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FLOW INSTABILITY AND ITS CONTROL IN COMPRESSION SYSTEMS

This paper reviews the development in the research of flow instability and its control over the recent ten or more years. This development was largely stimulated by the novel idea of active control of the aerodynamic instability in compressors. Three topics are covered in the paper, which appeared as the major themes towards the goal of stability enhancement. The first topic is the pre-stall behavior of rotating stall, which plays a vital role in designing the control scheme and discovering the convenient route to find the causal factors of flow disturbances potentially leading to stall. The second topic is the mechanism of blade passage flow during stall and its inception, which is the basic knowledge needed to manipulate the blade design for the stability improvement and eventually to predict the unsteady performance of the compressor system. The third topic is the recent trend of the control strategy based on the learning of active vs. passive methods. To introduce to the discussion of these topics, a brief description of the history of the recent development is given at the beginning of the paper. In discussing each topic, future works are also highlighted to enhance the further development of this long-standing problem in turbomachinery research and application.

Introduction. The phenomenon of flow instability in the compression system, typically rotating stall and surge, is a long-standing problem of concern for turbomachinery research and application. Rotating stall is typified by one or more stall cells of degraded blade flows traveling around the compressor annulus, while surge is a mean flow oscillation that often involves reversed flow. Both of them appear as the stability limiting factors to the compressor operation because of the consequences invoked by them in deteriorating the compressor performance and in the danger of mechanical failure. Numerous research and application work have spanned over decades, with its practical aim being the stall margin provision and the mechanical excitation alleviation. In recent years, however, revitalized efforts can be witnessed primarily due to the new "smart engine" concept [1] and its successful implementation for active control of aerodynamic instabilities. These research efforts have led to a number of important results and innovative ideas have been continuously updated. It is this new development that the present paper is trying to give a review through discussing some aspects of its successes and lessons.

Several review articles were already available, two appeared in 1998 [2, 3] and the other two in 2000 [4, 5]. Among them the one by Greitzer [2] is very specific in describing the methodological aspects of this research such as the

[1]Статья публикуется в авторской редакции.

cross-disciplinary approach, the value of team work, the system view on the phenomenon and the interplay between modeling and experiment. It is therefore not the author's intention to make this article in full coverage of related topics. Rather, the selected topics are those that emerged as the research efforts went on and the research subjects were updated. Many of the material covering these topics are from the results obtained in my institute during the same period of time. One topic is the research on stall in its early emerging period, which appeared in parallel with the theme of active control. Another topic concerns the effort to extend our understanding of the dynamic characteristics of rotating stall in compressors to its internal fluid mechanics in the blade passages. The third topic discusses the recent trend of control strategy based on the learning of active vs. passive methods. Before discussing the three topics, a brief history of the recent development is given so that the overall picture of the still developing process would not be missed. Finally the paper is ended with summaries and conclusions.

History of Recent Development. The concept of "smart engine" first appeared in the open literature was given by Epstein in 1986 [1]. He described the gas turbine engine whose performance can be controlled through closed loop operation from sensors to actuators. Among different possible applications of this concept, the active control of aerodynamic instability in compression system, due to its value in practical application and perhaps the better formulation of its basic characteristics, was the first to put forward into practice. The basic idea came from a joint work by the experts of compressor aerodynamics and anti-noise acoustics [6] which states that the feedback control on the small disturbances preceding rotating stall and surge can change the dynamic behavior of the compression system, render a given unstable operating point stable, and enhance the operating range. One of the preparatory works before this idea came into the light was the modeling of compression system by Greitzer [7] and the modeling of post-stall transients in compressors by Moore and Greitzer [8, 9] which later became the theoretical framework for many of the active control study on the compressor flow instability. This theory when applied to the active control proposes a linear process of development into stall, which was then supported by the experimental work of McDougall et al [10] and Garnier et al [11]. The early attempt was very encouraging as can be seen in the two results for surge control [12, 13] and two results for the control of rotating stall [14, 15], conducted in the two gas turbine labs in MIT, US and in Cambridge University, UK. The extension of the stable operating range by about 25 % could be attained for surge and 4...20 % for stall control. In a hope of dramatically improving the stability of compressors, the research soon became the hot point among researchers and engineers of turbomachinery, control and other disciplines, with high project investment and thus large manpower involved.

