Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46118

A SUMMARY OF STALL WARNING AND SUPPRESSION RESEARCH WITH MICRO TIP INJECTION

Feng Lin, Zhiting Tong, Shaojuan Geng, Jingxuan Zhang, Jingyi Chen, Chaoqun Nie

Institute of Engineering Thermophysics
Chinese Academy of Sciences, P. R. China

ABSTRACT

Micro tip injection is a stall control technique in which engineers inject small-flowrate yet high-velocity jets into the tip region of axial compressor rotor blades to extend the stable operation range, while keeping the entire compressor characteristic line nearly unchanged. This paper summarizes the related research performed in Chinese Academy of Sciences in the past several years, ranging from understanding the fundamental mechanisms to demonstrating the technology in a laboratory compressor. A brief review in tip injection research indicates that for each compressor, there exists a critical injection momentum ratio, below which the injection flows may work differently from those over the critical value. Detailed casing unsteady static pressure measurements and the related sophisticated data processing proved the existence of self-induced unsteady tip leakage flow, which was also confirmed by unsteady CFD simulations. It is showed that this kind of unsteadiness in tip leakage flow might be responsible to make the auto-correlation coefficient drop significantly as the compressor operated at lower flowrate close to stall limit. This warning signal, which was first successfully used by other research groups with little care taken on its flow mechanism, appears much earlier than the classical modal-wave or spike stall precursors. Micro tip injection was effective if it interacts with the unsteady tip leakage flow long before the stall precursor emerges. As a technology demonstration, a DSP board with a build-in auto-correlation early-stall-warning algorithm and an on-off controller of injection valve worked well to drive a micro tip injection system and successfully delayed the stall in a low-speed compressor with much less jet flows than the continuous micro tip injection.

NOMENCLATURE

C_p	Static pressure coefficient, $C_p=(P-P_{t0})/(0.5\rho U_{tip}^2)$
U_m	Blade speed at mean radius
Ψ	Total-to-static pressure rise coefficient
ϕ	Flow coefficient
T_{bp}	Time of blade passing period

Abbreviations

BPF	Blade passing frequency
MF	Main flow
MTI	Micro tip injection
RMS	Root mean square
SFB	Signature frequency band
TLF	Tip leakage flow
URANS	Unsteady Reynolds Averaged Navier Stokes
UTLF	Unsteady tip leakage flow

1. BACKGROUND AND MOTIVATION

Tip air injection is not a new idea in stability enhancement of axial flow compressors. As early as 1968, Koch and Smith ([1]) reported the performance of tip injection in the context of casing bleeding and blowing. While the bleeding becomes a popular technique of surge protection in many industrial compressors/fans/blowers, tip injection was not nearly as popular. It received extensive study in late 80's and early 90's when the concept of Smart Jet Engines ([2]) was initiated and promoted aggressively in the aero-engine research community. As one of the few effective means of stall/surge margin extension that can be actively controlled at will by control designers, tip injection is an ideal candidate of control actuators ([3-5]) because among several competing techniques such as variable guide vanes ([6]) and mechanically flexible plenum ([7]), it has the highest possible bandwidth to fulfill the requirements of fast response to stall precursor detection and early stall warning signals.

Apart from the context of "smart jet engines" ([2]) in which the air tip injection is by default an unsteady controlled jet, the steady blowing through discrete injection nozzles mount on casing had also been carefully studied, both experimentally and numerically ([8-16]). These studies include single rotor and multistage, low-speed and high-speed (even transonic) compressors, as well as micro- and macro injection air flowrates. Parametric studies, such as nozzle geometry, injected flowrate, injected flow velocity, temperature of injected air, etc., were also performed with the purpose of optimizing the injector design. The recent development includes incorporating tip air injection with stall warning techniques and implementing both with a DSP board.

Like several other stability enhancement techniques (casing treatments with circumferential grooves or axial skewed slots, variable inlet guide vanes, blade sweep and dihedral, aspirated blades, etc.), tip injection possesses its own pros and cons when applied to compressors. Three major advantages make it particularly attractive as stall controlling technique. First, it is probably the most effective stall control techniques of all. It is the only one that can pull compressors out of the stall and recover stable operations. Second, it is flexible enough to act as needed and at will. Third, it does not alter the compressor blade geometry at all. This last point is considered as an advantage simply because of the fact that the decision of whether adding tip injection or not will not interfere with compressor blade design process itself. The modern compressor design has already been such a complicated, multi-objective and nonlinear optimization problem, adding more degrees of freedom into the decision matrix without reliable databases to support the design decisions may not be the best interest to compressor designers at all. In many cases, tip injection can simply be used as a remedy to improve off-design performance as well as enlarge the stable operation range without asking the designer completely rebuild the entire machine.

However, the drawbacks of tip injection are also obvious. The entire system itself consists of pressurized air source, pipes/ducts/hoses, valves and nozzles. It adds an additional subsystem onto the engine whose surface has already been jammed with lubrication, cooling, fuel injection and control subsystems. Additional control logic is also needed to be embedded into the engine controller (but it is quite simple compared to the rest of the job the controller handles constantly). All these complexity and additional weight are the major drawbacks of tip injection systems. The highly pressurized air may come from two sources: directly withdrawn from the high-pressure back stages (such as [8]) or an auxiliary pump (such as [13]). Both can be considered a loss in term of overall efficiency consideration.

Micro tip injection (MTI) minimizes the negative effects of these drawbacks in two ways ([13]). By scarifying some capability of stall enhancement, MTI can still achieve significant amount of stable range extension yet without modifying the original overall performance curve. This in turn means it would not alter engine operating line and would not add any new degree of freedom to the compressor and engine design. In addition, because its consumption of air can be as little as in the order of 1 out of ten-thousandth of the main mass flow, a convenient small auxiliary displacement pump may be used. Its negative effects on the compressor efficiency can be negligible. The range extension (typically less than 10%) is thus a net gain to the entire engine. This is why micro tip injection can be a very attractive technology for stall control.

The objective of this paper is to summarize the research efforts on MTI done by the group of researchers in the Chinese Academy of Sciences in the past decade, especially in the latest five years. Nie et al (13)) were the first to propose MTI and applied it to a low-speed laboratory compressor. They showed that the mechanism of stable range extension on which MTI was based might be an unsteady one. Further research discovered that this unsteadiness resided in the tip region at near stall operating points, and closely related to the interaction between tip leakage flow (TLF) and the main flow (MF) ([14]). The mechanisms, the onset conditions and the general existences of such unsteadiness in a number of different compressors have been investigated and published in a series of papers since then. Most of the papers are in Chinese and there are too many to list here. A typical example is Lin et al. ([19]), in which a detailed CFD study of a German transonic rotor were presented and validated with the publicly available experimental data. Independent from our own work and roughly at the same time duration, Vo et al. ([20]) showed that the leading edge spillage of tip leakage flow can be one of the most important criteria for spike stall precursors. Tahara et al. ([21-22]) observed if a sensor was placed on the casing near to blade leading edge, the saw-tooth profiles that the sensor detected over the same blade passage cannot resemble themselves once the compressor was throttled close to the stall limit. They then proposed an idea to detect early stall warning by monitoring auto-correlation coefficients from the same sensor. Christensen et al. ([23]) and Dhingra et al. ([24]) elaborated this idea and developed a stability management system successfully. However, these authors ([21-24]) did not pay attention to the fluid physics that lie behind the auto-correlation coefficients. In this paper, we postulate that the unsteady tip leakage flow that we have been going after for several years is the main reason for the auto-correlation to drop significantly even before spike stall precursors emerge. By briefly summarizing all these years of work, we are hoping to promote a systematic stall control strategy, ranging from fundamentals in fluid physics to technologies in early stall warning and control actuating.

