THE WAYS OF THE FORMATION OF THE HORSESHOE VORTEX IN TURBULENT BOUNDARY LAYERS

K. W. Li
Department of Mechanics
Peking University
Beijing 100871, P.R. of China

Abstract

Detailed experimental observation and measurement were performed for the horseshoe vortex in turbulent boundary layer (TBL) through using a new method of flow visualization---moving laser light sheet and several experimental skills. It was discovered and discribed that the horseshoe vortices form in four ways---secondary instability, combination, deformation and burst. The formation and development of these horseshoe vortices were studied and compared. The test results show that these horseshoe vortices are different from each other in size, moving velosity and deformation.

I. Introduction

With more and more deeping of research, understand and application on TBL[1,2], some coherent structures had been found. Kline et al.[3] discovered the bursting phenomenon and low-speed streak in the 1960s. Blackwelder et al.[4] observed the counter-rotating streamwise vortices together with the resulting low-speed streak in the near wall of TBL and studied its relation with coherent structures such as the burst et al. in the 1970s. Cantwell[5] and Hussain[6] summerized the past research on the coherent structure of TBL. These results showed that many coherent structures and phenomena in TBL are closely connected with horseshoe vortex, and implyed that the study for horseshoe vortex is more important.

But, so far, the formation and development of horseshoe vortex is also an unclear problem, which caused the less guide for doing many experiments such as drag reduction and boundary-layer control as well as improbable compare of results of theory and computation with test in the aspect. As everyone knows, the complication, unsteady, random of TBL and the defect, imperfection of experimental method and skill make it difficult to do the research for horseshoe vortex. Head and Bandyopadhyay[7] ever made the observation and research for the horseshoe vortex in TBL and proved its existence by using the method of smoke line-laser light sheet. But the method leads the smoke line near wall to be too fuzzy to be studied. For avoiding the disorder background in TBL, researchers usually made artificial horseshoe vortex in laminar boundary layer (LBL) to study horseshoe vortex. Matzler (1980) first obtained the artificial horseshoe vortex in LBL, using a half-ball set on the wall. Afterwards several other methods to generate horseshoe vortex in LBL were used. For example, Acarlar[8] and Smith used half-ball and steady jet on the wall and Liu Tianshu et al.[9] used the wire heated by paused electric current, in LBL, to generate horseshoe vortex. These methods gave many helps and ideas in researching for horseshoe vortex.

But the artificial horseshoe vortex in LBL is, after all, different from the real horseshoe vortex in TBL. First, the former is sequential and the latter is random; Secondly, perhaps they are different in the ways and mechanisms of their formation; Thirdly, the enviroments that influence their formation, development and vanish are not same. These differences directly affect our knowledge of the real horseshoe vortex in TBL. Therefore, the best method to study horseshoe vortex is to observe and measure straight to it in TBL. With the limits in experimental technique, the investigation of horseshoe vortex is confined, partial and slow. If three-dimensional observation can be given for the formation and development of a horseshoe vortex, the investigation on it will make great progress.

This study were made in the water channel of the Beijing University of Aeronautics and Astronautics (BUAA) to serve the purpose of the observation under a comparatively clear background and low speed while the Reynolds number remains high. A new method of three-dimensional flow visualization were used to view the horseshoe vortex in TBL.

II. Experimental Facilities, Conditions and Techniques

The experiments were carried out in a recirculating water channel with an open-surfaced test section of length 686cm, width 40cm and depth 40cm in which the free-stream turbulence intensity was below 3%. A pulsing voltage at regular time intervals impressed on a platinum wire of 25 μm in diameter was given to produce hydrogen-bubble lines (time lines). The behavior of the vortices in the near-wall region of TBL were made visible by hydrogen-bubble technique through the laser light sheet or illuminating light, photographed by a camera typed Aero.3. At the platinum wire, the velocity of fluid was adjustable from 3.8cm/s to 8.6cm/s, and the Reynolds number based on the boundary-layer thickness δ was about 1800-2200.

