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DNS Study on Vorticity Structures in Late Flow Transition

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The formation and development of the vorticity structures during the process of late boundary layer transition on a flat plate are detailed discussed based on the high-order direct numerical simulation (DNS). In this paper, it can be concluded that the vorticity cannot directly represent vortex or rotation. A vortex is not absolutely the congregation of vorticity, but is a region where the vorticity overtakes deformation. Except for the vorticity lines which come from and end at side boundaries, another type of vorticity structure, self-closed vorticity lines named as vorticity rings, are found numerosely generated inside the domain during the transition process. There are more layers of vorticity rings generated around vortex structures. The generation and growth of self-closed vorticity rings are contributed by the buildup of the vortex. However, the vorticity ring still cannot represent vortex, since the vorticity rings also appear in the region where no vortices exist.

Key words: DNS, vorticity, vorticity lines, self-closed, vorticity rings, vortex, transition flow

Nomenclature

\[ M_\infty = \text{Mach number} \quad Re_{\text{in}} = \text{Reynolds number} \]

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\( \delta_{in} = \) inflow displacement thickness \( \mu_\infty = \) viscosity
\( T_\infty = \) freestream temperature \( T_w = \) wall temperature
\( R = \) is the ideal gas constant \( \gamma = \) the ratio of specific heats
\( \rho_\infty = \) freestream density \( U_\infty = \) freestream velocity
\( x, y, z = \) streamwise, spanwise, normal directions
\( L_{zin} = \) height at inflow boundary
\( L_x = \) length of computational domain along \( x \) direction
\( L_y = \) length of computational domain along \( y \) direction
\( x_{in} = \) distance between leading edge of flat plate and upstream boundary of computational domain

1 Introduction

Vorticity and vortex in fluid dynamics have been treated as the same things by many authors [1-3] in past decades. Vorticity \( \omega = \nabla \times u \), where \( u \) is fluid velocity, has rigorous mathematical definition which is the curl of velocity field [4]. Some concepts such as vorticity line, vorticity tube, vortex filaments, vortex, vortices and etc. always confuse many people. In mathematics, vorticity line is defined as a curve which is everywhere tangent to the local vorticity vector; the vorticity tube is a tube-like surface formed by all vorticity lines passing through a closed curve, which could be considered as bundle of vorticity line without any vorticity line leakage. However, as denoted by Helmholtz [5], the vortex lines are the lines draw through the fluid mass so that their direction at every point coincides with the direction of the momentary axis of rotation of the water particles lying on it. Vortex filaments are also denoted by Helmholtz as the portions of the fluid mass cut out from it by way of constructing corresponding vortex lines through all points circumference of infinitely small surface elements. From Helmholtz, it is no doubt that a vortex is a fluid region with rotational motions. More explanations of vortex like ‘the sinews and muscles of the fluid’ and ‘the sinews of turbulence’ were respectively given by Kuchemann [6] and Moffatt et al. [7]. While some people regard a vortex is a vorticity tube surrounded by irrotational fluid and classify vortex into axial vortex and layer-like vortex [8], here layer-like vortex is the vorticity layer with large vorticity but without rotation, which is some extent contradictory to the vortex definition by Helmholtz. Wu et al. [1] claimed a vortex as a connected fluid region with relatively high concentration of vorticity. However, there are also other voices, vortex is not necessarily congregation of vorticity lines, but dispersion in most three dimensional cases [9], which means the vorticity in a vortex is not necessarily larger than the surrounding area in many 3D cases.
Several vortex identification criteria, such as $\Delta$, $\lambda_2$, $Q$, and Omega criteria [10-13], have been proved to be efficient in visualizing vortex structures when applied to DNS data of a transitional boundary layer [14]. For deeper investigation on the difference between vorticity structures and vortex structures which were treated as the same or similar things by many people, a boundary layer transitional flow on a flat plate at a freestream Mach number of 0.5, is utilized by high order DNS, and some view points towards vorticity structures are obtained in this paper. The paper is organized as follows: Section 2 presents the numerical methods and the case description; Section 3 provides our DNS results and addresses the details about the generation process of the vorticity structures especially vorticity ring generation in the flow transition. The last is our conclusion.

4 Conclusions

In this paper, different types of vorticity structures (not vortex structure) in the process of laminar boundary layer transition flow on a flat plate, are compared with the vortex structures based on our high-order direct numerical simulation (DNS). Several conclusions for our DNS results are obtained as described follows:

(1) The vorticity cannot directly represent vortex or rotation. A vortex is not absolutely the congregation of vorticity, but is a region where the vorticity overtakes deformation, since the weight of deformation in the whole velocity gradient cannot be ignored, no matter how large the vorticity is.

(2) Except for the vorticity lines which come from and end at side boundaries, another type of vorticity structure, self-closed vorticity lines, which can be named as vorticity rings, are found numerously generated inside the domain during the transition process. There are more layers of vorticity rings generated around vortex structures.

(3) The generation and growth of self-closed vorticity rings are contributed by the buildup of the vortex. The basic reason for their generation is that the new vortex rings generate low speed zone which causes high shear layer around them. The high shear layer is new vorticity near the vortex rings. However, all newly generated vorticity can only have a unique form which is self-closed rings without exception, since the vorticity lines cannot interrupt, start or end, inside the flow field. We believe this is the mechanism why we can find many self-closed vorticity rings near vortex rings. Self-closed vorticity rings in other places should have similar mechanism of generation.

(4) These self-closed vorticity ring may be part of vortex or may not be vortex at all, since the vorticity rings can also appear at the region where no vortex is. In addition, the vorticity magnitude could be relatively very small.
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References


