the study of compressors is crucial. In order to reduce the number of compressor stages, it is necessary to obtain a higher pressure ratio at each stage of the compressor and make the compressor do more work. According to the flange work formula.

$$L_u = u\Delta w_u \quad (1)$$

We can see that higher work requires a higher linear velocity at the blade tip, thus increasing the boost ratio. In the past studies, we have adopted the method of increasing the load coefficient. But after decades of research, it is difficult for the load factor to significantly affect stage pressure ratio further. Even with the use of advanced flow control methods, the contribution to the increase of pressure ratio is small. Therefore, nowadays people focus on improving the direction of tip linear velocity. Mathematically, the load coefficient has a linear correlation with the compressor's power capacity, while the blade tip linear velocity has a quadratic relationship with the power capacity. At present, the development of supersonic and transonic compressors has been the general trend in the huge space for the improvement of blade tip linear velocity. Now the most used transonic compressor, its key and difficult part is still the supersonic part.

NASA has been studying supersonic compressors for a long time. Among the earlier achievements are the internal shock rotor supersonic compressor proposed by Kantrowitz and the ram-rotor supersonic compressor proposed by Klapporth. [1] Although the early studies improved the pressurization ratio well, the efficiency was very low. This is because we did not pay attention to the study of blade shape and shock wave distribution at the very beginning, and did not have a thorough understanding of the three-dimensional flow in the compressor, which led to the lack of consideration in shock wave distribution and other ways, so that we could not study the supersonic compressor with higher efficiency. And the in-depth study of supersonic cascade was made after 1960. Researchers of supersonic compressor began to pay attention to the study of supersonic cascade, and accepted the research results of early supersonic compressor to develop the transonic compressor.

In these studies, NASA observed the phenomenon of unique intake Angle and starting problem of supersonic cascade through experiments and put forward a preliminary explanation. VKI proposed a wedge-shaped ultrasonic cascade with blunt trailing edge pressurized by shock string, and designed and tested an ultrasonic rotor. ARL designed and tested a compressor with a stage pressure ratio of 3.0, and designed the first pre-compressed vane ARL-SL19 [1]. In recent years, the international research on supersonic and transonic compressors has been more in-depth. In the last two years,

Aravinth Sadagopan and Cengiz Camciy have studied the viscous flow and performance of a 6:1 supersonic mixed-flow compressor with a series diffuser. In China, Zhang Chengfeng et al. have carried out numerical research on the influence of tip clearance modification on the performance of transonic compressors, and Li Xiaodong et al. have carried out mechanism research on the stability of the rotor of supersonic compressors. Based on the research of supersonic and transonic compressor cascades in recent years, this paper summarizes and generalizes the research progress of the influencing factors and key technologies of supersonic cascades, and prospects the future research.

2. Working Principle of Supersonic Compressor

A whole compressor is composed of a plurality of working elements, and the gas working under supersonic conditions of the device is ultrasonic element level. It has been pointed out above that increasing the blade tip linear velocity helps to greatly improve the compressor's ability to do work. If the relative velocity w_1 exceeds the local speed of sound, this level constitutes the ultrasonic elementary level. As can be seen from the figure1, since the blade is relatively straight, the flow direction of the air flow through such a channel is basically unchanged. The principle is that the supersonic airflow will produce shock waves. After passing through the shock wave, the speed of the gas decreases and the static pressure rises, so it plays a pressurization effect. Because u and Δw_u are larger than the sound base, the processing capacity and pressurization effect is better.

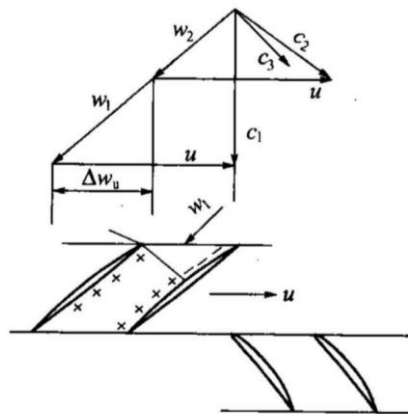


Figure 1. Schematic diagram of ultrasonic primitives working

3. Unique Intake Angle

First of all, we know that the flow of ultrasonic compressor is different from that of subacoustic compressor, and its flow is only related to the speed of rotation, but not to the pressure ratio. This situation is due to the only intake angle. In a two-dimensional supersonic flow, the ultrasonic flow has a component of 1 in the direction perpendicular to the Mach line. It can be expressed by the following formula:

$$Ma \times \sin \mu = 1 \quad (2)$$

The unique intake Angle is formed:

