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Identification of vortices in a transonic compressor flow and the stall process

HUANG Xu-dong, CHEN Hai-xin, FU Song,

David Wisler, Aspi Wadia, G. Scott McNulty

(School of Aerospace, Tsinghua University, Beijing 100084;

GE Aircraft Engines, Mail Drop A411, One Neumann Way, Cincinnati, OH 45215, USA)

Abstract: A novel vortex identification method for the visualization of the flow field is used for the study of the stall process of a transonic compressor. The parameter η_4 , which is one of the five invariants formed by the strain rate and vorticity tensors from the theory of modern rational mechanics, is found to have good ability to identify vortex stretching and vortex relaxation/breakdown processes, is introduced here to identify the tip leakage vortices. Compare with former generally used *DPH* (dynamic pressure head) contour, the new method reveals much more flow details which may advance our understanding of the compressor behaviors. The Vortices details are revealed in both peak efficiency and near stall condition. A possible stall process is also suggested based on the vortices analysis. The tip leakage flow from mid chord, besides leading edge leakage flow, is also considered to play an important role in the stall process.

Key words: transonic compressor; stall; vortex identification; tip leakage vortex

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Introduction

Vortex is often the essential element responsible for triggering stall and surge in compressors. So the identification and the analysis of the vortices in compressor are usually quite helpful for the understanding of the compressor behavior. However, the generally used dynamic pressure head (*DPH*) contours and the streamlines are not enough for the identification of the blade tip leakage vortices (BTLV). It is often difficult to reveal the details of the BTLV only by the *DPH* contours and streamlines. Sometimes they may even lead to confusion and misunderstanding of the flow.

An early study showed that the parameter η_4 , which is one of the five invariants formed by the strain rate and vorticity tensors from the theory of modern rational mechanics, is found to

have good ability to identify vortex stretching and vortex relaxation/breakdown processes^[1]. The definition of this parameter is $\eta_4 = S_{ij} W_{ij}^2$, with the strain rate tensor $S_{ij} = 0.5(u_{i,j} + u_{j,i})$ and vorticity tensor $W_{ij} = 0.5(u_{i,j} - u_{j,i})$. On the principal axes of the strain rate tensor, it can be shown that $\eta_4 = S_{11} W_{23}^2 + S_{22} W_{31}^2 + S_{33} W_{12}^2$. Furthermore, if the vortex is dominated by W_{23} with its axis along S_{11} , as often to be the case, $\eta_4 \approx S_{11} W_{23}^2$. Thus, the vortex stretching mechanism is associated with $\eta_4 > 0$ since a positive S_{11} represents the flow acceleration. When S_{11} is negative, i.e., $\eta_4 < 0$ the vortex breakdown or relaxation occurs. However, the determination of the principal axes of the strain rates in a complex flow is tedious, η_4 is therefore a good choice because of its invariant character.

The authors' previous paper^[2] has compared the η_4 method and the *DPH* method in detail,

which proves that the η_4 method is not only valid but also resultful on the revealing of the vortex details. Based on those results, the authors will try to open out the stall process of the transonic compressor in a certain configuration in this paper.

Nomenclature

- CGCT circumferential grooves casing treatment
- BT LV blade tip leakage vortex
- DPH dynamic pressure head

1 Configuration of current study

The NASA Rotor 37^[3] is a high pressure ratio transonic compressor rotor. With comprehensive measured data and flow images, it was used as a blind test case for CFD codes in the “IGTI Gas Turbine Conference” in 1994.

The parameters for this rotor are listed in Table 1. The detailed numerical methods for this study and the code validation can be found in References [4] and [5].

Table1 Parameters of NASA Rotor 37	
Parameter	Value
Number of blades	36
Rotation speed/ (r/min)	17 188.7
Tip/ hub diameter/ m	0.507 4/0.357 6
Designed pressure ratio	2.106
Designed mass flow rate/ (kg/ s)	20.19
Tested choking mass flow rate/ (kg/ s)	20.93

2 Results and discussion

The different vortices topology at maximum efficiency condition and near stall condition will be showed in the following subsections. The discussion of the stall process will be given on the basis of the comparison.