While the research strategies were various among different groups, the reactions in industry were also mixed. The cautious reaction came primarily from the complexity of the active control technique applied to the engine environment, which reduces its reliability and robustness. Technically, its practical application was questioned because the ultra-short time period of sensing, processing and actuating that are needed in the feedback loop of active control. Therefore, concurrently with the emerging research of active control, the study on the behavior of stall in its inception period rather than fully developed stage also received a great deal of attention. The research resulted not only in evidences of the linear development of stall as assumed in the modeling of [6], but also in the discovery of nonlinear inception of stall [16]. Understanding the stall behavior from its infant stage is the vital part to initiate the control loop and also very helpful in clarifying the flow mechanism of rotating stall. Thus the research scenery in the period of early 90^{th} could be signified as the co-development of these two branches, active control and stall inception. The active control technique kept developing in many ways. Good examples are the aero-mechanical scheme of control on surge and rotating stall [17, 18], which used the structural feedback instead of sensors and external actuators, so that the cost of implementation could be reduced. The scope of stall inception study also increased covering the precursor detection, characterization, signal processing, underlying mechanism and stall warning. This was also the period when we started the research in the field, resulted in the successful active control of surge by Nie et al. [19] and the early study of stall inception in centrifugal compressor by Chen et al. [20].

In the following period from around mid 90^{th}, as the research efforts went on and diversified stall and its inception characteristics were evidenced [21], the need became more apparent for going deeper into the fluid mechanics aspect of the phenomenon rather than the description of only its dynamic characteristics. Therefore the strengthened efforts in studying the internal flow mechanism in blade passages can be witnessed. The question to be answered is what happened in the blade passages while the rotating stall takes place in the compressor. This would make our understanding of the flow instability more complete, in both blade and system scales, and make the control strategy more pertinent and effective to the causal factors for the loss of compressor stability, in particular if one wishes to manipulate the blade design for stability improvement. In a long run, it should be an important step forward towards solving one of the key problems in designing turbomachinery, the prediction of the full range compressor performance.

It is interesting to note that as the research on stall inception and on internal flow mechanism strengthened, the strategy of active control also updated. The history is likely going back, via a spiral development, to its original aim of stability enhancement. This was indeed the scenery from the end of $90tpth$to the present time, when the passive control strategy such as casing treatment regained its development. The new development of passive control is in many ways benefited by the innovative ideas gained in the course of active control study. Other possibilities such as combined active/passive control are also under investigation. It seems that the ten-plus years development of compressor instability research, started from the breakthrough idea of its active control and enriched by the numerous successes and lessons, is now entering a new period, which is viewed not by the scale of its activities but by the realistic aim and refined means to achieve its goal.

Pre-Stall Behavior. Numerous evidences have been accumulated for the stall behavior immediately prior to the established stall cells. This time period is usually referred as the period of stall inception and the flow disturbances discovered and believed to trigger the stall are called stall precursors. Normally, stall precursors are identified in the dynamic pressure or velocity signals measured by sensors in the tip region in front of rotor blades and commonly fall into two types. The first is the mode type of long length scale wave which appears tens of rotor revolutions time in advance of stall and builds up linearly before evolving into the finite stall cells [11]. The second is the spiky type stall inception which initiates with a small amplitude short length scale disturbances that can be detected only few rotor revolutions time before straightly developing into stall cells [16].

Now we may ask what we have learned behind such characterization of stall precursors. One of the questions is under what condition which type of stall inception may happen. The first attempt to study this question was given by Day [16] linking the type of stall inception with rotor blade tip clearances. Although no parametric relation could be built, the tip clearance did influence the type of stall inception presumably by altering the blade passage flow in the tip region. In further research along the same line, based on the experimental results, a simple model of critical incidence was proposed by Camp and Day [22]. The model states that in the throttling process of compressor, if the peak of the overall characteristic is reached before the critical value of rotor incidence is exceeded anywhere in the compressor, then modal oscillations will occur. If, on the other hand, the critical incidence is exceeded before the peak of compressor characteristic, then spikes will occur and lead the compressor to stall before any chance of modal activity. This model, by showing the interplay of system mode and localized event in blade passages, could successfully link the physical difference of stall precursors with the flow parameter in compressor.