Fig.1 is the device to produce moving laser light sheet with adjustable velocity and three moving ways---uniform motion, accelerated motion and decelerated motion. The device is easy to move here and there and give any directional laser light sheet for visualizing any part of the flow. Fig.2 is an experimental arrangement. In fig.1 and fig.2: (1)water-channel sidewall made of plexiglas; (2) a trip wire of 15mm in diameter; (3) platinum wire parallel to sidewall; (4) laser light sheet; (5) camera; (6) illuminating light; (7) laser with 25 mw; (8) air cushion chute; (9) slide block; (10) air pump; (11)reflector; (12) focusing glass; (13) rod to spread laser beam. When the laser light sheet is caused to move from upstream to downstream or on the contrary in flow direction by the moving of the slide block, the photographs at different flow position (or x-position) can be taken.

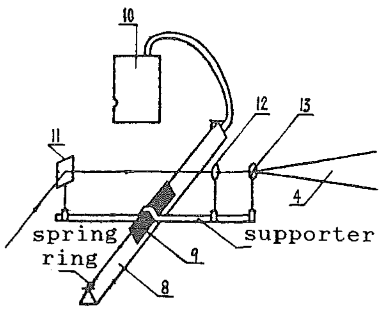


Figure 1. Device for Moving Laser Sheet

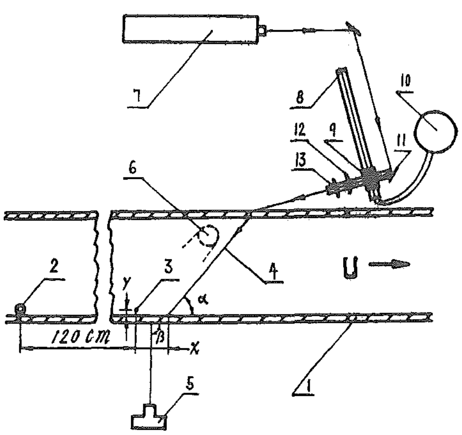


Figure 2. Experimental Arrangement. (If No Illustration Is Given, α=45°, β=90°)

III. Experimental Results and Discussion

Formation and Development of Secondary-Instability Horseshoe Vortex

Formation The most horseshoe vortices in TBL form in this way. It's due to the secondary instability of the vortex. The process of the formation can be described as shown in fig.3: When a streamwise vortex Γ_2 appears (or forms) near the streamwise vortex Γ_1 , they induce and get

