AN EXPERIMENTAL STUDY ON THE MECHANISM OF INTERACTION BETWEEN SPANWISE BLOWING AND LEADING-EDGE VORTEX*

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Abstract

In this paper a new interaction mechanism between spanwise jet and leading-edge vortex is suggested based on the analysis of the experimental results obtained in 0.36- by 0.6-m low speed wind tunnel of Nanjing University of Aeronautics and Astronautics using a 60° delta wing with sharp leading edge at an angle of attack of 24°. The smoke technique was used to visualize the vortex core, and two-component Laser Doppler Velocimeter was used to examine the influence of the jet on the leading-edge vortex structure.The three velocity components were measured in two successive test runs. Velocity survey in the leading-edge vortex region showed that the spanwise jet alone produces a pair of additional leading-edge vortices over the delta wing with high swept and sharp leading edge of the delta wing. Together with incoming flow the entrainment of jet could be considered as introducing an velocity to the freestream, consequently, we have an increase in axial velocity but also the vorticity of the leading-edge vortex. It is concluded that the effect of SWB on the leading-edge vortex is primarily caused by the jet entrainment, rather than by the mixing. On the base of this mechanism the optimum jet position should be kept at a distance from the wing apex and leading-edge.

Nomenclature

Cr	wing root chord
C_μ	jet momentum coefficient
G	jet weight flow rate
h	distance of LDV sample volume above wing surface
Re	Reynolds number
U_∞	freestream velocity
U	velocity component parallel to freestream velocity in the vortex core(also referred as axial velocity)
V	velocity component normal to freestream velocity in the vortex core
W	spanwise velocity component in the vortex core
X	freestream direction
Y	derection normal to the freestream
Z	spanwise direction
α	angle of attack

Introduction

At moderate to high angles of attack, the flow over wings with highly swept, sharp leading deges is dominated by large vortex structures, formed from the flow separation at the leading edge. The high vortex lift increments and vortex breakdown phenomenon depending on the particular angles of attack and geometrical configuration have been studied for many years[1-5].

Recently, the designers of modern and next generation advanced fighters have exhibited an unprecedented level of interest in maneuverability, supersonic cruise, short take-off and landing performances, specially in supermaneuverability or post stall maneuverability, which demands significant improvements in aerodynamis characteristics at high angles of attack . In other words, the

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high perforamance aircrafts are expected to operate routinely at angles of attack at which vortex breakdown over the present wings uaually occurs,moreover an asymmetry in the flow separation over the forebody is observed. Breakdown of the vorticies over wings causes great deterioration in aerodynamic performance. So many attempts of vortex control and vortex breakdown delay have been made by aerodymics researchers[6–8].

The spanwise blowing (SWB) concept has been studied for almost three decades, and numerous results were obtained,which showed that it is an effective aerodynamics measure for enhancing the strength of the wing leading-edge vortex and delaying the vorex breakdown to higher angles of attack.Subsequently, the extra vortex lift and high lift drag ratio could be obtained. However the mechanism of interaction between SWB and leading-edge vortex requires further clarification.

The idea of some researchers focused on blowing as nearer the center of the core as possible to increase the axial velocity[9], but other investigation has shown that it was not optimal arrangement. Campbell[10] discovered that the greatest benefit obtained from spanwise jet occurs in the region near the origin of the vortex flow rather than in the vortex core. T.T.Ng, et.al[11] revealed that the optimal jet nozzle position is not at the vortex core and suggested its location should not be too far downstream, since then there was no sufficient time for mixing. They suggested that a small distance of nozzle downstream from the apex is needed, where the mixing and entrainment are more effective. However, due to the lack of data of the vorticity flow field the machanism is still not well explained. Qin and Shen[12] found that the optimal position of nozzle should be at the conjunction with fuselage,and at a distance from the wing apex,such as 30 % – 50 % Cr,to keep the jet not to across the core of vortex.

In order to find the optimal nozzle position, it is neccessary to explore the mechanism of effect of SWB on the vortex structure. An experimental investigation has been conducted for a 60° delta wing with sharp leading-edge using smoke flow visualization and LDV technique.