But this is not the end of the answer. A question remains of whether any events preceding the stall precursors exist, and if they do, what is the influential mechanism for their existence. In fact, Tryfonidis et al. had tried this question in their early study on pre-stall behavior in compressors [23]. They distinguished the whole stall events into three stages — the fully developed rotating stall, stall inception and so called pre-stall. While the stall inception, as described above, was attributed to the interrelated system and blade flow effects, the pre-stall, according to the authors of Ref. [23], was susceptible to excitation by geometric non-uniformities in the compressor. However this idea was not clarified in Ref. [23] and the evidences shown in pre-stall stage were limited to the type of travelling wave, in spite that the wave can be detect at least 100-200 rotor revolutions prior to the inception of rotating stall.

It was perhaps because of the general lack of more effective technique then to treat the measured data, and thus prevented from the further study of the pre-stall behavior. Indeed, to identify the pre-stall disturbances out of the weak and unsteady signal is difficult because they are blended within the blade passage flow and measurement noise. Furthermore, we want to not only detect them, but also to track their development with time. This is especially complicate for the unsteady and nonlinear spiky type signals. Several authors tried different techniques to this problem. Bright et al. [24] and Lin [25] applied nonlinear time series analysis and Liao et al. [26] introduced the wavelet transform to the stall inception analysis. The initial motivation of using wavelet transform was mainly due to its auto-focusing capability to adapt the large frequency range for the signal under consideration, and thus the time-frequency analysis can be performed. As this work went on, more advantages of using wavelet transform were explored [27–30] and more applications were obtained in stall inception analysis [31, 32]. Early flow disturbances can be detected over thousand rotor revolutions prior to stall, the behavior of disturbances in different scales can be distilled, and the whole evolution process to stall can be tracked in both time and space.

In one example taken from the test on a low-speed three-stage axial compressor [30], the time and frequency plots of wavelet power spectrum for three different time intervals along the pre-stall process are shown in Figs. 1, (*a*)–(*c*). In these figures, the signals processed are taken from seven pressure sensors