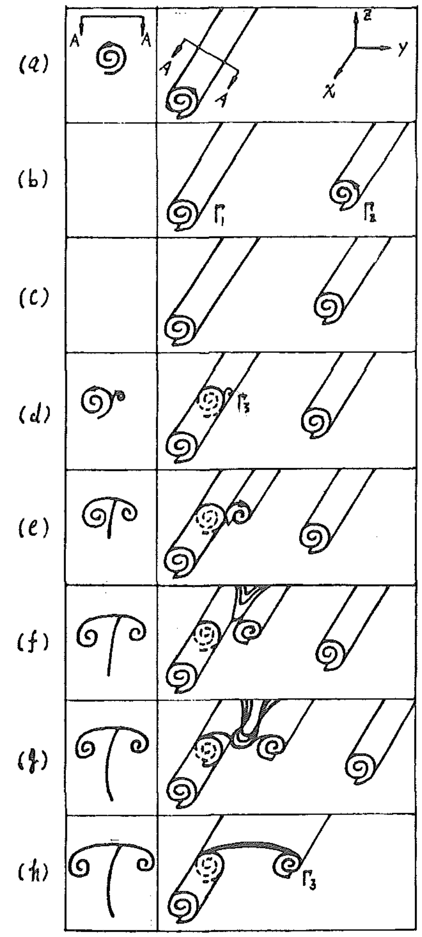


Figure 3. Formation and Development of A Secondary-Instability Horseshoe Vortex

close to each other. As the result, the effect of Γ_2 on Γ_1 is more and more strong and the reverse vorticity or circuitation become more and more great between them. The instability of the vortex causes the formation of a reverse vortex near the Γ_1 . The vorticity of Γ_3 constantly increases, and meanwhile the Γ_3 gradually moves far from Γ_1 as the induced effect of Γ_1 and Γ_2 on it. Then a higher pressure in the inferior region and a lower pressure in the superior region between Γ_1 and Γ_3 are caused, respectively due to pulling in or pulling out the fluid by Γ_1 and Γ_3 . So the inferior flow is slower and the superior flow is faster. When the difference of the velocities between the inferior and superior flows increase to certain degree, the shearing of the two flows leads a transverse vortex linked with the Γ_1 and Γ_3 to forms i.e. a horseshoe vortex to forms. With the motion of the horseshoe vortex along the streamwise direction, its head gradually rises up to a stable height and its three vortex tubes constantly stretch and deform. Afterwards the vorticity of the horseshoe vortex get to dissipate. At last, it vanishes. Fig. 4 was photoed with an unmoving laser light sheet (α=90°, β=45°)

and fig.5 was pictured by an uniform-speed moving laser light sheet from upstream to downstream ($\alpha=45°$, $\beta=90°$), and they separately reflect the way and features of the formation of the secondary-instability horseshoe vortex.

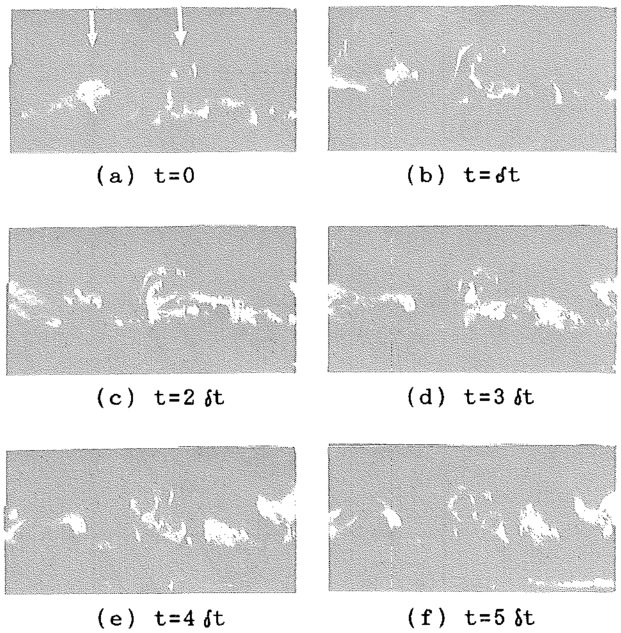


Figure 4. Cross Section of Process When A Horseshoe Vortex Pass A Section of An Unmoving Laser Light Sheet, $y/\delta=0.26$, $x/\delta=1$, $\delta t=0.083s$

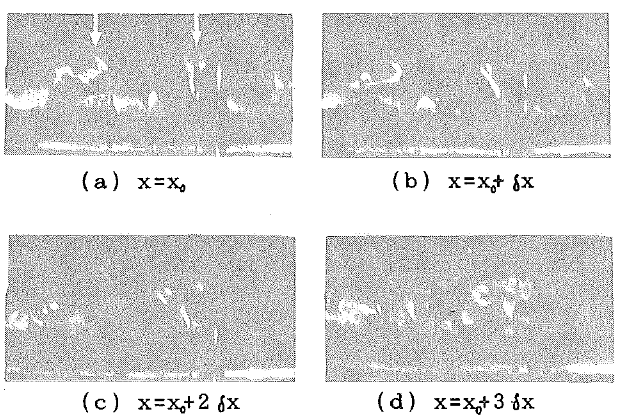


Figure 5. Cross Section of The Spacial Structure of A Horseshoe Vortex Obtained by A Moving Laser Light Sheet, $y/\delta=0.26$, $x/\delta=0-3$

But it is not certain that a horseshoe vortex forms when two streamwise vortices affect on each other. The test results show that the two vortices probably combine together, or independently develop until vanish, which associate with their intensity, distance between them and enviroment around them.