2.1 Vortices at maximum efficiency condition

Fig. 1 shows the flow image of NASA Rotor37 at maximum efficiency condition. In each picture, the upper passage shows the *DPH* contour and velocity vector, while the lower passage shows the η_4 contour. Comparing the *DPH* con-

tour and the η_4 contour, and with the help of velocity vector we can find the basic features of the vortices at maximum efficiency condition:

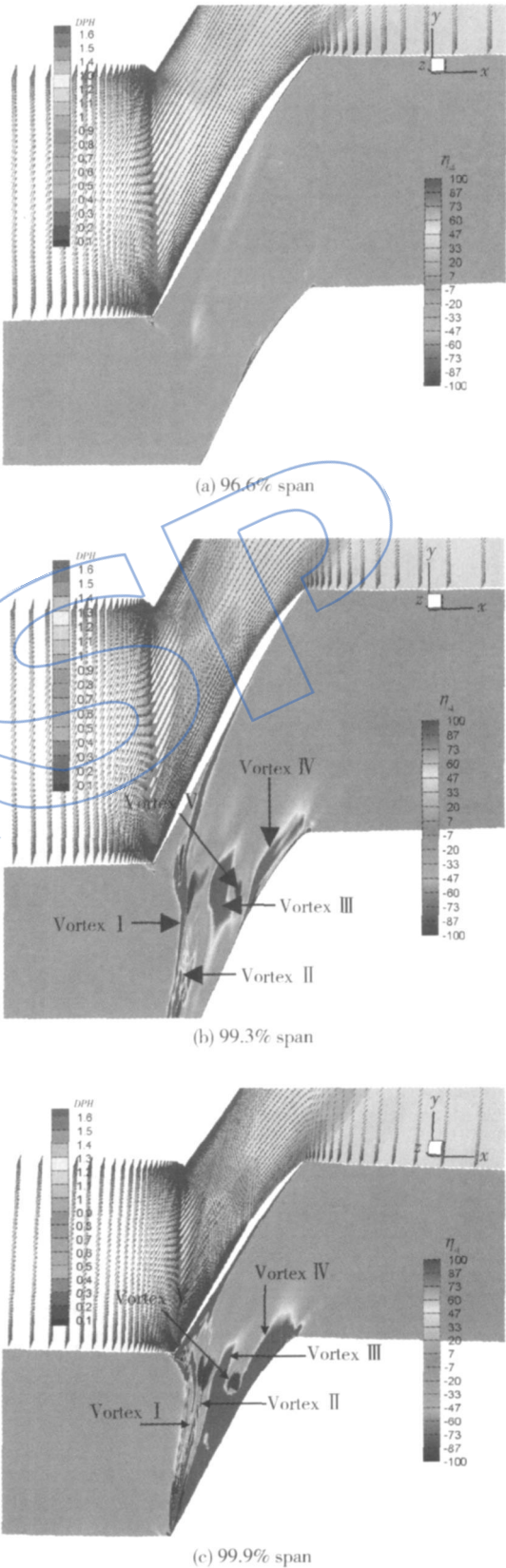


Fig. 1 Vortices at maximum efficiency condition (Top view)

First, on the converging line of the blade tip leakage flow and the main flow there is a slender vortex (designated as “Vortex I” hereafter), which will relax a little when it interact with the passage shock and then reach the pressure side of the adjacent blade.

Second, the leading edge BTLV (Vortex II) can only influence the region above 99% span, and it undergoes an obvious breakdown at the passage shock (Fig. 1 (c)). After shock it forms the large low DPH region together with Vortex I. Fig. 2 illustrates its intersection with the shock and the shape change after the shock by the iso surface of η_4 .

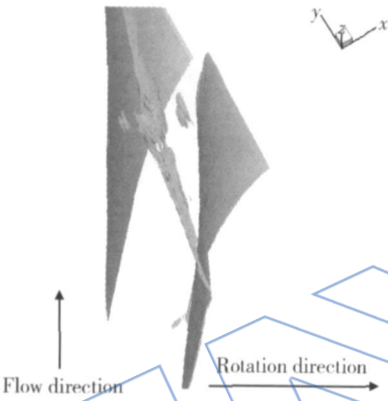


Fig. 2 Iso surface of η_4 showing BTLV (Vortex II)

Third, besides Vortex I and II, there is a large flow structure (designated as Vortex III) locates in the central of the passage above 99% span. Although from top view there is no abnormality in velocity vectors, the side view in Fig. 3 shows a sharp shear between the tip leakage flow from mid-chord and the passage main flow. This shearing structure interacts with the shock and extends to the hub direction.