This paper will be organized as follows. A brief survey of tip injection performance is given in Section 2, followed by a discussion on the mechanism of how MTI may act differently from tip injection with large injected flowrate in Section 3. In Section 4, a new view of the flow mechanism of early stall warning using auto-correlation data is given, while in Section 5, the role of TLF/MF interface to spike and the interaction between the MTI and this interface are given. All of the above are integrated into Section 6, where a MTI system controlled by a DSP board is demonstrated in a low-speed compressor in laboratory environment. Conclusions and discussions are given in the last section of the paper, followed by Acknowledgement.

2. A SURVEY OF TIP INJECTION PERFORMANCES

The tip injection can be classified casually as follows. There are continuous and discrete tip jets based on the nozzle arrangements on casing ([9, 12]), or steady ([8-11]) and unsteady (pulsating or actively controlled) jets ([4-5]), or the micro and non-micro jets based on the ratio of jet mass flowrate over the main mass flowrate ([13]). In this section, we focus on steady and discrete jets with different injected mass flowrates. Later in this paper, a simple on-off controller will be applied to demonstrate the effectiveness of MTI. In which case, the jet will be pulsated (so it will be unsteady), but the fundamentals of our controller are different from active controllers designed based on complicated linear or nonlinear control theories.

Suder et al. ([9]) and Kefalakis et al. ([10]) did exhaustive experimental studies of tip injection on compressor stability enhancement. Both used discrete jets on high-speed compressor stages. Suder's work was done on the high-speed NASA Stage 35, while Kefalakis' was on the first stage of an aircraft engine named Larzac engine, which is also transonic. Parametric studies were performed to examine the effectiveness of tip injection by varying injected flow rate, injected flow angle, numbers of injection nozzles, compressor rotating speeds, and even frequency of pulsating jets. What's most interesting to us is the efforts that both papers made in order to unify the large amount of test results by selecting proper scaled independent variables. Among several of those choices, the ratio of injected jet momentum to free stream momentum did the best job according to Kefalakis ([10]). With this inspiration, we collected all the data from Suder and Kefalakis, added the test results of two compressors of our own ([17-18]), and presented them all in one figure. Figure 1 depicts the final result. In this figure, the labels for "low subsonic" and "high subsonic" are used for the two compressors of our own. The abscissa is the ratio of the injected jet momentum to free stream momentum.

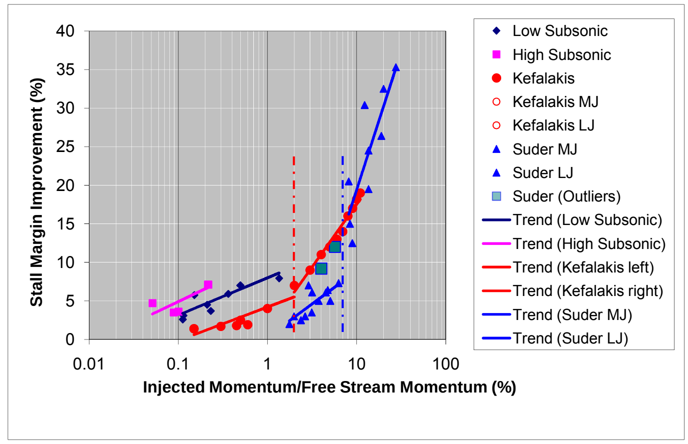


Figure 1. A unified view of tip injection data in literatures and our own tests. MJ = Micro Jets; LJ = Large Jets.

In a logarithm scale, the trends of data from these four compressors appear to be straight lines. In our own tests, we were so concentrated on the effects of MTI that no attempt was made to inject large flow rates and improve the stall margin by more than 10%. Kefalakis'data formed a nice curve that can be viewed as two piecewise straight lines in log scale. By drawing a line of 2% of momentum ratio, Kefalakis' data on the left of this line displayed the same trend as our MTI tests. Therefore, it is expected that for Kefalakis' compressor, the injection with momentum ratio less than 2% perform the same way as our MTI tests. Suder's data looked messy at the first glace. However, if excluding two points of outlier, the critical line for Suder's compressor can be placed at 7% momentum ratio, below which the data exhibited almost the same trend as the other three compressors. Above the critical values, the tip injections followed different trends to improve stall margin. Note that the outliers in Suder's data were identified because all the other tests with similar injected flowrate produced much less stall margin improvement.

In short, Figure 1 tells us that there were two different fluid physics on which the injected jets were based, even though the critical value for each compressor may be different. As shown in Figure 1, we use the dash-dotted line as the boundary of the two physical mechanism. The fact that the critical values that separate the two mechanisms vary from compressor to compressor indicates the dimensionless parameter, the momentum ratio, is not perfect to summarize all the test results. Perhaps it is not even correct, although it did the best job so far. It is natural to think that this phenomenon must be closely related to tip leakage flows. Vo et al. ([20]) proposed a hypothesis about criteria for spike stall precursors. The leading edge spillage of the interface between tip leakage flow and main incoming flow (or free stream flow) is considered as the most crucial criterion. Bennington et al. ([25]) experimentally and computationally verified the existences of such interface and recorded its movement as the compressor is throttled to stall. Figure 2 depicts the result. As the main flow reduced, the interface moved towards the leading edge. At the last several stable operating points (near-stall points), the interface was very close to the leading edge. An unsteady Reynolds Averaged Navier Stokes (URANS) solver was able to capture this experimental fact.

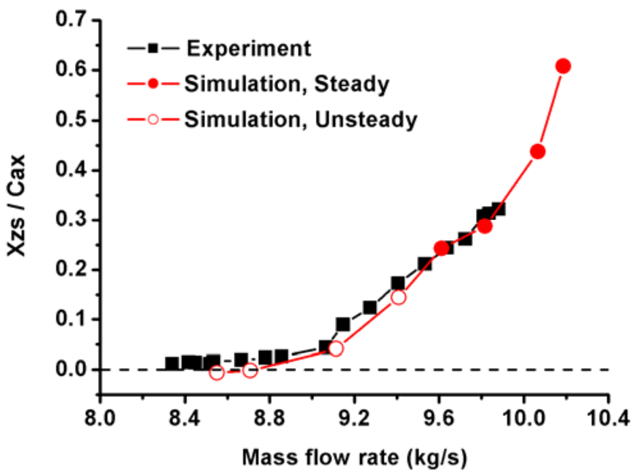


Figure 2. The experimental evidences of the TLF/MF interface ([25]). The ordinate is the axial distance of this interface from leading edge normalized by the blade's axial chord.