<u>Spacial Shape</u> By analyzing the test results, the spacial shape of the secondary-instability horseshoe vortex can be given as shown in fig.6. Although it bears a resemblance to that described in refrences [7] and [9], they are not quite a same. The main distinguish is that the former has two different-length horns before its head shown in fig.7 and is not consummate horseshoe vortex.

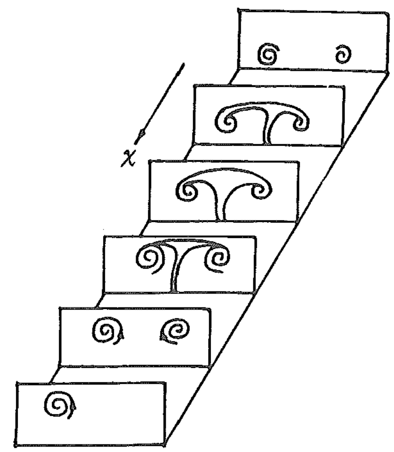


Figure 6. Cross Sections of The Spacial Structure of A Horseshoe Vortex

Figure 7. A Typical Plan View of The Horseshoe Vortex Obtained by Using Illuminating Light Combined with Moving Laser Light Sheet, $y/\delta=0.09$

<u>Development</u> The transverse size of the horseshoe vortex increases at uniform velocity to its stable size as shown in fig.8. This is different from the artificial horseshoe vortex whose transverse size varies fast and increases constantly. Fig.9 shows that the horseshoe

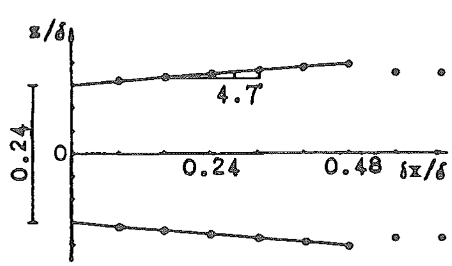


Figure 8. Development of Transverse Size $y/\delta=0.09$

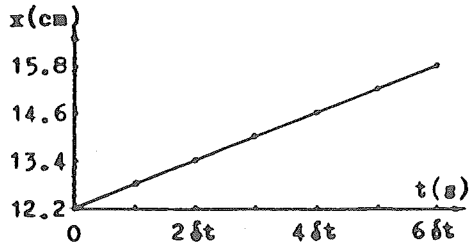
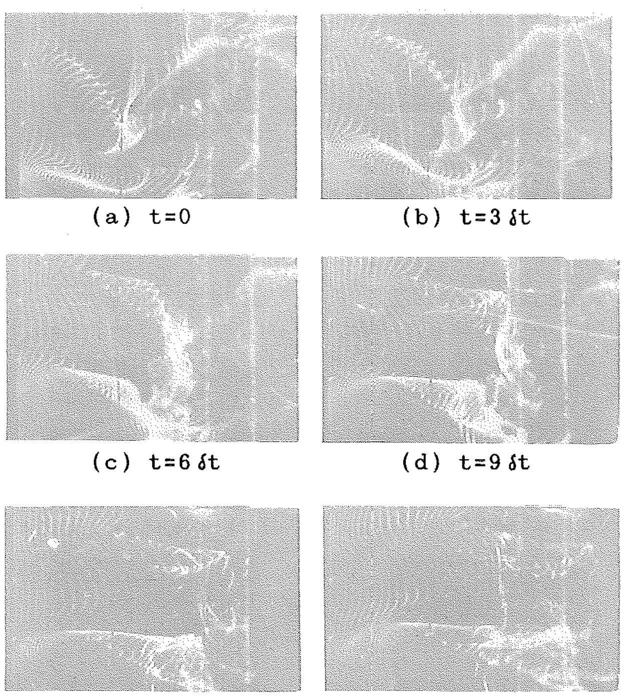


Figure 9. Velocity of The Vortex Head, δt=0.1664s, y/δ=0.09

vortex keeps a uniform motion after it forms. In the experiment, the horseshoe vortex with inclination of 45° towards the wall was not obtained. This is perhaps because that it was not photoed or that it is not 45° inclined towards the wall.

