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Development and evolution of flow over three-dimensional cylinder

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By solving the three-dimensional (3D) time-dependent compressible laminar Navier–Stokes equations with a finite-volume method incorporating the third-order-accuracy discretization scheme, the flow structure around a 3D cylinder is investigated and its evolution mechanism is presented in this paper. At high incidence angles, a shed vortex series forms at leeside of the 3D cylinder with its sectional flow pattern very similar to the Karman vortex street developed behind a two-dimensional cylinder. The main, the secondary and the tertiary vortex system compose a hierarchical structure over the 3D cylinder. Each tertiary vortex develops into a new main vortex after the breakaway of its former main vortex, and merges the secondary vortex on its opposite side of the symmetry plane.

Keywords: 3D cylinder, flow mechanism, vortex merger, quasi-Karman vortex street
PACC: 4700, 4710, 4725R, 4725F

1. Introduction

Flow over a blunt body is one of the important topics in the field of fluid mechanics and physics of fluids.[1,2] At certain Reynolds numbers the wake flow behind a two-dimensional (2D) cylinder develops into a Karman vortex street,[2,3] as is known widely. As to the flow over a three-dimensional (3D) cylinder, the separated flow structure has also been extensively investigated experimentally and numerically.[4] A 3D cylinder is a cylinder inclined to the flow at certain incidence and with a head or nose of cone, ogive, semi-ellipsoid or hemisphere, etc, on it. An obvious flow phenomenon is that the symmetric vortex pair on the leeside of the cylinder becomes asymmetric at certain incidence. If the cylinder is long enough and the incidence angle further increases, a multiple shed vortex series develops over the cylinder.[5] The sectional flow pattern of this vortex series is very similar to the Karman vortex street formed behind a 2D cylinder. Since the development processes of the flow around a 3D cylinder and the flow behind an impulsively started 2D cylinder are similar, this resemblance causes many researchers to draw analogy between some 3D flow phenomena and the flow characteristic of a 2D cylinder.[6,7]

This analogy is indubitably helpful in understanding the 3D flow phenomena. However, real knowledge of the evolution mechanism for the development of vortex series on the 3D cylinder has still not been properly understood. One important reason is that the problem of the axial flow component is not properly disposed of in the analogy. Another reason is that some researchers focus their attention on the main vortex and ignore the hypo-structure of the vortex system. This might be related to the visualization methods used in the experiment, since it is not easy to observe an integrated vortex system using some methods such as the schlieren.[6]

Numerical simulations of flow around a 3D cylinder are performed, the integrated flow configuration over the cylinder is illustrated and a hierarchical structure of the vortex system is given in this paper. A phenomenon of the different vortex merger is found. On the basis of the generation, development and merger of the vortex system, the evolution mechanism of the leeside vortices on the 3D cylinder is presented.

2. Computational procedures

The computational procedure used in the present study was originally developed by Thomas *et al*,[8] and later was used by Hsieh and Wang,[9] and Wang and

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Liang.[10] Their numerical results proved to be in good agreement with their experiments.

The governing equations are 3D time-dependent compressible laminar Navier–Stokes equations; the conservation form in generalized coordinates (ξ, η, ζ) can be written as

$$\frac{\partial}{\partial t}(Q)+\frac{\partial}{\partial \xi}(F-F_v)+\frac{\partial}{\partial \eta}(G-G_v)+\frac{\partial}{\partial \zeta}(H-H_v)=0,$$

where $Q=(J^{-1})\,(\rho,\rho u,\rho v,\rho w,e)^{\mathrm{T}}$, F, G and H are the inviscid flux vectors and F_v, G_v, H_v represent the viscous terms; J is the Jacobian $\partial(\xi,\eta,\zeta)/\partial(x,y,z)$, u, v and w are the Cartesian velocity components in x, y and z directions, respectively; ρ is the density, p the pressure, e the total energy related to the flow variables by $e=p/(r-1)+\rho(u^2+v^2+w^2)/2$. For the inviscid fluxes F, G and H, a flux difference splitting scheme of Roe[11] is used, readers could consult the original work for details. The physical model configuration consisted of a $L_{\mathrm{N}}/D=3$ tangent ogive nose and a L_{A}/D=16 cylindrical afterbody. On the model surface no-slip, no penetration wall conditions are imposed. The computational grids size is 175 (axial) ×90 (circumferential) ×100 (radial). The working Reynolds number is Re=$V_\infty D/\nu$=1.0×10^5, where D is the cylinder diameter. A micro-disturbance strip is set on the tip of the cylinder head at meridian angle of θ=130°. Its geometrical size is $\Delta l/D$=1.8×10^{-3}, $\Delta b/D$=3×10^{-5} and $\Delta h/D$=3×10^{-4} in length, width and height, respectively.

3. Results and analysis

3.1. Quasi-Karman vortex street developed on the leeside of a 3D cylinder

The flow structure over a 3D cylinder develops with the incidence changing. At low incidences (α=5°), the boundary layer separates and rolls up into a symmetric vortex pair at the leeside of the cylinder. As the angle increasing, the vortex pair becomes asymmetric, with one going into higher vortex (VR1 in Fig.1) and the other into lower vortex (VL1 in Fig.1).