URANS simulation also revealed a special kind of oscillation of tip leakage flow occurred as the compressor approached to stall. The onset of such an unsteady oscillation is also associated with the location of the interface. This had happened in all compressors that we had explored in the past five years. We named it as the self-induced unsteady tip leakage flow, or abbreviated as the self-induced UTLF. Therefore, it occurred to us that if we act on the interface early, so early that when the tip leakage flow exhibits the self-induced unsteadiness yet the compressor is still stable on time average, we can push back the interface and hold it longer with much less injected momentum. To accomplish this, it requires two conditions: 1) we would be able to detect the self-induced unsteady tip leakage flow long before spike emerges, and 2) we would need a means to act on the interface and only the interface. For the former, the auto-correlation coefficient can be an excellent indicator, while for the later MTI is an ideal candidate.

The next three sections will answer the following three questions, respectively:

1. Is the self-induced UTLF a general phenomenon for axial compressors?
2. How to detect the self-induced UTLF in realistic casing pressure measurement data?
3. Is it really true that acting early on the interface between tip leakage flow and the main flow will be able to delay the stall with minimum injected momentum?

The answers to these questions turn out to be positive. At the end of the paper, we demonstrate an implementation of this stall control strategy in our laboratory compressor with a DSP board.

3. EVIDENCES OF UNSTEADY TIP LEAKAGE FLOW AT NEAR STALL

Complex flow structures resides in tip region of rotors, such as tip leakage vortex, corner vortex, secondary passage vortex, leading-edge and inside-passage shock waves (if transonic), just to name a few. The dynamics of these flow structures makes the unsteady version of these flows and their interaction even more challenging. In this section, a brief review is given on the self-induced UTLF, which distinguishes itself from the others in two characteristics: signature frequency band and structured RMS contours. (RMS stands for root mean square.) The signature frequency band differ the self-induced UTLF from those random unsteady flows such as vortex breakdown and other turbulences, while the structured RMS contours makes it different from non-flow vibrations such as rotor whirl.

Figure 3 depicts a comparison of static pressure contours taken from a URANS simulation. The contour plot on the left is a snapshot of one time instant when the flow is oscillating at a smaller flow coefficient. The plot on the right is the steady flow at design operating point. The rotor is the rotor of the low speed compressor tested by Nie ([13]). Figure 3 indicates that the oscillation was induced by the impingement of tip leakage vortex onto the blade pressure side, which altered the blade loading directly, changed the tip leakage flow, and thus generated cyclic effect. This only happened at near stall because at design point, the tip leakage vortex flew through the passage smoothly. Because it is a cyclic effect that was induced by the tip leakage flow itself, we called it the self-induced UTLF.

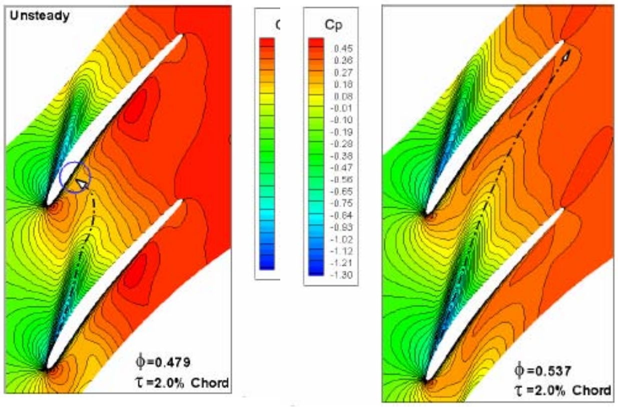


Figure 3 Comparison of static pressure contours between near stall and design points (taken from [15])

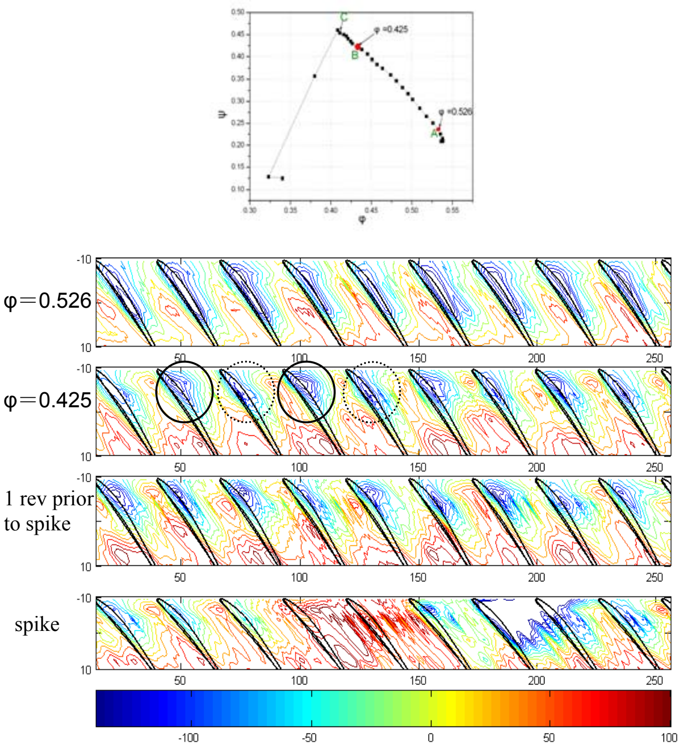


Figure 4. A comparison of casing pressure contours for the three points ([15])

The CFD results showed that this kind of unsteadiness had its signature frequency band. In this low-speed rotor, its frequency at the relative coordinate (i.e. observed by observers on the rotor rotating frame) is very close to 50% of blade passing frequency (BPF, which is NOT the shaft speed). If observed from casing, it was expected to see the casing static pressure contours alternated from one blade passage to another. The signature frequency should still center about 50% of BPF. This was exactly the case in experiments. Figure 4 depicts the instantaneous casing pressure contours at three different mass flowrates. The contour alternation is clearly visible at small flow rate. Note that the experiment was done with a tip gap of 1.1% of blade chord. So figures 3 and 4 are not exactly corresponding to each other.

The signature frequency band can be seen in Figure 5. In this figure, the abscissa is the frequency normalized by the rotor frequency (or the shaft speed). The signature frequency band grew as the flow coefficient reduced. For one moment, we thought the phenomenon was the "rotating instability" ([26]). But immediately we realized we stumbled into a new phenomenon, because this unsteadiness is confined within a single passage as our computation indicated. It is not rotating. Recently, we have enough computing power to perform a full-annulus URANS simulation on the same rotor. Similar phenomenon was observed. Although there were phase lag among the blade passages, the oscillation itself was not rotating around the annulus at a speed of 50% BPF. See [30], in particular Figure 11 of that reference.

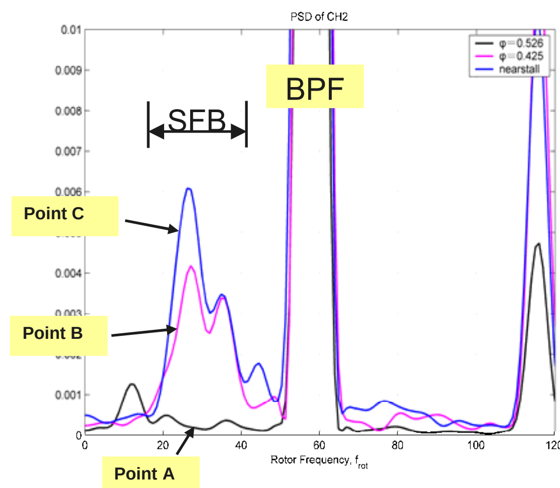


Figure 5. A comparison of power spectrum density plots for the three points ([15])

Research efforts were extended from the low-speed compressors to high-speed transonic compressors. Four compressors, NASA Rotor 37 and Rotor 67, ND-TAC of University of Notre Dame, USA and Rotor 1 of Technological University of Darmstadt, Germany were all numerically simulated (see [16], [27], [25], [19], respectively). Qualitatively, the same phenomenon was found in all these rotors. Figure 6 depicts a comparison of RMS contours between CFD result on the left and the test result on the right. The test was done independently by the researchers in Darmstadt, Germany. One can clearly see the same structured RMS contours in both CFD and test results. The two locations with the strongest oscillations were at the pressure side near the leading edge and at the trajectory of the tip leakage vortex.