Experimantal Technique

All the experimental results presented in the paper were obtained in 0.36- by 0.6m low speed wind tunnel of NUAA (Nanjing University of Aeronautics and Astronautics) on a delta wing at angle of attack of 24°, coresponding to Reynolds number of 6.6×10^4. The nozzle was placed at 0.30 Cr and aligned perellel to the leading edge, and the jet momentum coefficient C_μ was kept constant during the tests.

Three types of flow field round the wing, including incoming flow alone, spanwise blowing alone, and incoming flow with spanwise blowing were visualized and measured respectively.

The vortex core was visualized with a dense white smoke and recorded by a still photography.

The two component LDV sample volume is moved throughout the flow field by a manual-controlled, three-axis traversing system.A frequency shifting system was used, hence the velocity in opposite directions can be distinguished. A nonuniform survey grid (Fig.1)was used for measured planes. One plane was taken near the jet exit, the other one near the vortex breakdown region without blowing, the third along the vortex core axis approximately. Three components of velocity were obtained in separated two test runs, of which one was measured with the model installed normally in the wind tunnel, the other with the model turned 90 degree around the wind axis (see Fig.2).

Results and Discussion

Structure and Breakdown of Leading-Edge Vortex

In view of the previous researches the leading-edge vortex over a wing would be stable if the flow separate from leading-edge to roll up forming a free vorticity and spanwise component of freestream velocity reaches a certain value. On the high swept and thin wing with sharp leading-edge the flow meets these two requirements and a pair of stable vortex over the wing exists at certain angles of attack.

It is found that the natural characteristics, primarily the axial velocity in the vortex core plays a critical role on stability of leading-edge vortex. When the axial velocity in the core is increased at the same circumferential velocity value the vortex breakdown point will be delayed, i.e. the vortex stability is enhanced.Fig.3(a) and (b) present axial velocity distribution at two transverse sections respectively. It is seen that the distribution of axial velocity at section 1 shows a distinct peak near leading-edge and close to the wing surface, while at section 2 the peak of velocity distribution collapses showing vortex burst occured. It is also noted that the region of minimum velocity is farther from leading-edge than that of velocity at section 1, which indicates the leading edge vortex core track moves inboard and upward over the wing when the vortex grows downstream. To understand streamwise variation of vortex core structure more clearly, the axial velocity distribution in the longitudinal plane was measured at some special positions and ploted in Fig.4 as a normalized average of axial velocity based on the freestream velocity versus a distance from the wing surface. It can be seen at the apex of wing the normalized velocity equals one approximately, showing the leading-edge vortex has not formed yet. Along the vortex axis the axial velocity increases rapidly downstream up to 1.6 times of freestream velocity at 10%Cr, and then increases slowly up to its maximum value, $2.3U_\infty$ at 31%Cr. And after that the axial velocity begins to decrease, but its profile still is of jet-like (see the results at x/Cr=0.4. As seen above, in the fully developed region of leading-edge vortex, the pattern of axial velocity distribution is of jet- like which is an inherence property of stable leading-edge vortex. Further downstream the axial velocity decreases rapidly and its distribution changes from jet-like to wake-like at 0.44 Cr, and finally decreases down to zero marked the vortex breakdown at 0.466 Cr , where the same phenomenon could also be seen in flow visualization. Further downstream the avarage axial velocity tends to recover to positive level.It is believed that the turbulent flow exists in the breakdown region instead of the concerntrated vortex flow. From some amplitude probability density functions it can be seen that the transient reverse flow in the core always exists and most of flow particles with reverse velocity occur near the center of vortex core rather than at the edge of vortex core.

As the measurement position comes closer to the breakdown region,the larger the instantaneous reverse velocity is and more frequently it appears. It suggests that the flow particles in the vortex core center are spiralling outward , consequently, the flow particles of downstream move towards upstream under the adverse pressure gradient, forming the transient reverse flow. As a result, the average axial velocity of vortex is decreased gradually till zero, and vortex breakdown accompanies with it finally.

In the case mentioned above, the inner core in the stable vortex rotates like a solid body and the radial distribution of circumferential velocity is almost linear at transverse section (see Fig.5), but in the outer core the radial gradient of velocity is decreased, and the velocity distribution is just like a potential flow type.