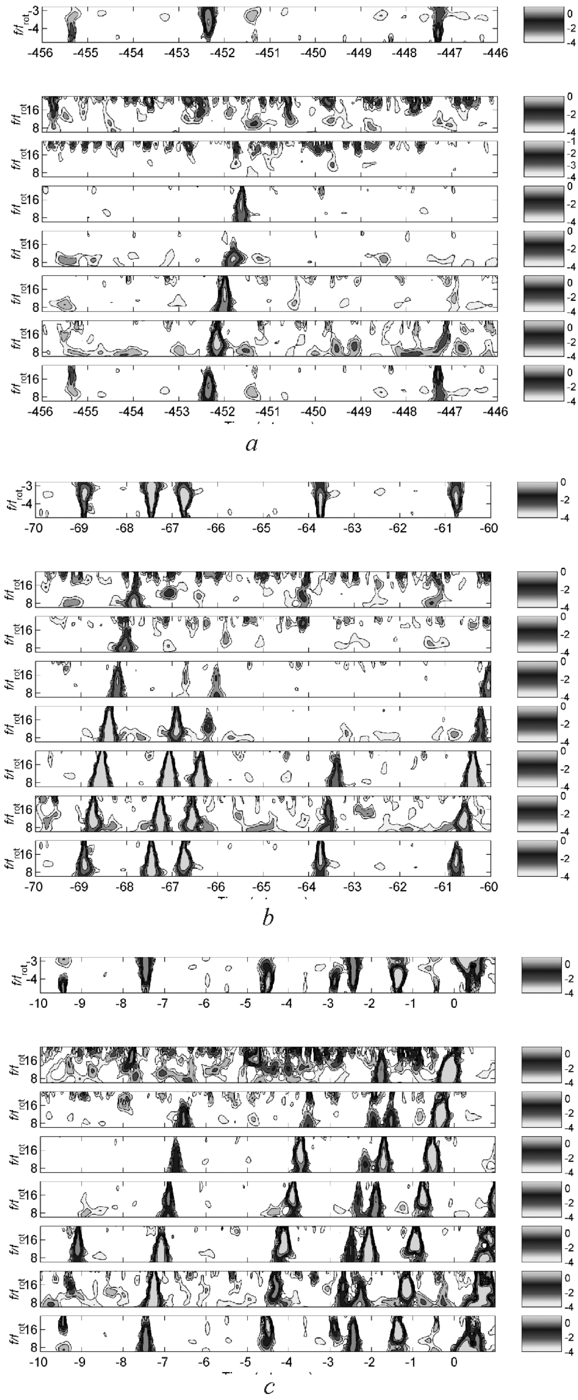

Fig. 1. Wavelet spectrogram for data from seven annularly distributed sensors in early pre-stall period showing the intermittent emergence of spiky disturbances (*a*), in a period closer to stall showing the more frequent and longer lasting spiky disturbances (*b* and in aperiod immediately prior to stall showing one spiky disturbance growing up to stall cell

circumferentially mounted on the casing wall 45° apart from each other from sensor 1 to sensor 7 in one cross section in front of the first rotor (sensor 1 for the bottom plot and repeat at the very top) and the frequency range is chosen for the appearance of the spiky disturbances. From these figures, the intermittent character of the emergence of spikes and their annular propagation can be clearly tracked. Fig. 1 (*a*) shows the period of early emergence of spikes several hundreds rotor revolution times ahead of the final stall, during which two spikes appear randomly in time, but disappear before returning to where they were born. As the compressor is throttled closer to stall, the spikes appear more frequently and last longer than before as shown in Fig. 1, (*b*). It is interesting to note that the spikes were all born at the same location near sensor 1 where the structure asymmetry was found since far more early time period (not shown here). Fig. 1, (*c*) depicts how the stall is finally triggered. Among the four spikes born in this period, only one of them finally develops into full stall in less than five rotor revolution times, and the other three didn't get the chance. The result of this kind reminds us to look back the early proposition of Tryfonidis et al. and makes us possible now to study the stalling process from its pre-stall stage rather than the stage of stall inception. The further research should include the characterization of the behavior of flow disturbances in the pre-stall stage and their possible link with the known types of stall inception, and the exploration of such behavior with geometric non-uniformities when the disturbances emerge and with blade flow mechanism when the disturbances grow.

Blade Passage Flow Mechanism. It is generally known that the formation of stall cells is routed in the fluid mechanics behavior of blade flow. The model in terms of the effect of blade flow on the formation of rotating stall was first given by Emmons et al. [33] and was well received since then. The stall cell, according to this model, is meant to a flow blockage caused by the flow separation in blade passages, which in turn is caused by external disturbance such as the deviation of incoming flow towards the increase of the angle of attack. In particular, the model could give an explanation of why the stall cell becomes propagating around the compressor annulus. However, the effect of tip leakage flow, reverse flow and the three-dimensional migration of stall cells, exhibited in the further research, have hinted much complex blade passage flow in the stalling process, which is beyond the effect of incoming flow in the two-dimensional consideration of Ref. [33].

To study such internal flow mechanism of rotating stall requires high resolution measurement system in experiment and huge computation power in numerical computation, and therefore its development was hindered for a long time but revitalized in recent years along with the advancement of experimental and numerical techniques and the emerging research of active control. The initial attempt was an experimental study of the transient internal pressure patterns on the outer surface of revolution in centrifugal compressor impellers, using the time-traced pressure data measured by a series of transducers along the flow path on the casing wall of the compressor [34]. The method was later extended in an experimental study of the transient characteristics of rotating stall in a transonic axial compressor [35]. These investigations showed the details of redistribution of blade loading as the flow changes from steady to unsteady and could locate the time and length scales for the formation of stall cells. Similar approaches are also implemented recently in Ref. [32, 36] in supplement with numerical study. Nevertheless, the experimental results remain two-dimensional and are limited to the pressure fields rather than the velocity ones. It seems that these restraints can only be released at the present time by the numerical computation of the unsteady internal flows.