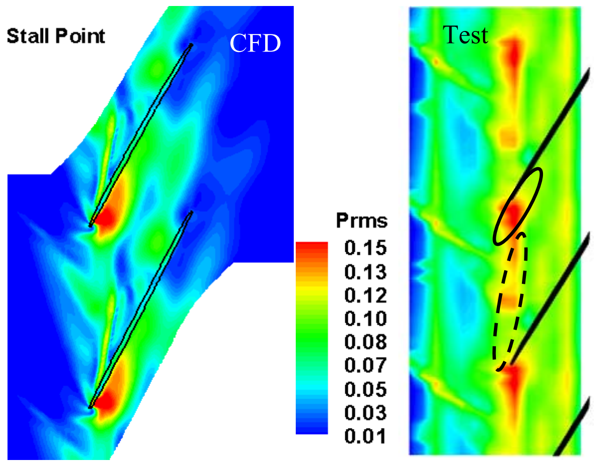


Figure 6. Comparison of structured RMS contours of Rotor 1 of Darmstadt ([19])

In addition to the existences of the self-induced UTLF, the onset condition, the originating mechanism and some parametric studies were also studied. The details are out of the scope of this paper. Interested readers may find information in related publications.

4. The SELF-INDUCED UTLF AND EARLY STALL WARNING

The question that we were asked most frequently was "why do you care (about this particular unsteadiness)?" The answer is that it provides early warning and early stall suppression even before spike stall precursors emerge. If a compressor is the kind in which Vo's criteria for spikes hold, it is likely that the self-induced UTLF be an intermediate step between design point and stall. Once it is detected, it indicates that the TLF/MF interface is close to the leading edge. If a control actuator can be turned on at this moment, it can push the interface back or hold it at minimum costs.

Although we found the self-induced UTLF independently, a group of Japanese scientists published a similar observation in as early as 2001 ([21]). Figure 7 explains well how the three steps of tip leakage flow development are identified by them, which coincides with our results as shown in Figures 3 and 4. Figure 8 demonstrated that as the flow coefficient reduced, the casing pressure profile across the same blade passage started to wobble, but these wobbling are most pronounced in Sensors f (at the leading edge) and i (at the middle of tip leakage vortex trajectory). The unsteadiness increased as the flow coefficient reduced, although no theoretical explanation was given in [21]. This figure was the foundation of the early stall warning method with auto-correlation coefficient.

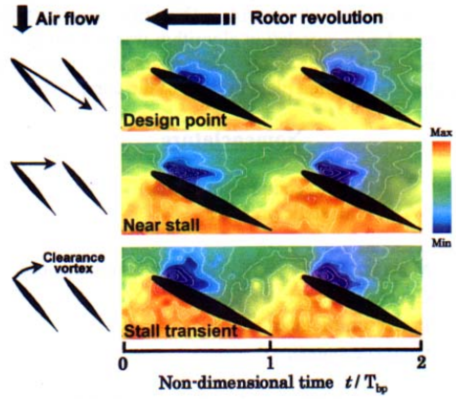


Figure 7. Three steps of tip leakage flow development from design to stall as identified by [21]

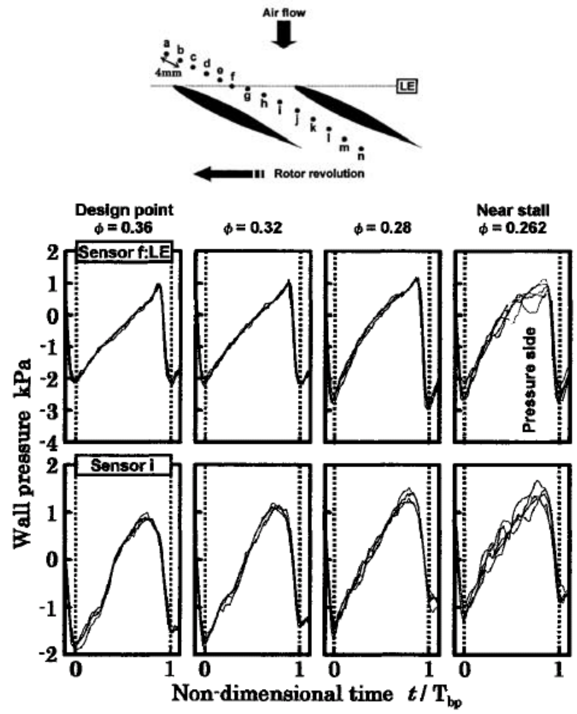


Figure 8. The unsteadiness increased as the flowrate reduced ([21]).

In our work (as seen in Figures 3-5), we encountered the same particular unsteadiness. To verify this, we reprocess our test data the same way as Figure 8. We first use a key phasor to do a precise phase locking per revolution (illustrated in Figure 9), then overlap the phase-locked pressure profiles together for a few revolutions (Figure 10). The results are qualitatively the same as Fig. 8. Since this is the same data used in Figures 3-5 and we had showed that the self-induced unsteadiness can be detected in these data, we thus postulate that it is the self-induced UTLF that causes the wobbling pressure profiles for the same rotor blade passage as the flow coefficient is reduced. The fact that the wobbling phenomenon was most pronounced at the neighborhood of blade leading edge supports this postulation. However, to actually prove it, we will need to measure the intensity of other unsteady sources such as turbulence, vibration and others, and then identify the contribution of each source. At this moment, we are unable to exclude other sources from experimental data yet, although one thing for sure is that the wobbling profiles were not caused by spikes that might have come and gone hundreds or thousands revolutions before stall. This is because the wobbling phenomenon happens at a range of operating points far away from the stall limit. No spikes at those points yet (such as Point B of Figure 4).

We can do one more step forward to support our postulation. That is, we will use our CFD data and resemble the test measurements on casing from the numerical simulations, and then repeat the same phase locking procedures on the CFD data. In addition to verify what's observed in Figure 10, we also examine the data for other compressors. Figures 11 and 12 depicts the results for two transonic compressors, one is the Rotor 1 in Darmstadt, Germany and the other is the ND-TAC in Noter Dame, Indiana, USA. The curves in these two figures were the results after emulating what a casing pressure sensor would sense for the same blade passage after a number of rotor revolutions. Note that in these two cases, the simulation was done in a single passage. Therefore, there is absolutely no wobbling of pressure profile in design condition because it is completely steady. But in near stall, the self-unsteadiness is the only reason that causes the wobbling profile, because it is a pure URANS result. No turbulence or mechanical vibrations can contribute to the wobbling in these numerical results.