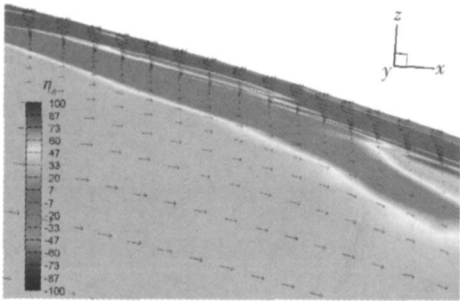


Fig. 3 Vortex III at maximum efficiency condition (Side view)

Fourth, at the blade tip, near the trailing edge of the suction side, there is a vortex formed from the interaction of the trailing edge tip leakage flow and the main flow, which is designated as Vortex IV. Between Vortex IV and Vortex III there is a small vortex relaxing region designated as Vortex V, which may come from the induced local separation.

Finally, we can draw a glancing conclusion of those vortices' influence region, showing in Fig. 4.

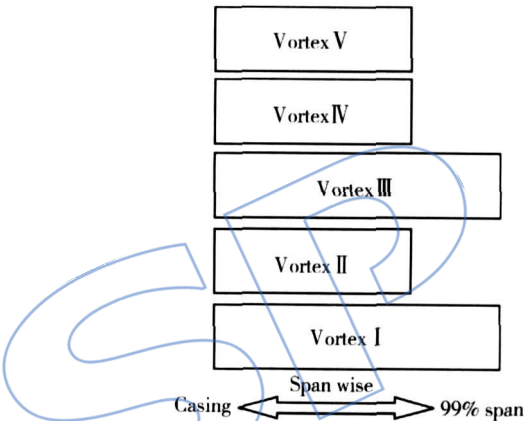


Fig. 4 Relative location in spanwise of vortices at maximum efficient condition

2.2 Vortices at near stall condition

At near stall condition, the topology of vortices change a lot. Fig. 5 shows some cross sections near the tip region. The vortices features can be concluded as below:

First, different from the maximum efficiency condition, the influence region of Vortex III is quite remarkable. It can affect a region deep to 85% span (Fig. 5 (a)) and wide to nearly half the passage at the near tip region (Fig. 5 (c), (d)). It locates nearer to the blade suction side and is the key reason for the large low DPH region at the blade trailing edge.

Second, the leading edge vortex, i. e. Vortex II can affect a region upon 98% span, which is a little larger than the maximum efficiency condition. It becomes much looser and breaks down at the intersection with passage shock (Fig. 5 (c), Fig. 6). Great attention should be paid that after the breakdowned Vortex II there is a new structure forms and designated as Vor-

tex VI in this paper. From the velocity vectors in Fig. 7 we can see that Vortex VI comes from the interaction of the fragment of Vortex II and the main flow, which jostles forward between Vortex II and III. Vortex VI is the actually direct reason for the low DPH region in the center of the blade passage.

Third, Vortex I at near stall condition doesn't change much. Only its influence region becomes a little larger to about 96% span. It also contributes part of the passage low DPH region like at the maximum efficiency condition. Vortex IV and V are almost the same as the maximum efficiency condition, and they bring on the low DPH region near the blade trailing edge together with Vortex III. From Fig. 8 we can see clearly about the flow separation at Vortex V.

Fourth, in front of the blade leading edge, at the tip region there is an obvious “spill forward region” designated as Vortex VII in this paper (Fig. 5 (d), Fig. 9). This phenomenon has been considered as the triggering of compressor stall by Hah etc.^[6] in their study on Rotor 8. However in this study we find that the spill forward region is only limited at the tip region, i.e. upon 99% span, so although the existing of this region can greatly enlarge the local relative instance angle, it doesn't make too much change to the entire flow field.

Finally, we can give the global view of the Vortices at near stall condition in Fig. 10, from which the whole topology of Vortex I, II, III and VI can be distinguished, while Vortex IV and V are not very clear as they immersed in Vortex III, and Vortex VII is too far away to be seen in this picture. Fig. 11 shows the relative location in spanwise of those vortices at near stall condition.