Formation and Development of A Combination Horseshoe Vortex

The second way of the formation of a horseshoe vortex is combination. The process of its formation is given as shown in fig.10 and can be roughly described as the following: The end of a streamwise vortex Γ_1 downstream and the head of the streamwise vortex Γ_3 which is one of two counter-rotating longitudinal vortices Γ_2 and Γ_3 upstream interact on and get close to each other. As the connection or interaction between the end of Γ_1 and the head of Γ_2, the head of Γ_2 also approaches Γ_3, which leads a more strong interaction among the end of Γ_1, both heads of Γ_2 and Γ_3.



(a) t=0 (b) t=3 δt (c) t=6 δt (d) t=9 δt (e) t=12 δt (f) t=16 δt

Figure 10. Formation of A Combination Horseshoe Vortex, y/δ=0.09, δt=0.0832s

In the result, a transverse vortex forms, which links with the end of Γ_1, both heads of Γ_2 and Γ_3. Because the intensity of Γ_1 becomes very weaken at this time, the transverse vortex, Γ_2 and Γ_3 construct a horseshoe vortex with a horn (in most cases) or two horns (in a few cases). There is not any other way of combination to be observed in the experiment.

Fig.11 and fig.12 respectively give the rules of the combination horseshoe vortex in the development of its transverse size and its motion, which are similar to those of secondary-instability horseshoe vortex. In addition, it has follow features: higher position of its head from the wall, incessent deforming and stretching, and obvious variance of the transverse size of its longitudinal vortex tubes along flow direction from small to large.

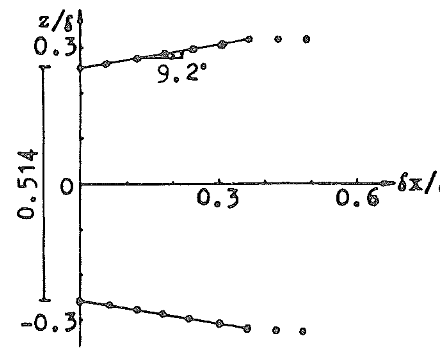


Figure 11. Development of Transverse Size, y/δ=0.09

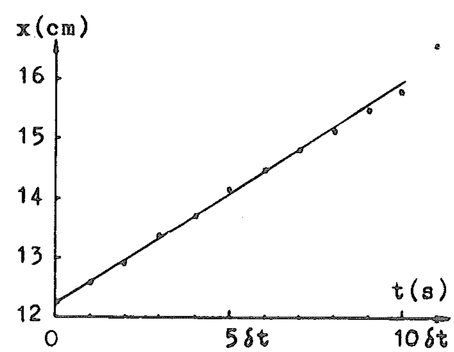


Figure 12. Velocity of The Vortex Head, δt=0.1664s, y/δ=0.09

Formation and Development of Deformation-Horseshoe Vortex

The third way of the formation of a horseshoe vortex shown in fig.13 is stated as follows: Influenced by the enviroments around it, the head of a moving and stretching streamwise vortex transversely bends up and stretches. The bended trnsverse part of the vortex bends up again back to upstream and stretches to forms a deformation horseshoe vortex with two different-length longitudinal vortex tubes. It stretches, expands and moves both in streamwise and crosswise.