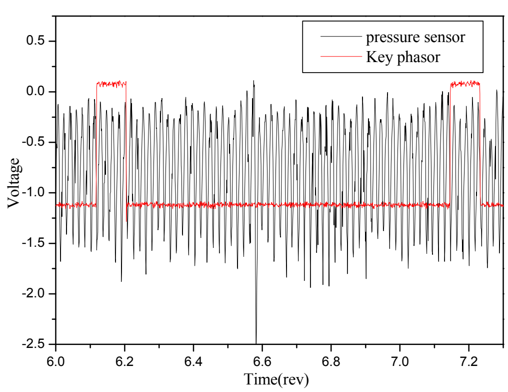


Figure 9. An illustration of how to do a phase locking per revolution using a key phasor.

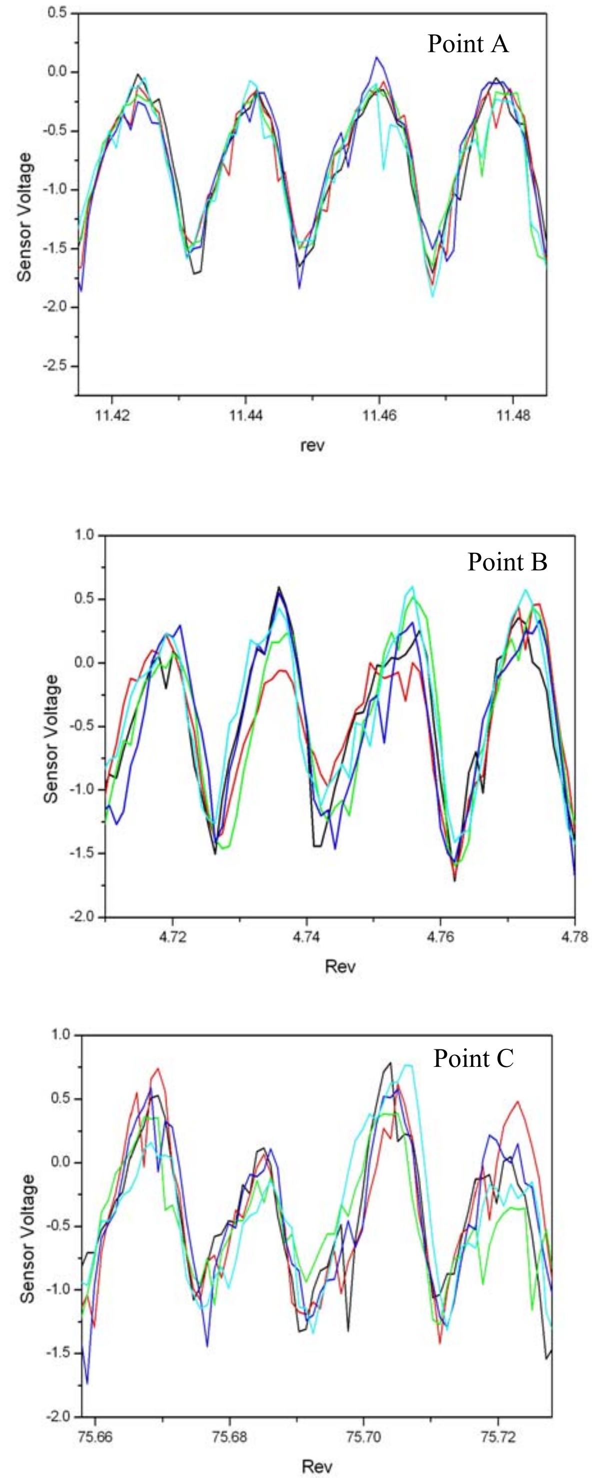


Figure 10 Overlapping the phase-locked pressure profiles together for five revolutions at Points A, B and C.

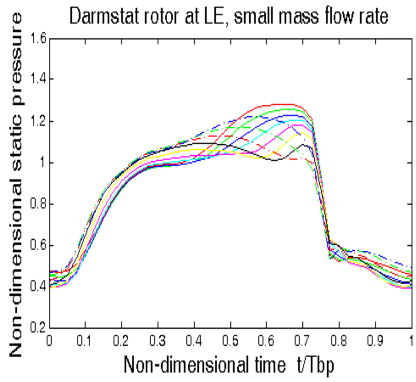


Figure 11. Reproducing experimental phase locking profiles when the self-induced UTLF was present using CFD results: Darmstadt Rotor-1

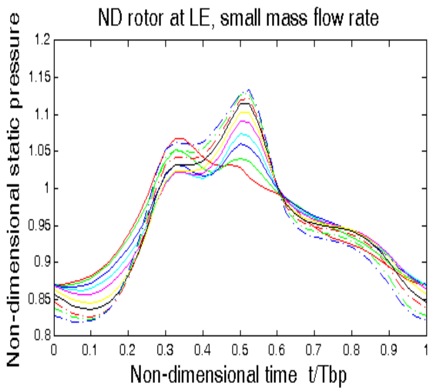


Figure 12. Reproducing experimental phase locking profiles when the self-induced UTLF was present using CFD results: Notre Dame ND-TAC

5. THE MICRO TIP INJECTION AND THE TLF/MF INTERFACE

In previous two sections, we have examined the evidences of the existence of the self-induced UTLF and its significance in early stall warning. Using the auto-correlation coefficient, we are able to detect the self-induced UTLF, which basically tells us that the TLF/MF interface is close enough to the leading edge so that it is the time to do something about the interface. Although compressor is still stable on time-average, starting the controller at this moment is hoped to keep the interface within the blade passage at minimum costs. However, one question is still not clear: Does controlling the interface really help in delaying stall? In this section, we will answer this question in two ways. On one hand, we show that spike stall precursor can be brought forward by making the interface move forward purposely with circumferential inlet distortion. On the other hand, we show with our CFD how MTI acts on the unsteady tip leakage flow and alter the interface.

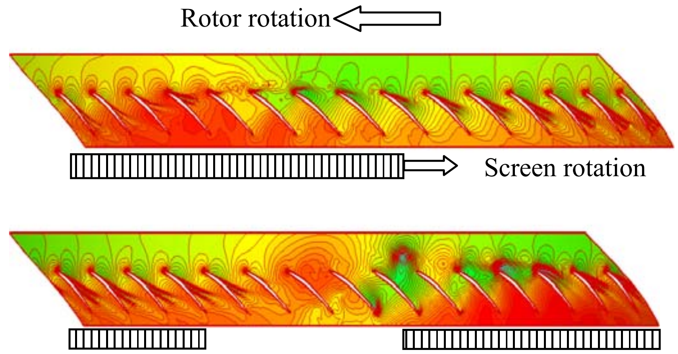


Figure 13.The snapshots of the influence of the distorted sector on the TLF/MF interface using CFD results [3-5]