2.3 Stall process

From the comparison of the different vortices topology between maximum efficiency condition and near stall condition, we can imagine the process of stall at this configuration. With the increase of the back pressure, the passage shock

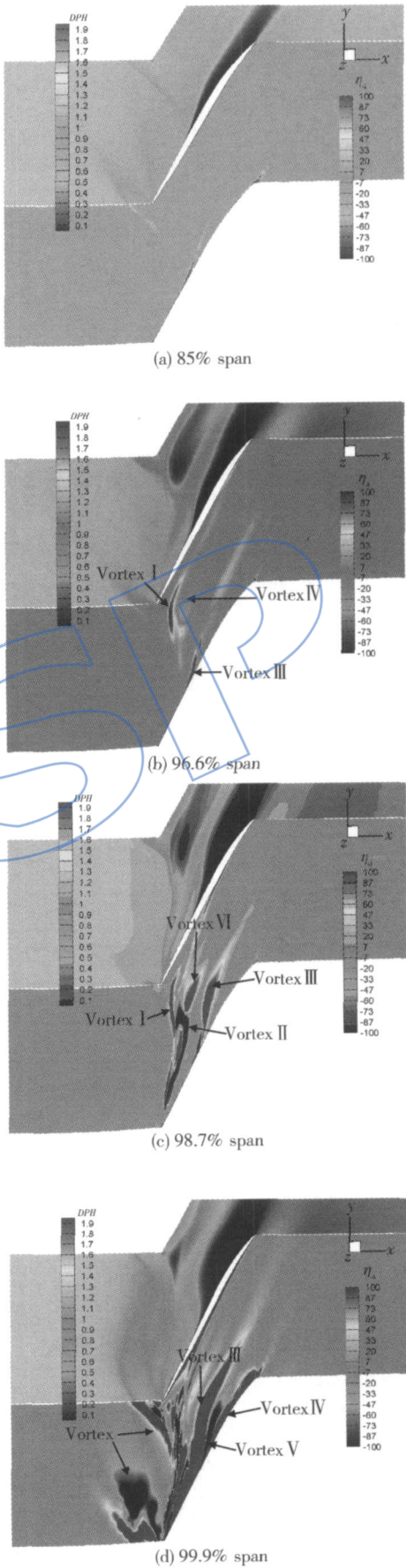


Fig. 5 Vortices at near stall condition (Top view)