Several authors have tried such numerical simulation with different schemes but the general trend is from two-dimensional to three-dimensional and from inviscid Euler to viscous Navier-Stokes computation schemes [37–39]. The numerical computation was mostly performed with multiple blade passages even entire blade rows. In addition to the characteristics of developed stall such as the number and propagation speed of stall cells, internal flow structure during stall and its inception can be described which could clarify the role of tip clearance vortex in the stall via short length-scale inception process [38, 39]. To further explain this phenomenon, from the recent results of numerical computation in Ref. [40], Fig. 2, (*a*) shows a comparison of 2D (naturally without tip clearance) and 3D (with clearance) computation in obtaining different type of stall precursors and different time elapse of their existence, Fig. 2, (*b*) shows a comparison of 3D computation with and without tip clearance in resulting to the different stability limit of compressor operation.

It should be noted that the computation results for the role of tip clearance vortex in stall inception were obtained for the case of tip critical low-speed compressors. Many challenges remain for cases of high-speed compressor in describing the internal flow structure of stall and its inception. It is also a challenging task to find the link of stalling process with the blade design parameters, especially for multi-stage compressors. Gong et al. [41] attempted this task by a new 3D computation scheme coupling the system model and the model of blade row flow, represented by a body force field in terms of the prescribed blade's pressure rise and turning characteristics. In the low-speed multi-stage environment, the method succeeded in capturing the development of both long and short wavelength compressor instabilities. For the short wavelength disturbances, the method is able to depict their occurrence on the negatively sloped part of the overall compressor characteristic proving the experimental result in Ref. [22], and to show the suppressing effect on their growth by closing the rotor-stator gaps which was later experimentally proved in Ref. [32]. The similar approach was also given by Nakano et al. [42] for numerically studying the instability inception in high-speed multi-stage compressors.

Therefore the numerical simulation, along with its further development, should offer many possibilities for studying the phenomenon of compressor instability, from the detailed fluid flow mechanism in blade passages to eventually the stability prediction of the matched or mismatched compressor system. As will be discussed in the next section, the numerical simulation, in complement with experiment, can also be used in studying the control effect to the compressor instability.

Active vs. Passive Control Strategy. As described above, along with the emerging technology of active control for improving the compressor stability, the traditional means of passive control also obtained its new development. It is interesting to follow this development taken the air injection control in the tip region of compressor annulus as an example. The design principle of the injection could be either active or passive. In a low-speed four-stage axial compressor experiment, Day applied an active control scheme and succeeded with 4–6 % improvement of stability boundary at the expense of injected air maximum 1 % of the compressor flow rate [14]. Years later, in the works of Behnken et al. [43] on a low-speed single-stage compressor at Caltech and Weigl et al. [44] on a transonic single-stage compressor in NASA, while the main purposes are still