The normal and spanwise velocity component data at two sections have been used to calculate axial vorticity distribution, which are plotted in contour form in Fig.6 at flow condition without jet. In Fig.6(a) , the vorticity is highest within the vortex core region at section 1, meaning there is a fully developed vortex being consistent with the results of axial velocity distribution there. The negative vorticity near the wing leading-edge shows the existence of the secondary vortex. When Bursting of the vortex occurs abruptly the higher vorticity value in the core disapears, and the vorticity spreads throughout the entire vortex region (see Fig.6(b)).

Spanwise Jet over the Wing

It is well known that the flow field induced by a free circular jet is axisymmetrical and a jet over a infinite wall, referred as the wall jet, induces a flow field with higher axial velocity near the wall[13], while the spanwise jet over a wing induces a flow field quite different from that induced by either the free jet or the wall jet due to the leading-edge of wing, in which it not only induces a velocity along the jet axis over the wing, but also a flow around the leading-edge and if the leading-edge is sharp the induced flow would separate from the leading-edge. Consequently, the spanwise blowing over a wing provides two conditions for forming a stable concentrated vortex. The present investigation verify the concept put forward by authors, and the related test results are discussed below.

The photoes in the Fig.7 give the flow picture around the delta wing with spanwise jet alone using smoke technique. It can be seen that a small vortex with its origin at the apex of wing is formed near the leading edge, which can be considered as the result of the entrainment effects of the jet. The characteristics of the jet induced-vortex are similar to the natural leading-edge vortex over wing with high sweptback,sharp leading-edge at some angles of attack with incoming flow. It can also be seen that the jet induced-vortex is kept some distance from the spanwise jet initially without mixing between them, and then encounters with the jet downstream and vanishes finally.

It is concerned where is the optimal chordwise position of jet such that it induces a stronger leading-edge vortex with the same jet momentum. Fig. 8 illustrates the variation of flow pattern over the wing with jet at different chordwise position. It is obvious that the jet which is near the apex of wing, induces a vortex within a small region. This is because the vortex encounters the strong jet and is destroyed immediately by the jet , while the jet at downstream induces a weaker vortex due to the weaker inducing effects on the flow around the leading-edge near apex of wing. Accordingly, an optimal chordwise position of jet could be expected.

Fig. 9(a) and (b) indicate the axial velocity distribution with jet alone at two transverse sections respectively. At section 1, the axial velocity distribution could be divided into two regions with distinct boundary, the high speed region near the root chord having the character of jet, and the rest part of low speed region which is induced by jet. No obvious high axial velocity peak could be found near the leading-edge. But it is seen in Fig.10 that the existence of vortex could be verified by the velocity vector, which is consistent with the photo in Fig.7. At section 2 the boundary of jet becomes vague which means the jet has already expanded and covered the wing leading-edge, and no trace of vortex could be detected.

So, it seems certain that if the jet is located too close to the leading-edge, the jet with strong velocity during its expansion process would result a detrimental condition to separated flow to roll up around the leading-edge.

The Effects of SWB on the Leading -Edge Vortex and Its Mechanism

The axial velocity distribution of vortex at both of two sections obtained in the case of incoming flow with spanwise jet are shown in Fig.11(a) and (b), respectively. It is obvious that at section 1 the velocity peak, in comparison with the results without spanwise blowing, has higher value and is of great fullness, in which the flow can overcome larger adverse pressure gradient and therefore the vortex breakdown would take place at farther downstream position. It can also be seen that the velocity peak position moves closer to the wing surface and leading-edge. At section 2 the sink-like velocity distribution with incomeing flow alone shown in Fig.3(b) vanishes due to spanwise jet, instead a high velocity region spreads over a large area appears. Obviously, in the case of incoming flow with spanwise blowing the axial velocity is not only the sum of velocity induced by incoming flow and spanwise jet, but also contains the favourable interference between them , including the mixing effects to some extent.

Fig.12 indicates the axial velocity distribution at different positions along the vortex core with spanwise jet. It is seen that at all the positions, except the apex, the velocity distributions are all of jet-like and the magnitude is increased obviously, furthermore the maximum velocity is up to 2.70 U_∞, much larger then one without blowing, which means the leading-edge vortex is more stable,the breakdown point is moved farther downstream.