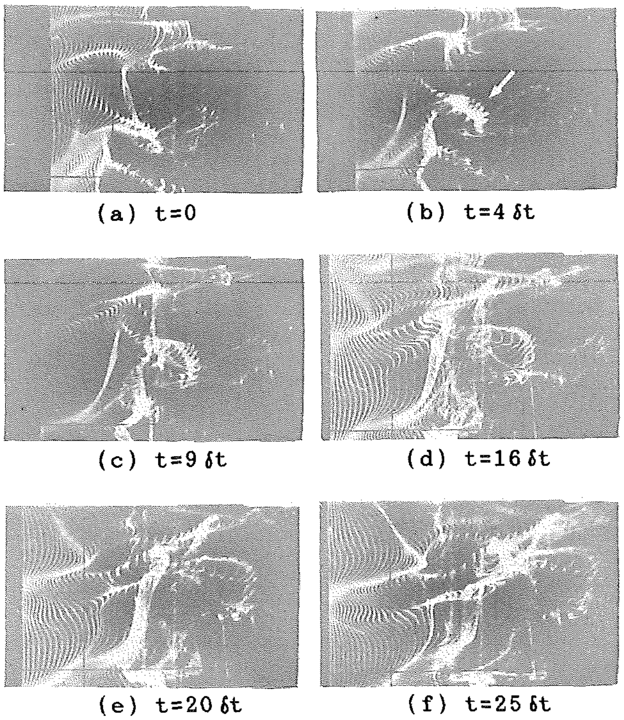


Figure 13. Formation of A Deformation-horseshoe vortex, $y/\delta=0.09$, $\delta t=0.0832s$

The development of its transverse size has its own feature shown in fig.14. When it first bends up its transverse size increases faster. After it bends up again the increase of its transverse size becomes slow. Its motion is nearly uniform as shown in fig.15.

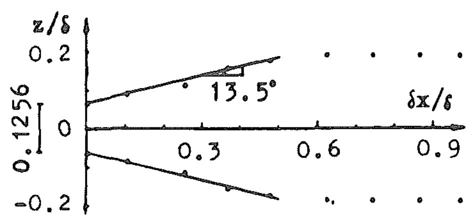


Figure 14. Development of Transverse Size, $y/\delta=0.09$

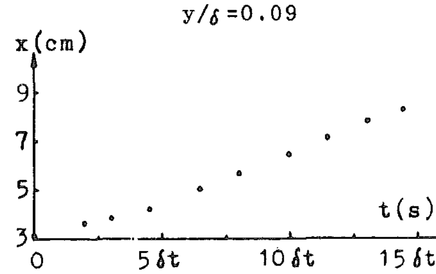


Figure 15. Velocity of The Vortex Head, $\delta t=0.1664s$, $y/\delta=0.09$

<u>Formation and Development of Burst-Horseshoe Vortex</u>

The formation of the burst-horseshoe vortex is almost sudden, which is similar to the above-mentioned artificial horseshoe vortex. As shown in fig.16, at the beginning two longitudinal vortices suddenly form (see fig.16a-b), and then a horseshoe vortex forms at once. In the following motion, its head gradually lifts and expands. Fig.17 basically reflects the spacial structure of the burst-horseshoe vortex: Its head rides on its two longitudinal vortex tubes;The positions of two longitudinal vortex tubes change from low to high along flow direction. Fig.18 shows that its formation is very fast and no more than one second. The velocities of the vortex heads in fig.16 and 18 are respectively 7.21cm/s and 10cm/s which are all faster than free-stream velocity. But, after its formation the velocity of the vortex head slow down at once. It is also discovered that its head often inclines towards the wall at an angle of 45°. this kind of horseshoe vortex is consummate.

The development of the transverse size and the velocity of a burst-horseshoe vortex are respectively given in fig.19 and fig.20. It is noticeable that its expanding velocity is almost equal to that of a artificial horseshoe vortex produced in the air.[9]

<u>Discussion</u>

This paper describes four ways of the formation of the horseshoe vortex in TBL.