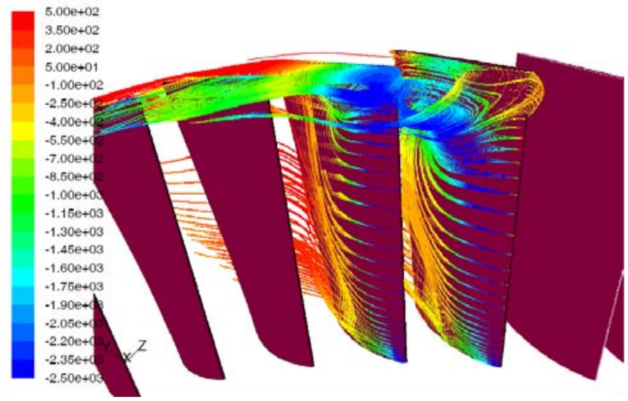
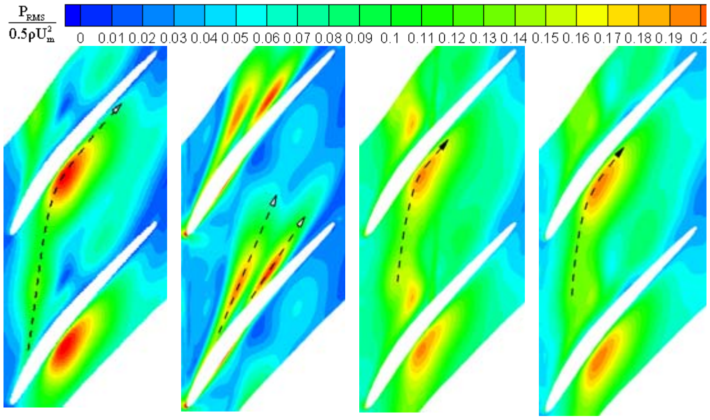


Figure 14. The snapshot of spike stall precursor ([28])

Figure 13 was two snapshots taken from a CFD simulation of the same rotor as the previous one in [3-5] subject to a rotating circumferential inlet distortion ([28]). The influence of the distorted sector on the TLF/MF interface is clearly visible. As the interface spilled forward, a vortex spun off. This vortex was actually the spike stall precursor. Later when it developed more mutually, a 3D snapshot was taken and its structure was clearly shown (see Figure 14). Although these figures are the results of CFD simulations, there were validated by experiments (See [29] in details). Moreover, the experiment showed that the tip leakage flow in the distorted sector was brought to be unsteady first before spike was initiated.

In order to demonstrate how MTI interacts with the TLF/MF interface, Geng ([16]) did a large numbers of URANS simulations to perform a parametric study. Figure 15 shows the effects of number of nozzles on the TLF/MF interface. Decreasing the number of nozzles would increase the time period between which the same blade interacted with the next jet. While keeping the same total injected flowrate, the less number of nozzles the worst the ability to push the TLF/MF interface back. Nevertheless, regardless the number of nozzles, the injected jet did help to ease the amplitude of the flow oscillation. Increasing the jet momentum can eliminate the unsteadiness completely, which is the case of the experiments done by Tong ([15, 17, 18]). Figure 16 shows an example.



Without injection | With 60 nozzles per annulus (1 per blade) | With 8 nozzles per annulus | With 4 nozzles per annulus

Figure 15 Effects of number of nozzles on the TLF/MF interface as presented with RMS contours

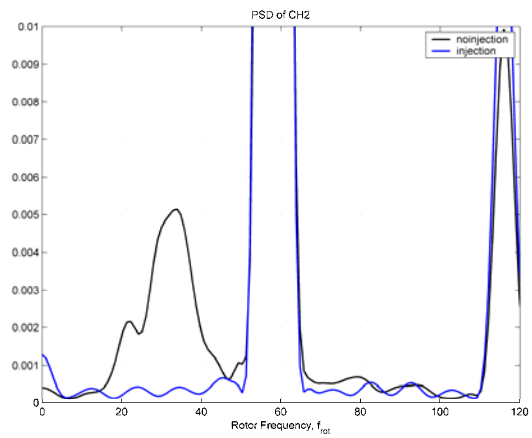


Figure 16. A comparison of power spectrum density plots with injection and without injection at Point B (taken from [15])

In case of high-speed transonic compressors, no experiment has been done yet. Computational studies were performed. However, with single passage simulations, we were able to simulate the MTI's effects on the self-induced UTLF. Figure 17 is one of the examples. Rotor 37 was the base rotor under investigation. The result showed that MTI was able to remove the self-induced unsteadiness.

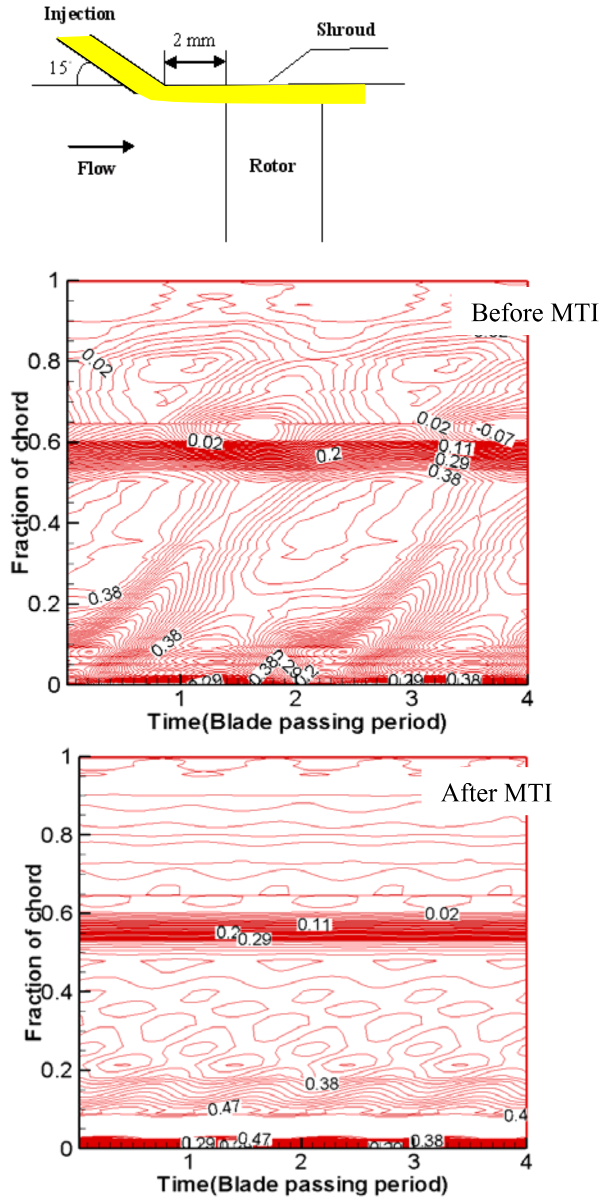


Figure 17. MTI was able to remove the self-induced unsteadiness for Rotor 37 ([16])

6. DSP IMPLEMENTATION OF MTI

Up to this point, we have shown the understanding of fundamental fluid physics associated with the unsteadiness in tip leakage flows. This first principle based understanding provides hints to uncover the mechanisms of compressor stall and some of the techniques that were developed as early stall warning and stall suppression. In particular, these techniques are the auto-correlation coefficients and micro tip injection. With some evidences, we postulate that the self-induced UTLF is the underlining physics for auto-correlation coefficient being able to act as a warning signal even before spike stall precursor emerges. With a careful study of the injected jet interacting with the self-induced UTLF, we are convinced that the MTI delays stall by pushing the TLF/MF interface back while the compressor rotor is still stable with only its tip region being unsteady. In this section, we demonstrate that by integrating these two techniques into one simple sensing-actuating system, we will be able to achieve the range extension nearly as good as continuous micro tip injection yet with only half of the injected flow rate.