It can be seen in Fig.13(a) and (b) that the vorticity is increased obviously by the spanwise jet compared with the case of without blowing at both sections, especially at section 1.And it also can be seen that the jet changes the initial flow field around the wing and forms a pair of much stronger leading-edge vortex.

It is importent here that the increment of vorticity is not well matched with the increment of axial velocity at section 2. These results verify again that strength of vortex is marked by the vorticity rather than the axial velocity. So, the criteria for the determination of the optimal jet position is to provide possible maximum axial velocity in the vortex core and at the same time the maximum possible concentrated vorticity over the wing surface.

Conclusion

The flow visualization and LDV technique were used to reveal the mechanism of using SWB to increase the strength of leading-edge vortex and delay the vortex breakdown point to farther downstream at given angle of attack. The spanwise jet could act on the global field around the wing by its entrainment effect rather than the direct mixing effect, changing the initial conditions of the formation of leading edge vortex, hence larger axial component of velocity and vorticity may be obtained. Accordingly, the nozzle should be located at a distance away from the apex or leading-edge of the wing to avoid early strong concentrated jet encounter with the leading-edge vortex ,thus hindering the vortex sheet to roll up.

Based on the present investigations we might draw the following conclusion: the optimal blowing position appears to correspond to where the entrainment of the jet is most efficient to the flowfield around the wing.

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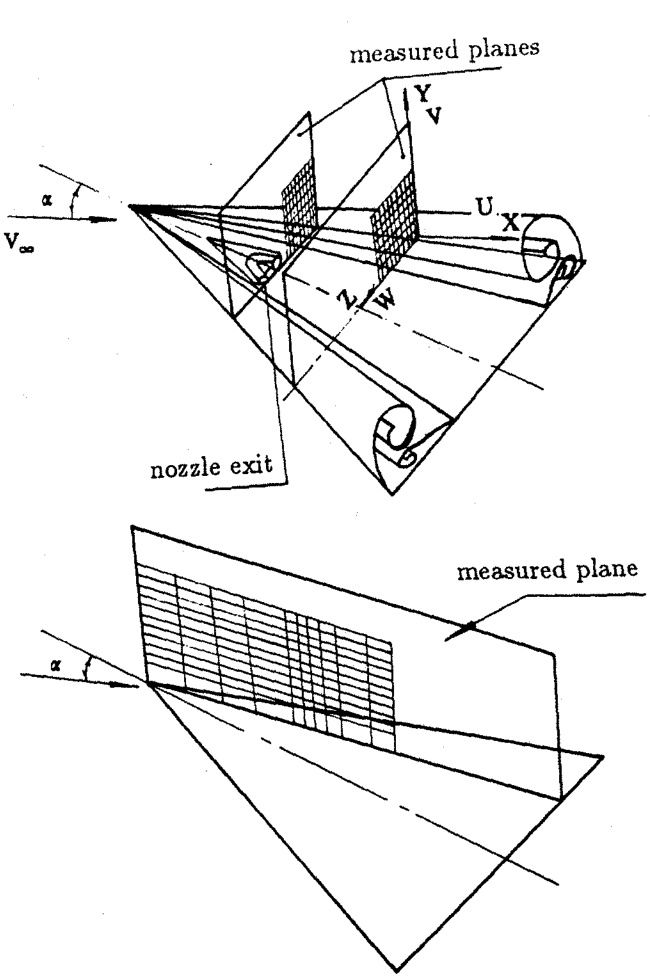