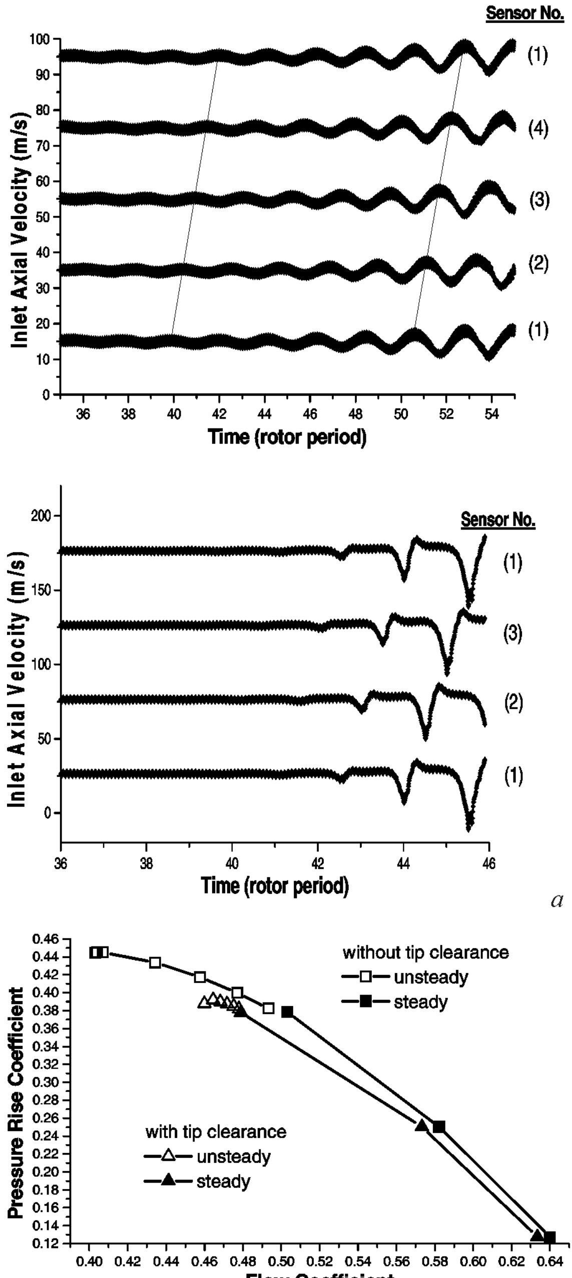

Fig. 2. Stall inception process by 2D vs. 3D computation showing different type of stall precursors and different time elapse of their existence (sensors distributed circumferentially) (*a*) and single rotor perfomance by 3D computation with tip clearance (2,1 % chord) and without tip clearance (casing stationary) showing different stability limit of compressor operation (*b*)

active injection control of rotating stall, some results were also reported for the use of injectors in a passive steady manner. These results showed comparable successes in using the two very different control schemes. In Ref. [44], with the same injection rate of 3,6 % of the compressor main flow, the steady injection gives 4,3 % extension of the stability boundary towards the lower mass flow and the controlled injection for zeroth, first and second modes of pre-stall disturbances gives 7,8 % improvement. Three years later since the investigation of Ref. [44], on the same test facility, Suder et al. [45] published their passive control results giving the reduction of the stalling mass flow by 6 % using steady flow injection of 2 % of the compressor flow rate. Unlike the traditional empirical design approach of passive control by trade-off for the improvement of compressor performance, detailed study was performed in Ref. [45], both experimentally and using steady flow CFD simulation, for the blade passage flow parameters, e.g. the redistribution of the incidence and blade loading towards decreasing at the tip under various injection configurations.

Judging the development of air injection control as described above, several lessons can be learned. Firstly, since the benefits of active and passive injection are comparable, it could imply that the unsteady characteristics of the compression system have changed to its improvement even though the control measure is a steady one. This proposition dictates a mechanism of unsteady response, which would exist in the compressor when the steady injection acts on the unsteady flow process of rotating stall. Secondly, in contrast to all the steady flow consideration when the amount of injected air needed is on the order of a few percentage of the compressor main flow in order to realize the effect on the mean flow parameters such as the incidence or blade loading, the amount of steady injected air considered for being effective only on the unsteady flow characteristics can be dramatically reduced. Thirdly, with such tiny amount of injected air, the steady compressor characteristic with no injection should not be influenced and thus could keep its shape unchanged, a problem that the traditional passive control scheme suffered for years. Based on the above argument, a new approach, steady micro air injection from the casing, was recently proposed in Ref. [46] and experimentally verified that the injected flow of only 0,05 % of the compressor main flow is able to trigger the unsteady response and lower the mass flow rate at stall for up to 5,8 %. The mechanism of unsteady response was demonstrated and proved through the tests at various injection configurations, plus wavelet analysis of measured pre-stall flow disturbances and numerical computation for the behavior of tip clearance vortex at near stall condition. The computation is now further extended to the operating point of full stall and Fig. 3, taken from Ref. [47], gives a visualized flow picture at 80 % span from hub for the whole blade row annulus, showing that the micro injection can keep the operation stable while, at the same compressor flow rate, the rotating stall already takes place for the compressor without injection.

The micro injection scheme is an example which shows how a new approach has been evolved from its past development and how it benefits from the past experiences. It must be stressed that in the case of micro air injection, the design philosophy remains unsteady (active) in spite that the control action could even be steady (passive). Moreover, this active control philosophy should be directly related to the unsteady blade flow physics on which the nature of stall is routed.