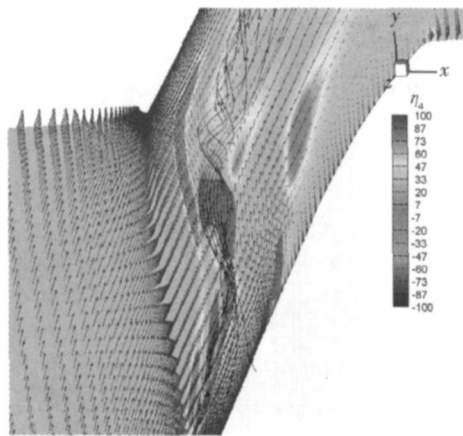


Fig. 6 Breakdown of the leading edge BTLV

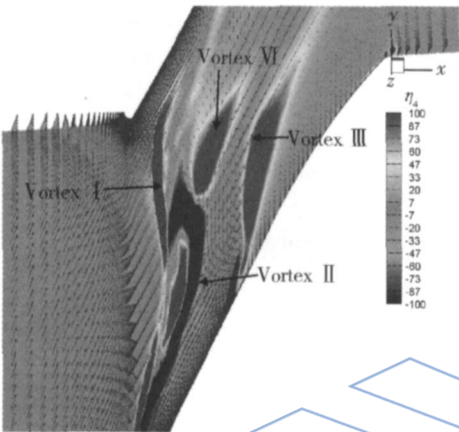


Fig. 7 Velocity vector at 98.7% span

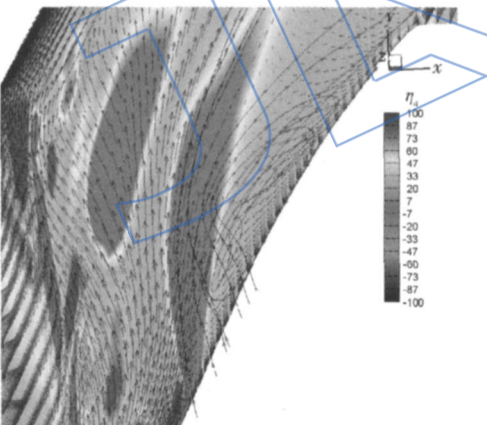


Fig. 8 Vortices at the trailing edge of the blade

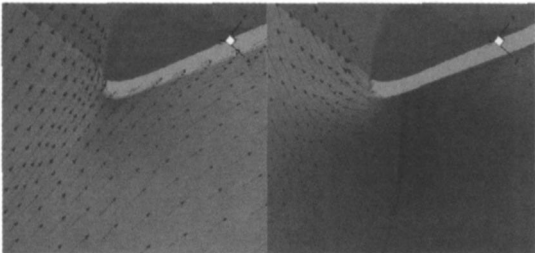


Fig. 9 Spill forward region at the leading edge at near stall condition (Top view)

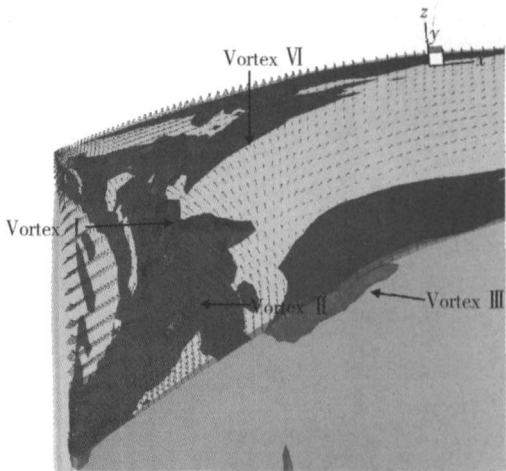


Fig. 10 Vortices at near stall condition(is σ surface of η_4)

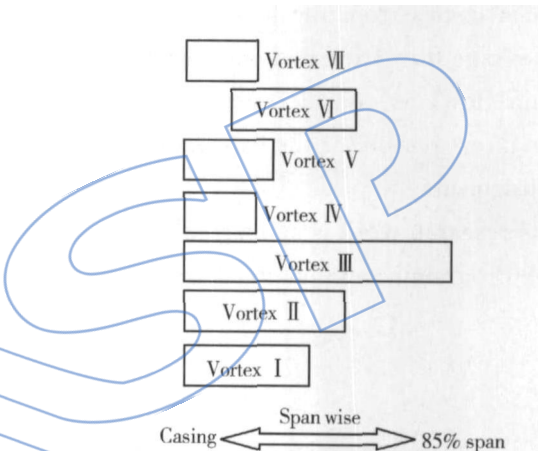


Fig. 11 Relative location in spanwise of vortices at near stall condition

moves upstream and becomes stronger; meanwhile the mass flow rate decreases. Those changes make the leading edge BTLV (Vortex II) become looser and weaker, and undergo a breakdown when it interacts with the shock. The expand of the Vortex II jostles Vortex III to the blade suction side, which makes the latter induce the large separation (Vortex V) at the blade trailing edge. The spill forward region (Vortex VII), as explained before, is considered to be only a flow phenomenon at the near stall condition but not the reason for the stall. So the two large low DPH regions (Fig. 5 (c), (d)) seem to be responsible for the triggering of the stall. It is difficult to say which one is more fatal now. But as Vortex III affects much larger region, it is more probable to be the key factor. When the back pressure increases further, those

two low DPH regions will block the flow passage and trigger the compressor stall.

3 Conclusions

With the help of a novel vortex identification method, the detailed vortices structures and topology in a transonic compressor have been revealed. The study distinguishes different vortices structures in the compressor, as well as their development at different operating condition. From comparison of the vortices in maximum efficiency condition and near stall condition, a possible stall process has been revealed and the vortex, which comes from the interaction between the tip leakage flow from mid chord and the passage main flow, is considered to be the most probable direct reason for the happening of stall.

Acknowledgments

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