Fig.1 Schematic of LDV measured planes

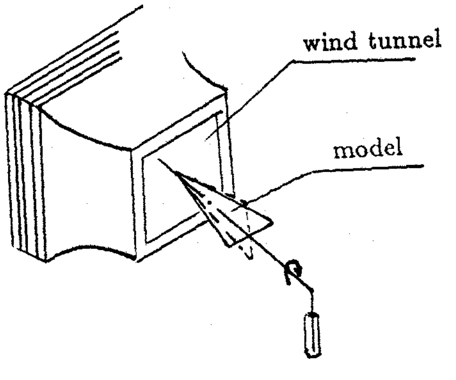
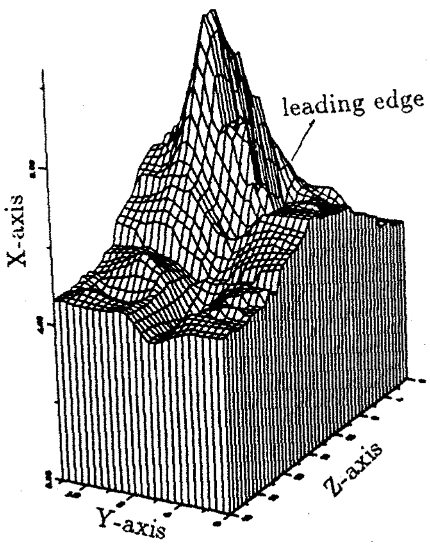
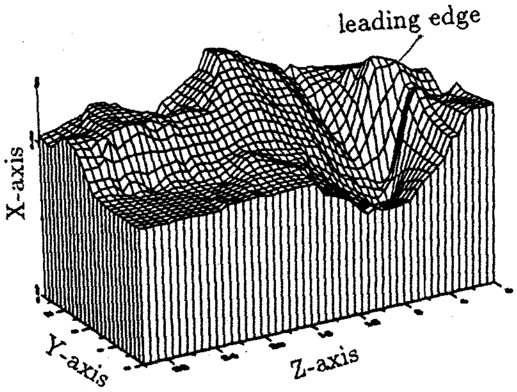


Fig.2 Model installation in wind tunnel



(a) X/Cr=0.31



(b) X/Cr=0.45

Fig.3 Axial velocity distribution at transverse sections

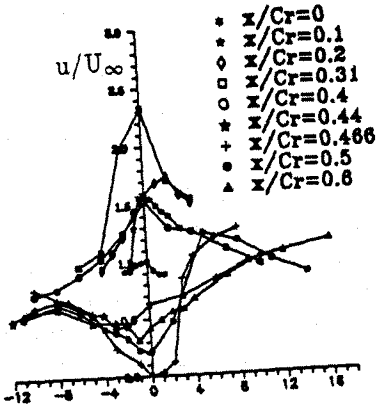


Fig.4 velocity distribution along vortex core axis

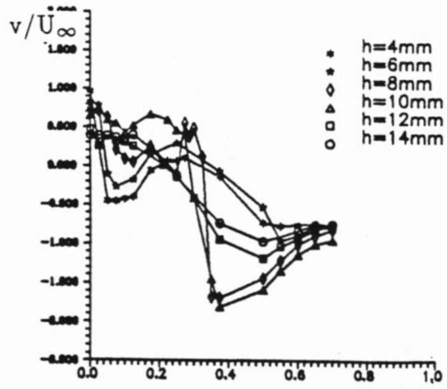
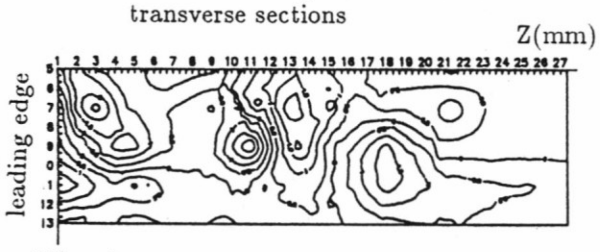


Fig.5 Normal velocity distribution at transverse sections



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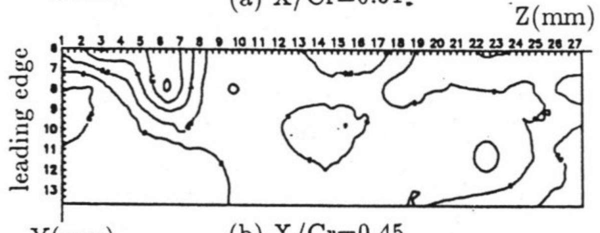


(b) X/Cr=0.45

Fig.6 Vorticity contours at transverse sections

(a)

(b)