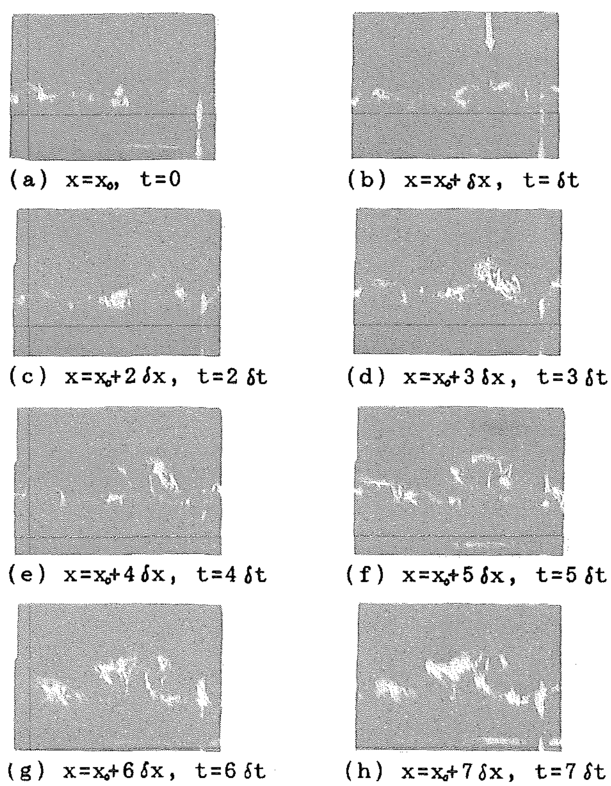


Figure 16. Formation of A Burst-Horseshoe Vortex, $y/\delta=0.27$, $\delta t=0.0832s$

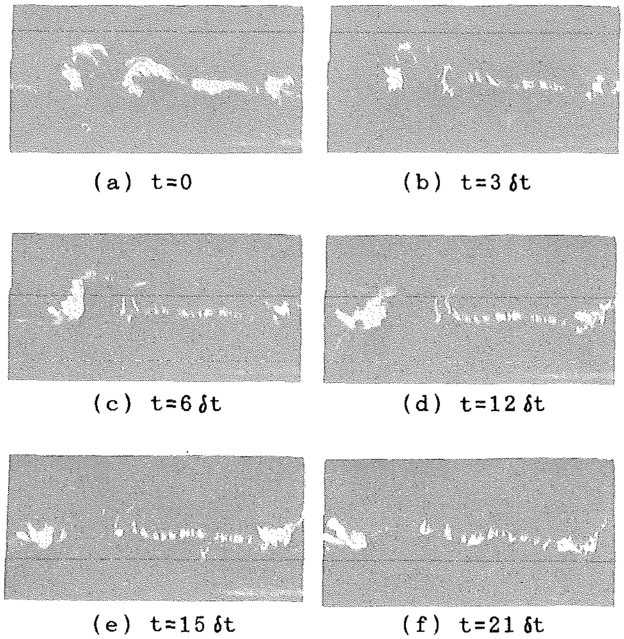


Figure 17. Cross Section of Process When A Burst-Horseshoe Vortex Pass A Section of An Unmoving Laser Light Sheet, $y/\delta=0.09$, $\delta t=0.0832s$

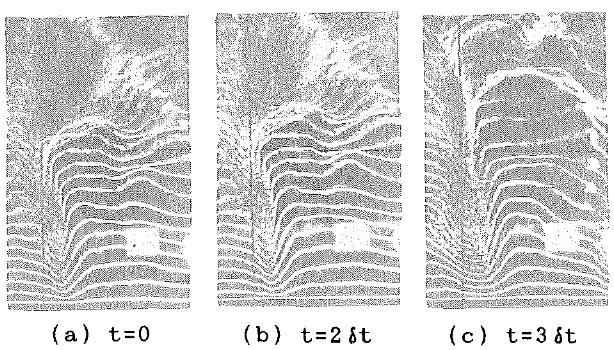


Figure 18. A Typical Plan View of A Burst-Horseshoe Vortex Obtained When It Forms by Using Illuminating Light, $y/\delta=0.09$, $\delta t=0.0832s$

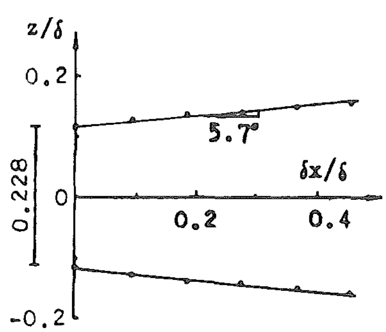


Figure 19. Development of The Transverse Size of A Burst-Horseshoe Vortex, $y/\delta=0.09$