Unique intake Angle is a phenomenon found in the study of supersonic cascade law. Perturbation occurs when the supersonic cascade works. To make its flow stable, only expansion waves and shock waves cancel each other in the far upstream of the supersonic cascade to form the stable flow we want. To calculate the unique intake Angle, start by using the Levin method. Later Lichtfuss and Starken proposed a more accurate four-conservation law with the semi-infinite cascade theory. In recent years, with the development of research, York and Woodard combined the eigenline method and the four-conservation law to solve the unique intake Angle of plane cascades, while Liu Cuie and Wu Wenquan combined the two methods to calculate the unique intake Angle of arbitrary rotating surface

cascades. [2] In recent two years, Hao Yan's research group carried out flow loss research based on the cascade designed with the unique intake Angle. It is found that the supersonic cascade loss can be reduced based on the combination of multi-channel oblique shock wave plus positive shock wave supercharging in this cascade design. In order to achieve this supercharging mode, the curvature of the blade surface should not be too large and should be kept as straight as possible.[3]

4. Geometric Structure of Supersonic Cascade

When designing supersonic cascade, the geometric structure design often directly determines its performance. For this aspect, the research has made great progress in recent years. In terms of loss reduction, Giovanni Venturelli and Ernesto Benini optimized DCR-PaV-1.5 cascades through a multi-objective optimization method. By improving the cascade geometry structure, the loss coefficient is reduced by 25%, the static pressure ratio is increased by 6.5%, and the loss in the front-end geometry is reduced by 95%.[4] In terms of actual production. Demetrios Lefas and Robert J. Miller found in their study that when the throat to inlet area ratio is high, the suction surface is separated by strong shock waves, while when the ratio is low, the blade is blocked. Thanks to the transonic relief mechanism, the spanwise height of the sonic flow tube can be self-regulated so that the ratio is close to the optimal value of 1.01. From this we know that, at design time or during operation, if the throat to inlet area ratio is not 1.01, transonic overflow will correct this value to an acceptable range. It is also pointed out that a high hub-to-tip ratio are likely to be nearly impossible to design because the Mach number at the inlet changes very little. This study demonstrates that the degree of freedom provided greatly saves design costs and improves operability.[5]

5. Shock Wave and Boundary Layer Interference

Shock wave/boundary layer interference is the main research content of viscous supersonic flows. Especially in supersonic cascade flows, the structure of shock waves is complex, the inverse pressure gradient is large, and the irregular curved channel flow is irregular. These characteristics make it difficult to calculate and analyze shock wave and boundary layer interference. However, in the design process of a supersonic compressor, the influence of boundary layer cannot be ignored, which is a major difficulty for the current innovation of supersonic compressor. In the design of supersonic blade, the shock wave must be included in the focus of consideration. The impact of shock wave on the generation of unique intake Angle and compressor performance is very great. To a large extent, the loss of transonic compressor is caused by the formation of shock waves induced by the interaction of supersonic cascade, tip leakage vortex and boundary layer.

In recent years, Richard Amankwa ADJEI and Weizhe WANG have studied the effects of unsteady shock wave motion and post-shock instability on compressor performance of bladed diffuser, and the effects of shock wave on impeller-diffuser interaction. It is found that the interaction between shock wave, tip leakage flow and boundary layer has the greatest influence on the loss, which leads to the increase of aerodynamic loss.[6]

In order to solve these problems, scholars around the world have made a lot of efforts in the measurement and control of shock waves. Della Posta et al. improved the DDES method, which improved the prediction accuracy of the average wall pressure and average velocity distribution of the separation bubble. They also successfully estimated the peak frequency of shock wave motion. a new length based on the orientation of the vorticity vector and on a solution dependent kinematic measure (VTM) is used to reduce the viscous convection of eddy currents in the RANS region. Unlock Kelvin-Helmez instability and accelerate the transition to 3D resolution turbulence.[7]

Li Yan, Han Wu, Wei Huang et al. used the RANS equation and the two-side equation SST k- ω turbulence model to numerically study the flow control efficiency caused by the combination of air extraction and suction in the boundary layer, and found that the secondary shock system would appear when the secondary recirculation flow control was adopted, which was conducive to the enhancement

of mixing.[8]After that, Ma Jiannci, Zhou Ling and Ji Lucheng summarized previous studies and proposed using root slots as a passive control means to control the angular region separation problem of transonic cascades. It is found that root grooving can effectively reduce cascade loss within the range of full attack Angle, and can improve shock wave intensity, so as to effectively improve the load level in the end area of the transonic cascade and improve the diffuser capacity of the cascade. [9] The above research results are helpful for us to carry out calculation and control near the boundary layer, so that we can predict the working condition of the compressor more accurately and improve its efficiency.Ziao Wang, Juntao Chang, Yunfei Li et al studied the shock waves of supersonic cascades controlled by suction force. The results show that the maximum back pressure can be increased by 20% and the main flow loss can be reduced by 8%[10] Through reasonable design of the surface and end wall size of the suction groove. Although remarkable results have been achieved. However, the control effect of shock wave flow in these studies is not large enough. In order to achieve better development, it is necessary to increase the experimental speed to more than 2 Mach number, and explore the control stability of the full speed range, how to maintain the efficiency of the full speed range, structural reliability and other aspects of the research.