Fig.7 Jet alone induced leading-edge vortex

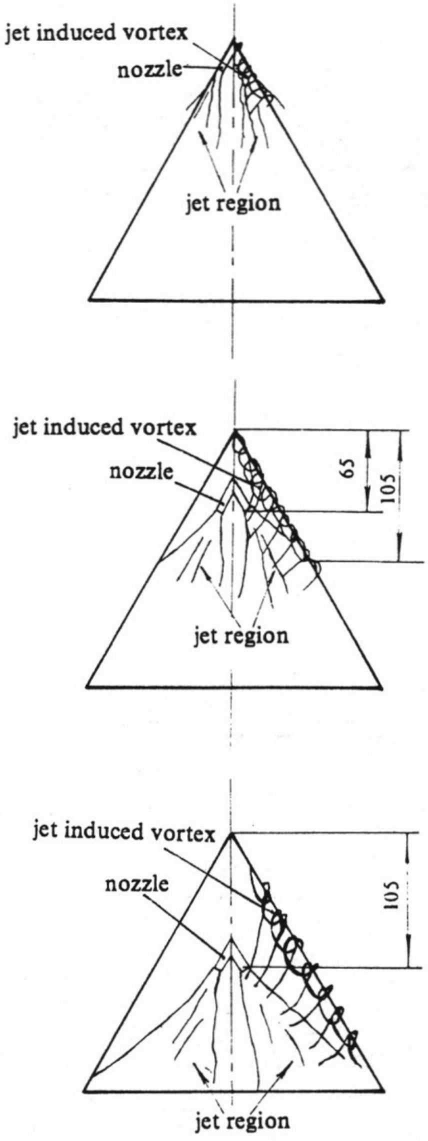
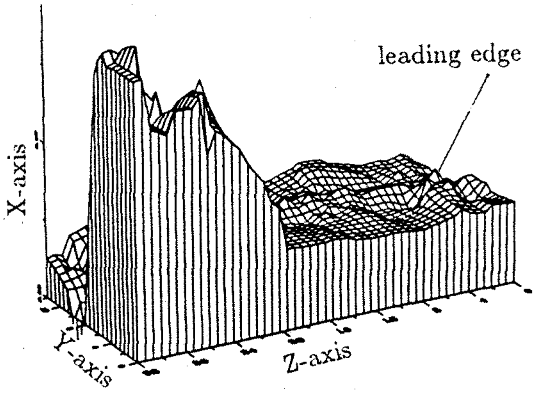


Fig.8 Effect of nozzle position on leading-edge vortex forming



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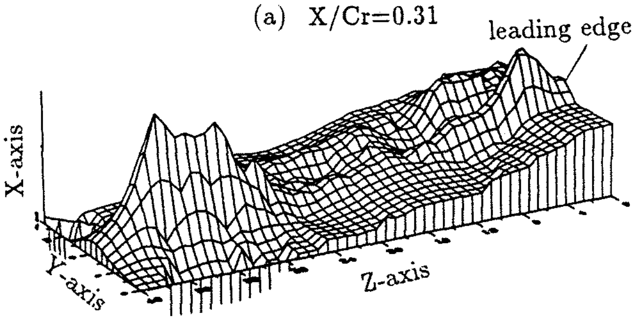
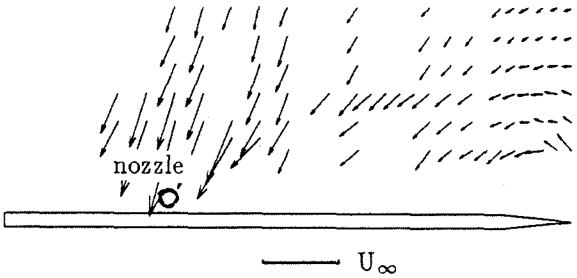