Figure 18 is the block diagram of the sensing-actuator system. It is control logic is an on-off switch, so simple that we won't call it a feedback controller. The center of this system is a DSP board that takes the measured signal, computes the auto-correlation coefficients and does the statistics constantly, and finally switch the valve on or off based on the preset threshold values. Its effectiveness can be demonstrated in Figures 19 and 20. In Figure 19, the real-time casing pressure measurements before and after the injected jets are presented. The operating point is Point 6 in Figure 18, which is close to Point B in Figure 4. At this point, the self-induced UTLF exists, but it is so far away from stall limit that no spike is possibly seen at this point. The test result showed that the MTI effectively suppress the self-induced unsteadiness, just as predicted by CFD. Figure 20 depicts the action history of the tip injection system. Since the system was controlled by the detection of the self-induced unsteadiness with auto-correlation coefficients, the system turned the jet off short after it was on because it eliminated the unsteadiness. Once it is off for a while, the self-induced unsteadiness reappears and the jet has to be on again This caused the intermittent pattern of jet injection as seen in Figure 20. Compared to the continuous blowing of the jets, this simple controller saved nearly half of the jet mass flowrate. This is a great saving in terms of cost minimization.

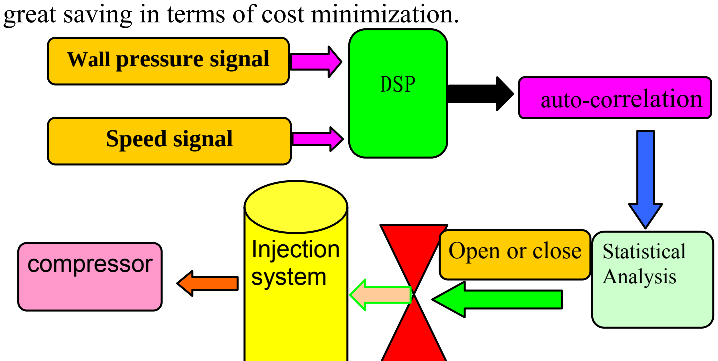


Figure 18. Flow chart of MTI with DSP implementation

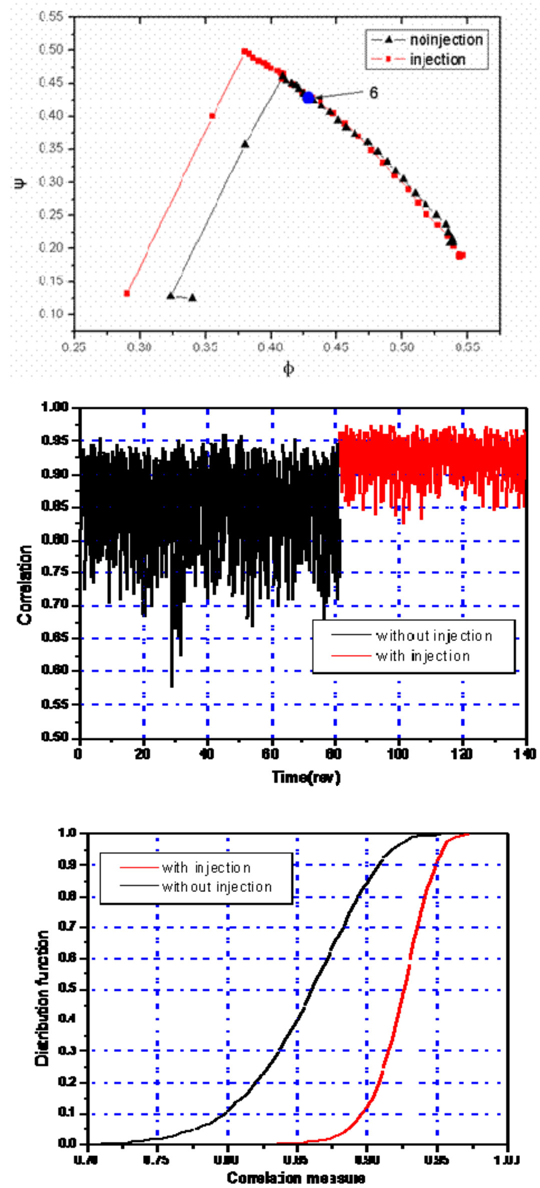


Figure 19. The effect of MTI as detected by auto-correlation method.

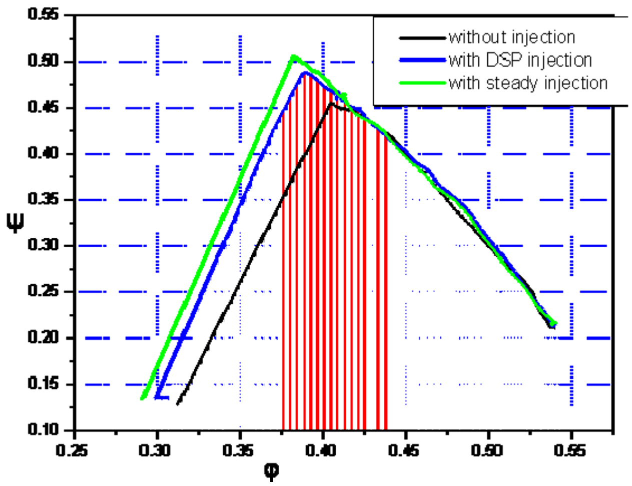


Figure 20. The intermittent pattern of micro jet injection. The straps were the moments when the jets were on.

7. CONCLUSIONS

This paper summarizes the work done by our research group in related to MTI and its mechanisms. The main conclusions are:

1. A short survey indicates that there are two different range-extension mechanisms of tip injections. For each compressor, there is a critical value of injected-jet/main-flow momentum ratio, across which the mechanisms of the jets can be fundamentally different. Our research suggested that the effects of "Micro-jets" (momentum ratio less than the critical value) are confined within the tip region. Their range extension is achieved mainly by manipulating the tip leakage flow.
2. A special kind of flow unsteadiness at tip region, the self-induced UTLF, was found in many compressors at operating points close to stall, including the "near-stall" point which is the last point before stall. The self-induced UTLF possesses two characteristics: signature frequency band and structured RMS contours, which distinguish itself from other unsteadiness in the tip region.
3. It is postulated that the self-induced UTLF is responsible to cause the auto-correlation coefficients to drop when compressors are throttled from large to low mass flow coefficients. This postulation were supported by the fact that only the data from a few selected probes can be effective when applying auto-correlation method to them, and these probes' locations coincided with the locations of large RMS values due to the self-induced unsteadiness. Another important supportive evidence is the CFD data duplicated qualitatively the wobbling casing static pressure profiles on which the auto-correlation method is based.
4. The relation between manipulating the TLF/MF interface and the initiation of spike disturbances are demonstrated. Applying inlet distortion forced the interface spilled in the distorted sector and then initiated the spike disturbance. On the other hand, applying the MTI pushed the interface back and therefore delayed the stall.
5. With all these understanding of fundamental mechanisms, a DSP-based controller is designed and applied to our laboratory compressor successfully. The new controller was able to reduce the jet flowrate by nearly half, compared to continuous MTI, yet obtained almost the same range extension.

All these work dash down a path through which the fundamental scientific research are connecting to practical applications. Although this path is far from solid and perfect, it does show some promises and potentials. More efforts are needed along the same path.

Acknowledgement

This work was both funded by the National Science Foundation of China, Grant NO. 50736007 and the National Basic Research Program of China(973 Program), Grant NO 2007CB210104.