6. Stall Stability

In the compressor, the rotating stall and surge not only affect the efficiency of the compressor, but also threaten the personal safety of the user. To reduce the occurrence of instability and its influence is also a problem that must be considered in the design of supersonic cascade. On the simulation of rotating stall, Song Moru, Yang Bo and Wang Yueheng did dynamic simulation analysis of rotating stall of transonic compressor. The modal energy criterion is discussed and selected. The results show that the criterion on the original flow field mode is applied to the stall-related flow field, and after verifying the precision of dynamic mode decomposition (DMD), it is found that only 20 modes are used in each stage, and the weight error is less than 3%. Provides an accurate and feasible analysis template.[11]

In terms of surge, Tianyu PAN, Zhaoqi YAN, Dakun SUN et al. studied the relationship between system response and surge. The system response amplifies the local total pressure oscillation from the stator hub by affecting the mass flow and back pressure. However, system response does not directly affect the generation of rotary stall unit. The lack of system response will make it unable to propagate continuous disturbance, resulting in peak-type stall, which leads to unsteady flow rather than surge. This indicates that in addition to high load, system response is also a necessary condition for surge.[12]

Great progress has also been made in delaying stall in recent years : Botao Zhang, Bo Liu, Xiaochen Mao by using the combined control of variable clearance and casing inspirations on the flow field and instability of transonic compressor blades, it is found that the expansion of blade clearance can attenuate the tip leakage vortex, thus delaying the compressor stall. The combination of casing suction and expanding blade clearance can further improve compressor performance. The best performance is achieved when the suction groove is located at 35% axial chord length. [13]Shan Ma and Wuli Chu studied the synergistic effect of micro-vortex generators (MVG) and boundary layer suction (BLS) combinations (COM) in high-load compressor cascades. COM plays a very strong role in stall condition. MVG induced vorticity can push low energy fluid backward and delay stall. BLS can inhibit secondary flow loss and can be used in combination to get good results.[14] Ryszard Szwaba, Piotr Kaczynski, Piotr Doerffer studied the effect of adding transition region on shock boundary layer. The suitable transition upstream of shock wave has a positive effect on the boundary layer interaction region. And applying appropriate roughness can reduce wake loss to a large extent.[15]

Although we have made great improvements and breakthroughs in the mechanisms and prevention of stalling and surge, the universality of these mechanisms and prevention needs more data and

theoretical support. Once stall and surge occur while driving, our options are limited. So not only do we need to look at ways to prevent a stall, but we also need to look at ways to get out of a stall.

7. Effects of Sweep Angle

Li Ziliang, Han Ge and Zhu Junqiang found through research that the position of shock wave at the inlet of the impeller directly determines the effect of the leading edge sweep design under design conditions. By changing the load distribution at the tip of the vane, the swept design affects the flow capacity of the vane, and also changes the shock structure and flow loss at the inlet.[16] In terms of forward sweep, the team of Shijun Sun, Songtao Wang and Shaowen Chen made further research. When the forward sweep height (forward sweep height) is kept constant, the stalling margin increases with the increase of forward sweep angles (FSA). However, when FSA is 10 degrees, it is a critical point, and the overall pressure ratio and efficiency tend to increase first and then decrease. At the peak, they increased by 0.4% and 0.19%, respectively. While keeping the forward sweep angles unchanged, increasing the forward sweep height (no more than 50%) is an effective measure to expand the improvement of stall margin.[17-18]

According to the above studies, sweep Angle will not only affect the efficiency, but also affect the stall stability. In the future, more attention should be paid to the relationship between sweep Angle and aspect ratio, full speed range effectiveness and compressor working stability, so as to lay a solid foundation for the technology in supersonic compressor engineering design.

8. Summary and Prospect

Supersonic cascade has many characteristics in design and application because the velocity of incoming flow is higher than that of sound. In terms of structure, the supersonic cascade element is straight. Because the supersonic compressor is pressurized by shock wave, it does not need high camber, which will affect the shock wave instead, thus making the pressurization effect worse. In the interaction between shock waves and boundary layer, boundary layer Angle separation and stall may be caused, so shock wave control is also a problem. In order to better serve the transonic compressor, in my opinion, the supersonic cascade needs to be improved in the following aspects: control stability of the full speed range of shock wave control, how to maintain the efficiency of the full speed range, and structural reliability; More data and theoretical support are needed for the universality of stalling and surge measures; The research on the relationship between sweep Angle and aspect ratio, full speed range effectiveness and compressor working stability lays a solid foundation for the technology in supersonic compressor engineering design.

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