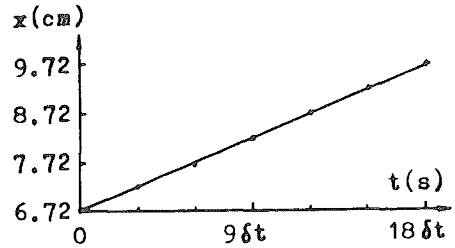


Figure 20. Velocity Of The Vortex Head, $t=0.0832s$, $y/\delta=0.09$

It is noticed that the vortex in TBL can break off in its middle and link with other vortices near it sometimes, although the vortex in the ideal and inviscid flow can not do. This phenomenon is reasonable and understandable because the vortex in TBL has a dissipation whose intensity is different at different part of the vortex. Another reason may be the sudden and strong influence on it.

Deformation and transverse drift also accompany when the vortex in TBL moves. The speeds of deformation of two longitudinal vortex tubes of a vortex are different. In transverse drift,combination and deformation horseshoe vortex move faster than secondary instability horseshoe vortex. Of the four kinds of horseshoe vortex, only burst horseshoe vortex has consummate shape of horseshoe. Perhaps this is one of the reason that few consummate horseshoe vortex are found in TBL.[10] Klebanoff[11] ever told before that the formation of the horseshoe vortex is due to secondary instability, but did not give its process and mechanism. Here the paper describes its process and mechanism points out it is one of the four ways to form.

IV. Conclusion

1. The horseshoe vortex in TBL can form in four ways: secondary instability; combination; deformation; burst.

2. The way and mechanism of the formation of a horseshoe vortex in TBL is different from that of the horseshoe vortex caused by artificial means: The former can form in several ways and is often lonely; The latter forms in only way and is always sequential.

3. The transverse size of the horseshoe vortex increases at uniform velocity upto its stable size. After it forms, the horseshoe vortex keeps a uniform motion. All of the four kinds of horseshoe vortex have the common characteristics as follows: longitudinal stretching, deformation and transverse drift. But they are different in size, moving velocity, deformation and drift.

4. The probability of the formation of

secondary instability-horseshoe vortex is the highest and the burst horseshoe vortex lowest, but only the burst - horseshoe vortex is consummate shape of a horseshoe.

5. The new method of flow visualization ——moving sheet of laser light can be used well for the research on the spacial structure of the horseshoe vortex and other phenomena in TBL.

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References

1. Hinze,J.O. Turbulence(second edition), 1975,McGraw-Hill,Inc.
2. Structure and Mechanisms of Turbulence 1-2, Proceedings of the Symposium on Turbulence, Aug.1-5, 1977, Edited by H.Fiedler
3. Kline,S.J.,Reynolds,W.C., Schraub,F.A. and Rundstadler,P.W.,The Structure of Turbulent Boundary Layer, J. Fluid Mech., 1967;30:741-773
4. Blackwelder, R. F. and Eckelmann, H. Streamwise vortices associated with the bursting phenomenon, J. Fluid Mech., 1979; 94: 577-594
5. Cantwell, C. T. Organized motion in turbulent flow, Ann. Rev. Fluid Mech., 1981;13:457-515
6. Hussain,A.K.M.F. Coherent structures-reality and math, Phys. Fluids, 1983; 26:2816-2850
7. Head,M.R. and Bandyopadhyay,R. New aspects of turbulent boundary-layer structure, J. Fluid Mech., 1981; 107: 297-338
8. Acarlar,M.S. and Smith,C.R. A study of hairpin vortices in a laminar boundary layer, J. Fluid Mech., 1987; 175:1-83
9. Liu Tianshu, Shi Shengxi and Zhou Mingde Investigation of horseshoe vortices in laminar boundary layer, 1989; 4: (3) 290-296
10. Lian,Q.X. A visual study of the coherent structure of the turbulent boundary layer in flow with adverse pressure gradient, J. Fluid Mech., 1990; 215: 101-124
11. Klebanoff, P. S., Tidstrom, D.K. and Sargent,L.M. The three-dimensional nature of boundary layer instability, J. Fluid Mech.,1962;12: