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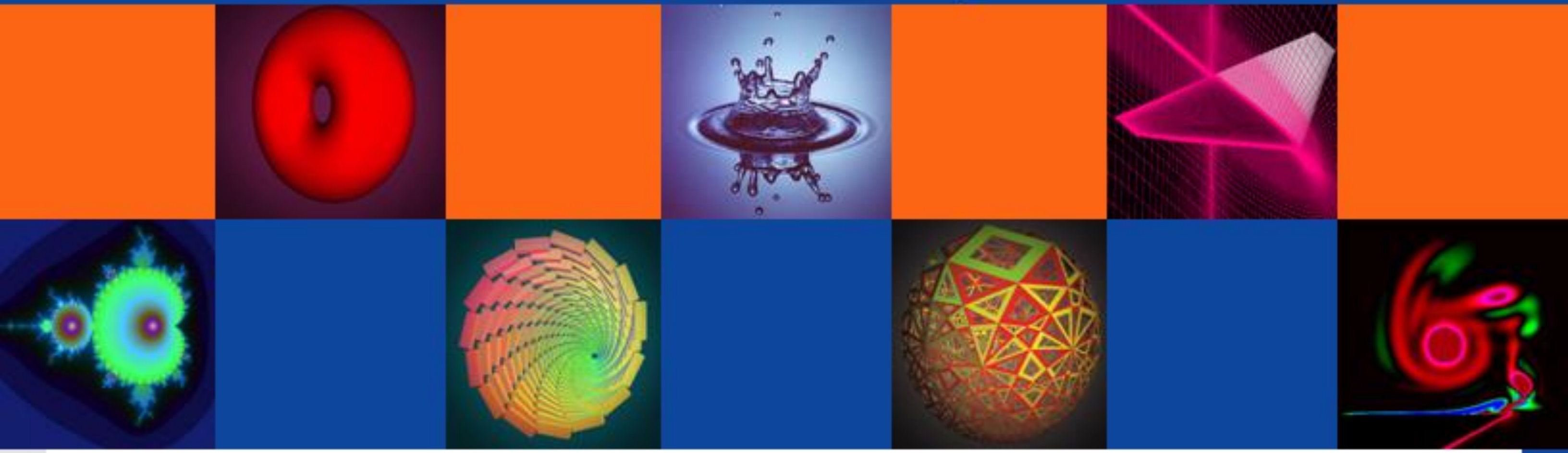

DNS Study on Hairpin Vortex Structure in Turbulence

Chaoqun Liu
Yonghua Yan
Hassan Al-dujaly

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DNS Study on Hairpin Vortex Structure in Turbulence

Chaoqun Liu, Yonghua Yan, Hassan Al-dujaly

University of Texas at Arlington

Abstract

A forest of hairpin vortices has been accepted widely as the common vortex structure in turbulent flow. It is commonly believed that the hairpin has leg, neck and ring head and the leg is attached on the wall. In our DNS study, it is found that the leg and ring head are separated and generated by different mechanisms. In addition, the ring head is Omega-shaped and separated from the leg and the leg is detached from the wall from beginning. The leg is not a vortex tube in any sense.

I. Introduction

A forest of hairpin vortices has been accepted widely as the common vortex structure in a turbulent flow (Wu and Moin, 2009.) Hairpin vortex (Figure 1)was found by Theodorsen (1952) and is widely believed has leg, neck and ring head(Figure 2.) They are three parts of a hairpin vortex as an integrated one. However, this will raise several questions:

1. Since the hairpin vortex has to be stretched, it will have to break down as the leg is placed on the wall surface where velocity is zero and the ring head is located almost near the inviscid area where the streamwise velocity is one unit. Rist et al (2002) believe the hairpin vortex will break down and reconnect. The vortex breakdown concept will directly violate the Helmoholtz vortex conservation law and there is no way to reconnect.
2. In order to explain the vortex package development, Adrian (2007) believes that the vortex is original attached on the wall and then detached from the wall. It is really hard to believe how the vortex leg is originally linked with wall surface and then detached from the wall. It sounds that we have no mechanism to perform the process from attachment to detachment.
3. Adrian (2007) believes that the vortex package with multiple vortex rings is auto-generated. We must be very careful to use the word “auto-generation” since everything must be generated with certain mechanism and, in general, cannot be auto-generated.
4. Wallace (2011) in his review paper addressed: “there has been remarkable progress in turbulent boundary layer research in the past 50 years, particularly in understanding the structural organization of the flow. Consensus exists that vortices drive momentum transport but not about the exact form of the vortices or how they are created and sustained.” If we believe the hairpin is an integrated body, it looks like there is no way to understand the turbulence generation.

We recently launched a high order DNS to study the hairpin vortex structure carefully and has quite a few new findings on the hairpin vortex generation mechanism and hairpin vortex structure.

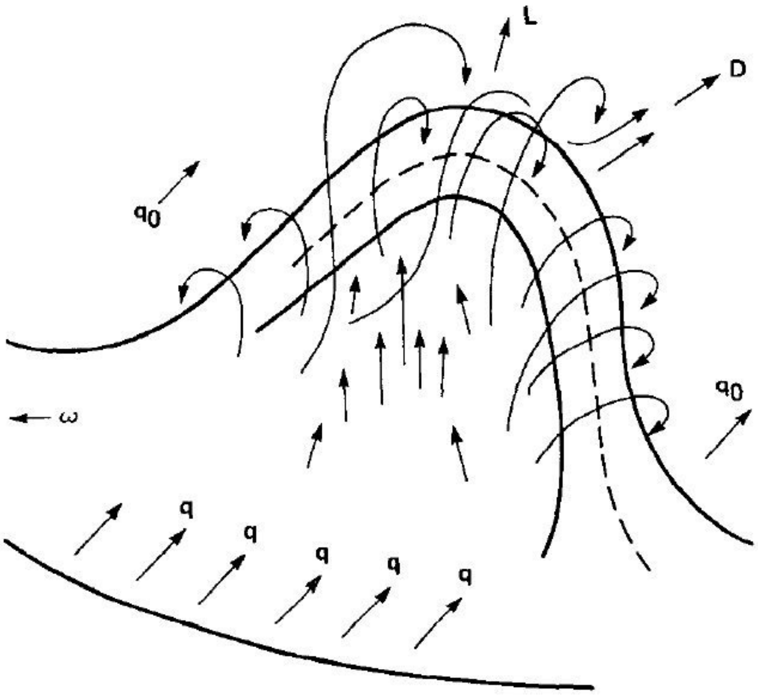


Figure 1: Hairpin vortex (Theodorsen, 1952)

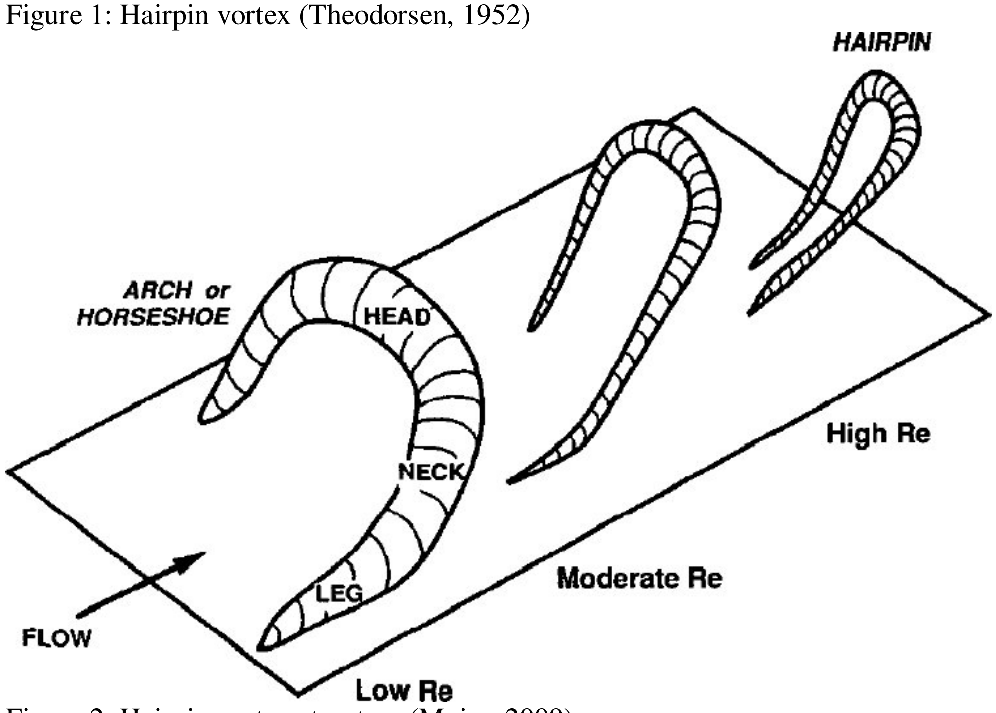


Figure 2: Hairpin vortex structure (Moin, 2009)

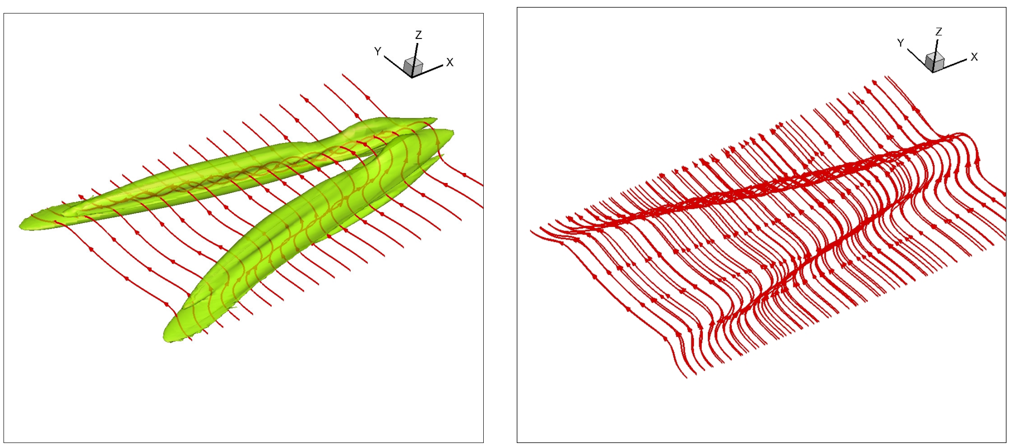
II Preliminary Computational Results and Analysis

1. **Hiarpin vortex is not a vortex tube**
   A vortex tube cannot be penetrated by vortex filaments, but the hairpin leg are penetrated by many vorticity lines, which clearly shows the vortex leg is not a vortex tube in any sense. Hairpin vortex legs are rotation cores or clustering of vortex filaments (Figure 3)
2. **Hiarpin ring head is separated from leg with an Omega shape**

We use the λ_2 iso-surface at $\lambda_2 = -.0.001$ to capture the hairpin vortex head and then trace the origin of the vorticity lines which consist of the ring-like head. We found that the ring-like head is Omega-shaped and separated from hairpin legs (Figure 4.) They are two separated parts and are generated by different mechanism as we reported in last year (Liu et al, 2013)

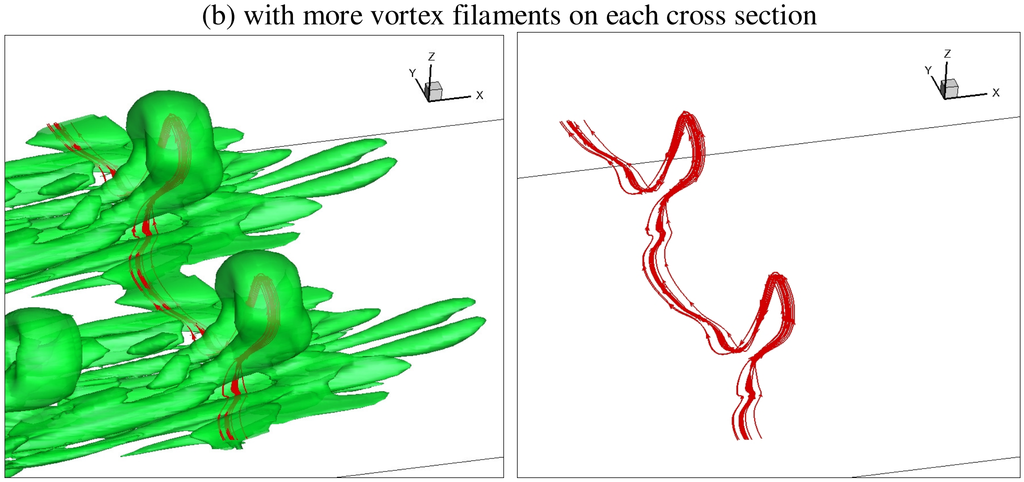
3. **Hairpin vortex are never attached with the wall surface**

If the hairpin vortex leg is attached on the wall surface, it must lead to vortex breakdown due to the zero velocity on the wall and fast moving of the ring head, which will directly violate the Helmoholtz vortex conservation law. Actually, the vortex leg is a concentration of more local vortex filaments. None of these filaments which consist of vortex leg are attached with the wall surface. They are all free to move. The ring head is generated by the shear layer located above the vortex leg by ejection (Liu et al 2013.) The ring-like head is separated from the leg and is completely free to move with a fast speed and stretch due to the higher speed on the boundary layer top and fluid deformation.



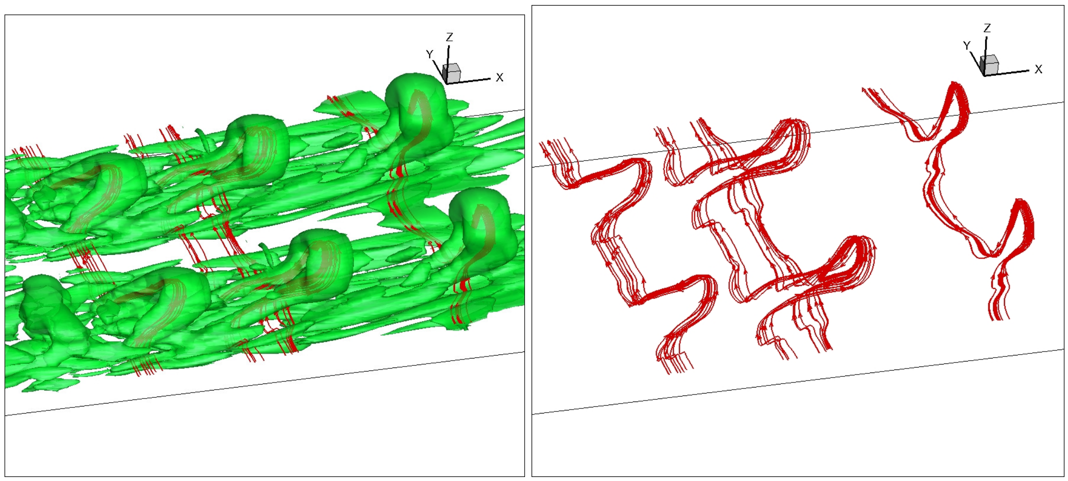
(a) (b)

Figure 3: Vortex filaments originate from the cores of Λ-vortex (a) λ_2-isosurface and vortex filaments; (b) with more vortex filaments on each cross section



(a) λ_2 iso-surface (b) Origin of the vorticity

Figure 4: The vorticity origin of the first vortex rings



(a) λ_2 iso-surface (b) Origin of the vorticity of vortex rings

Figure 5: The vorticity origin of the multiple vortex rings

III Important conclusions

Vortex ring head and vortex leg of the hairpin vortex are two separated parts. Vortex legs are not vortex tube. None of the vortex filaments which consist of the hairpin vortex are attached with the wall surface from beginning. They are all from spanwise boundaries and free to move with different speeds, higher on top and lower in bottom. There is no vortex breakdown and no any process from vortex attachment to detachment. In addition, the multiple vortex rings cannot be auto-generated and all of them are generated by shear layer instability (Liu et al 2013.)

IV Future work

More detailed description of the DNS results and analysis will be given in the final AIAA paper.

Reference

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