In this context, the active control in terms of long length scale waves is actually unable to effectively interact with the flow of short length blade scales, and therefore unable to realize the original goal of increasing the pressure rise in compressor characteristic. It is also worthy to note that in further research of control method, the improvement of the compressor stability is not necessarily targeted by sizable extension of the stability boundary. Instead, the ability of compressor systems to remain stable in the face of external disturbances is perhaps more practical. This concept, called operability enhancement of the compressor, was given in its clear and detailed description in Ref. [3, 48]. Technically, it could mean that the control power needed is only for the disturbance rejection at very early stage, any time when the external disturbance emerges, but not for the suppression of grow-up disturbances, i.e. no ability to drag the compressor back if it has already fallen into stall. It is hoped that in doing so, the expense of control power and the complexity of control system could be largely reduced.

Conclusions. Revitalized development in researching the compressor flow instability and its control has been described. It is hoped to be able to shed some light on the persevering efforts of research and development in attempting to break the barrier for the stable operation of compressors, the innovative approaches emerged in the course of these efforts, and the future perspectives towards the goal of stability enhancement.

In parallel with the emerging technology of active control, the research on the pre-stall behavior has been in the central attention for many years concentrating on the inception period immediately prior to final stall. The main outcome of the research lies in its ability to demonstrate the interplay between the system mode and the flow event on the scale of blade passages, resulting to different types of stall precursors and different control approaches. This understanding could be further extended if the behavior in the early pre-stall period can be clarified and included into the modeling and experiment work.

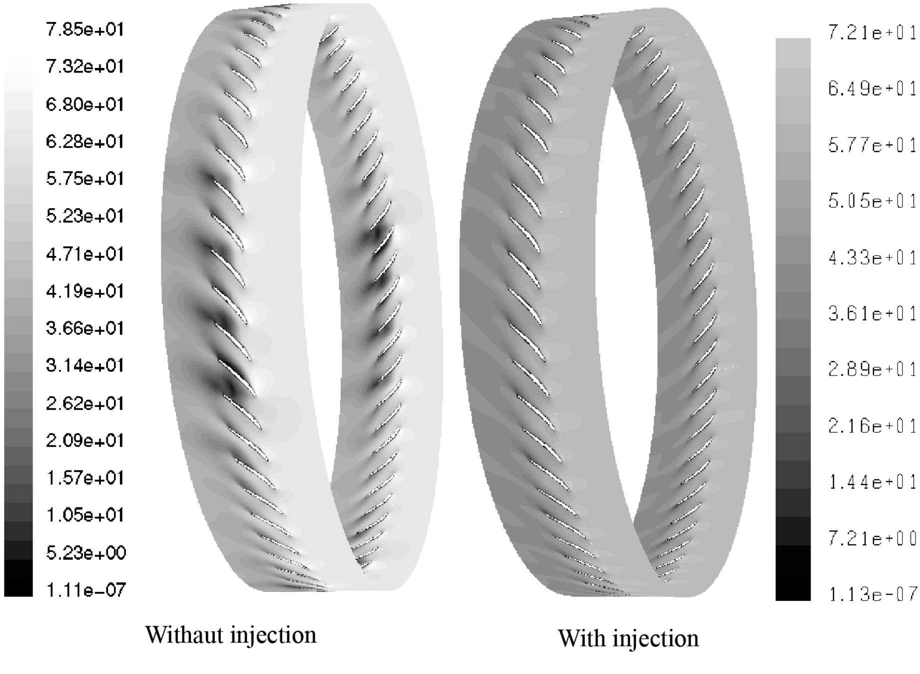

Fig. 3. Unsteady velocity patterns in full annulus of compressor blade row computed at the same compressor flow rate for the cases with and without micro injection showing the stability enhancement under micro injection

The work on numerical simulation of the flow instability beginning to gain its successes in recent years is an important basis for where to go in developing the control schemes. The simulation is meant not only for the blade passage flow but also in coupling with the compressor system including multi-stage matched and mismatched compressors, which will enhance the true predicting capability of the numerical tool for the unsteady compressor characteristic and for its use in practical design applications.

Benefited from the recent development of active control and many related disciplines and taken account that the targeted control subject is a typical unsteady flow phenomenon, the design philosophy of instability control should remain unsteady in spite that the control schemes could be various, active, passive or their combination. This principle is also in line with the initiative of the operability enhancement of compressor in terms of the early disturbance rejection, which could lower the cost of the control and enhance its robustness.

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