(b) X/Cr=0.45

Fig.9 Axial velocity distribution at transverse sections



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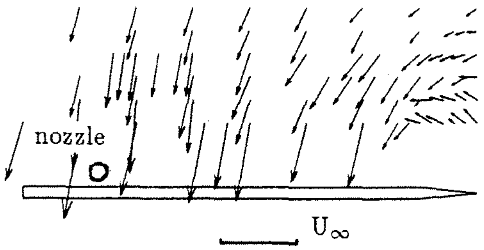
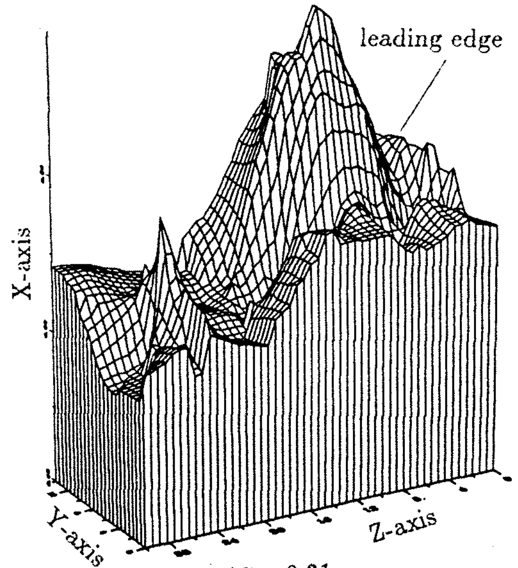


(b) X/Cr=0.45

Fig.10 Velocity vector at transverse sections



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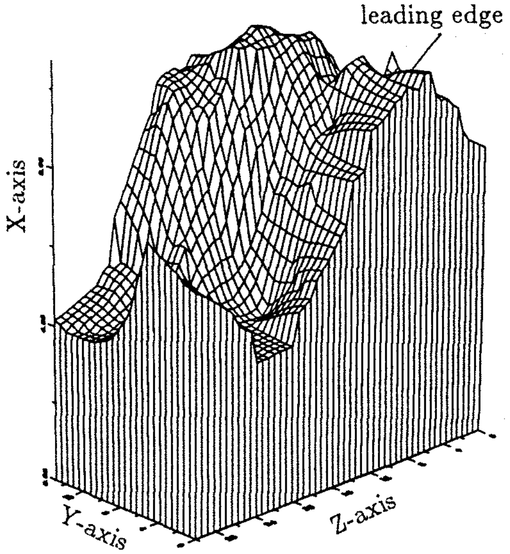

(b) X/Cr=0.45

Fig.11 Axial velocity distribution at transverse sections

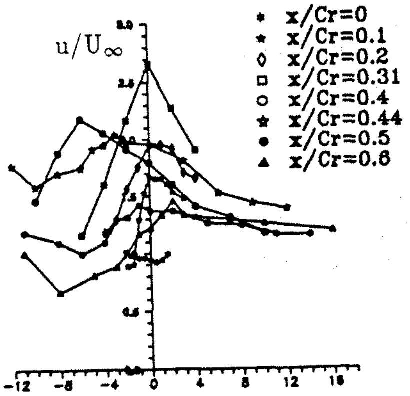

Fig.12 Velocity distribution along vortex core axis

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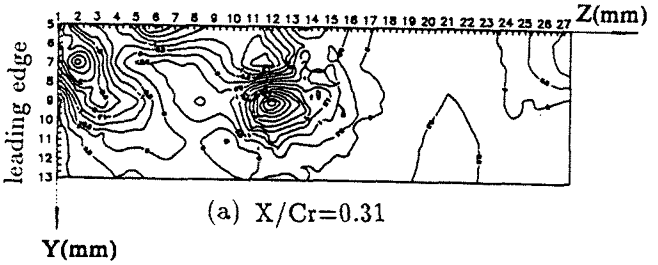

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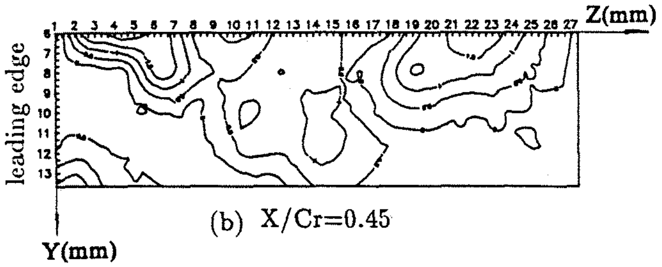

(b) X/Cr=0.45

Fig.13 Vorticity contours at transverse sections