REFERENCES

[1] Koch, C.C., and Smith, L.H., ''Experimental Evaluation of Outer Casing Blowing or Bleeding of Single Stage Axial Flow Compressor", Part IV—Performance of Blowing Insert Configuration No.1" NASA CR-54589, 1968.

[2] Greitzer, E. M., "Smart Jet Engines – Case History of a Multidisciplinary Research Program", JSME International Journal, Series B, Vol. 41, No. 1, 1998

[3] Day, I.J., "Active Suppression of Rotating Stall and Surge in Axial Compressors", Transaction of ASME, Vol.115, pp. 40-48, January 1993

[4] Weigl, H.J., Paduano, J.D., Frechette, L.G., Epstein, A.H.,Greitzer, E.M., Bright, M.M., and Strazisar, A.J., "Active Stabilization of Rotating Stall and Surge in a Transonic Single Stage Axial Compressor", ASME Journal of Turbomachinery, Vol. 120, No. 4, pp. 625-636, 1998

[5] Huu Duc Vo and Paduano .J.D., "Experimental Development of a Jet Injection Model for Rotating Stall Control", AMSE Paper 98-GT-308, 1998.

[6] Paduano, J. D., Epstein, A. H., Valavani, L., Longley, J. P., Greitzer, E. M., Guenette, G. R., "Active Control of

[7] Ffowcs Williams, J. E., Huang, X. Y., 1989, “Active Stabilization of Compressor Surge”, J. of Fluid Mechanics, Vol. 204, pp245–262
[8] Strazisar, A.J., Bright, M. M., Thorp, S., Culley, D.E.,Suder, K.L., “Compressor Stall Control Through Endwall Recirculation”, ASME Paper No. GT2004-54295, June 2004
[9] Suder, K.L., Hathaway, M.D., Thorp, S.A., Strazisar,A.J., and Bright, M.B., “Compressor Stability EnhancementUsing Discrete Tip Injection”, ASME Journal of Turbomachinery, Vol. 123, pp. 14-23, January 2001
[10] Kefalakis, M., Papailiou, K.D., “Detailed Measurement On An Axial Compressor Stage With Application Of Discrete Tip Injection For Increasing The Surge Margin”, ECT 2001, Paper 2001-044
[11] Cassina, G.; Beheshti, B.; Kammerer, A.; Abhari, R.;“Parametric Study Of Tip Injection In An Axial Flow Compressor Stage”, ASME Turbo Expo, May 14-17,2007, Montreal, GT2007-27403
[12] Sven-Jürgen Hiller,Roland Matzgeller,Wolfgang Horn, Stability Enhancement Of A Multi Stage Compressor By Air Injection, ASME Turbo Expo, 2009,GT2009-59868
[13] Nie, C., Xu, G., Cheng, X., Chen, J.Y, “Micro Air Injection and Its Unsteady Response in a Low-Speed Axial Compressor”, ASME J. Turbomachinery, Vol.124, 2002
[14] Zhang, H.W., Deng, X.Y., Lin, F., Chen, J.Y., Huang, W.G., “A Study on the Mechanism of Tip Leakage Flow Unsteadiness in An Isolated Compressor Rotor”, ASME Paper 2006-GT-91123
[15] Tong,Z.T.,Lin F., Chen J.Y., Nie C.Q., "The Self-induced Unsteady of Tip Leakage Vortex and Its Effect on Compressor Stall Inception" ASME-GT2007-277010, Proceedings of 2007 ASME Turbo Expo, Montreal, Canada,May,2007
[16] Geng S.J., Numerical Investigation on the Unsteady Response of Compressor Tip Leakage Flow to Discrete Micro Tip Injection and Its Effect on Stability Enhancement. Ph.D Dissertation, Chinese Academy of Science (In Chinese), 2007
[17] Tong,Z.T.,Lin L., Nie C.Q., Lin,B., Cui,Y.C., and Qi ,W., Online Stall Control With The Digital Singal Processing Method In An Compressor, ASME-GT2009-59059
[18] Tong,Z.T.,, The Interactive Unsteady Mechanism between Tip Leakage Vortex, Stall Inception and Micro Tip Injection in Low-Speed Axial Compressor, Ph.D Dissertation, Institute of Thermophysics, Chinese Academy of Science (In Chinese), 2006.
[19] Lin, F., Du,J.,Chen J.Y., Nie C.Q.,Christoph Biela，Flow Structures in the Tip Region for a Transonic Compressor Rotor， GT2010-23025 Glasgow, UK，2010.
[20] Vo, H.D., Tan, C.S. and Greitzer, E.M., 2008, “Criteria for spikeinitiated stall”, ASME Journal of Turbomachinery, Vol. 130(1), pp.011023
[21] N.Tahara , T.Nakajima,M.Kurosaki, Y.Ohta, E.Outa and T.Nishikawa, Active Stall Control With Practicable Stall Prediction System Using Auto-Correlation, AIAA 2001-3623.
[22] Tahara, N., Kurosaki, M., Ohta, Y., Outa, E., Nakakita, T.,and Tsurumi, Y., Early Stall Warning Technique for Axial Flow Compressor, ASME Paper No.2004-GT-53292
[23] Christensen, D., Cantin, P., Gutz, D., Szucs, P. N., Wadia,A. R., Armor, J., Dhingra, M., Neumeier, Y., Prasad, J. V.R., Development and Demonstration of a Stability Management System for Gas Turbine Engines, ASME Turbo Expo, 2006, GT2006-90324.
[24] Dhingra, M., Neumeier, Y., Prasad, J. V. R., Breeze-Stringfellow, A., Shin, H-W. and Szucs, P. N, A Stochastic Model for a Compressor Stability Measure,ASME Turbo Expo, 2006, GT2006-91182.
[25] Matthew A. Bennington, Mark H. Ross,Joshua D. Cameron, Scott C. Morris. Juan Du, Feng Lin, Jingyi Chen, An Experimental And Computational Investigation Of Tip Clearance Flow And Its Impact On Stall Inception,ASME Turbo Expo, 2010, GT2010-23516
[26] Marz, J., Hah, C., and Neise, W., “An Experimental and Numerical Investigation into the Mechanisms of Rotating Instability”, 2001, ASME Paper 2001-GT-0536
[27] Du,J.,Lin, F.,Zhang, H.W.,Chen J.Y., “Numerical Investigation on the Self-Induced Unsteadiness in Tip Leakage Flow for a Transonic Fan Rotor, Journal of Turbomachinery, APRIL 2010, Vol. 132.
[28] Lin, F., Zhang, J.X.,Chen J.Y., Nie C.Q., 2008, “Flow Structure of Short-Length-Scale Disturbance in an Axial-Flow Compressor”, AIAA Journal of Propulsion and Power, vol.24, no.6 (1301-1308).
[29] Zhang, J.X. The Unsteady Mechanism and the Role of Tip Clearance Flow in Distortion Induced Instability in an Axial Compressor, Doctoral thesis, Institute of Thermophysics, Chinese Academy of Science (In Chinese), 2007.
[30] Geng Shao-Juan, Lin Feng, Zhang Hong-Wu, Huang Wei-Guang , “Characteristics of Spike Type Rotating Stall in a Low Speed Isolated Axial Compressor Rotor”, Journal of Engineering Thermophysics, 2010,vol.31(6),pp:929-932,Chinese.