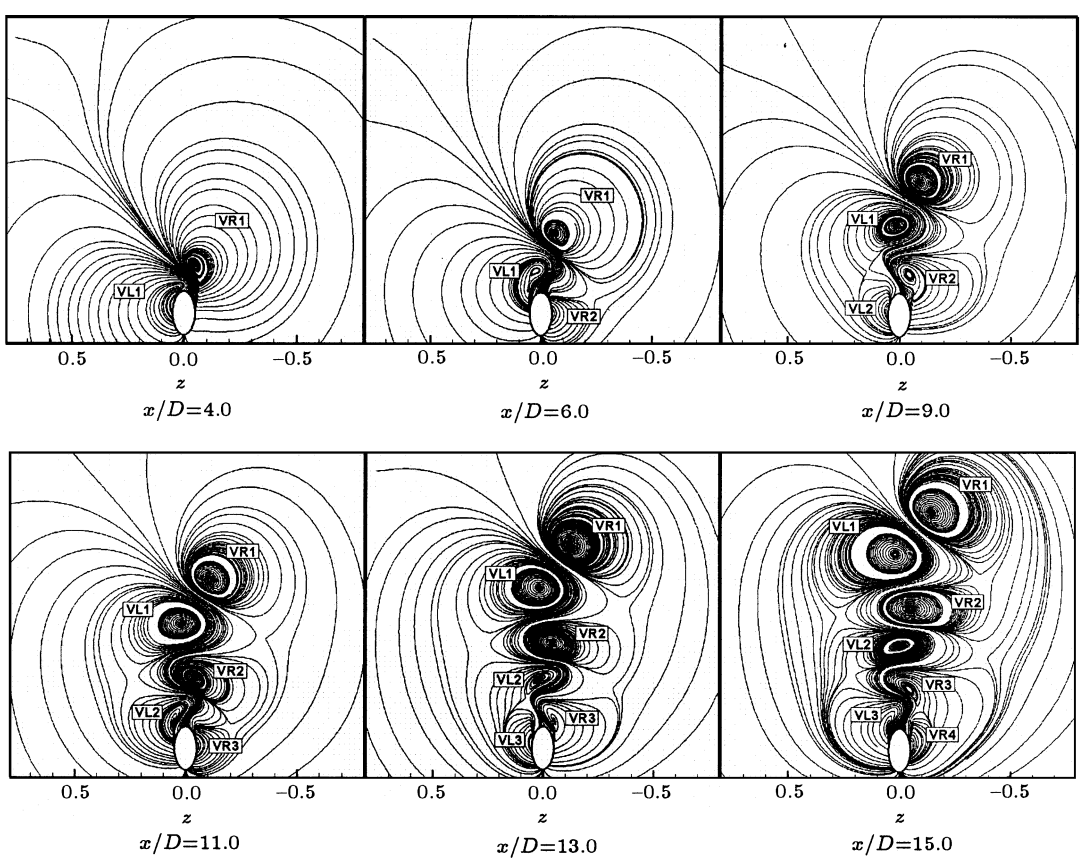


Fig.1. Quasi-Karman vortex street (α=58°).

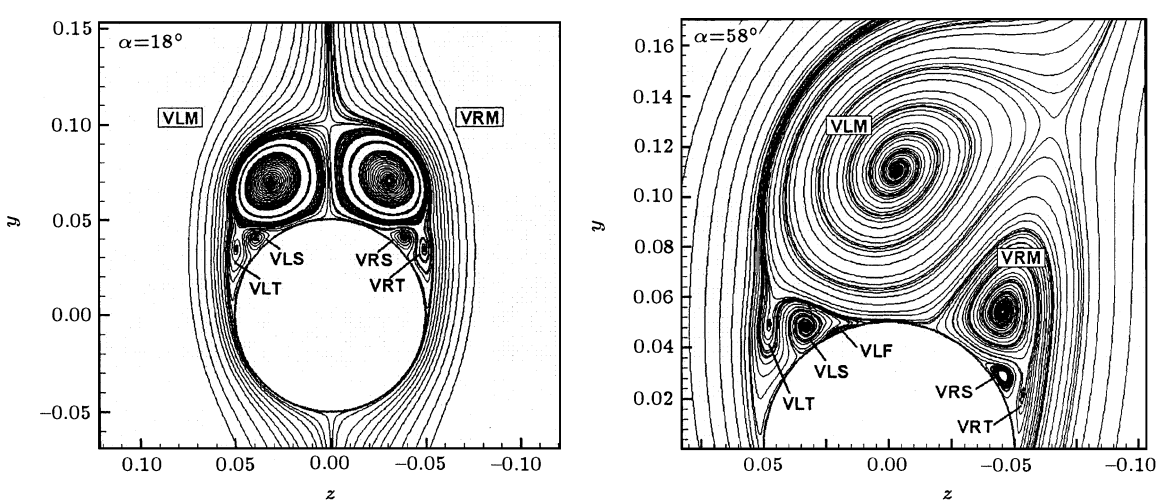
Then the higher vortex VR1 breaks away from the cylinder and becomes a shed vortex with α continuously increasing, while the lower vortex is still developing downstream along the cylinder. Here the shed vortex VR1 is on the right side of the body, and VL1 is on the left side. Since the boundary layer sustained separates from the body surface, a new vortex VR2 is generated on the right side of the body from the shed position of vortex VR1. Then vortex VL1 becomes the higher vortex and VR2 the lower vortex. Downstream further, VL1 get fully developed, breaks away from the body and becomes the second shed vortex. A new vortex VL2 is also generated on the left side of the body from the shed position of vortex VL1. Downstream along the body vortices VR2 and VL2 behave in the same way as vortices VR1 and VL1 do. If the cylinder is long enough, a vortex series develops in a sequence of VR1, VL1, VR2, VL2, VR3, VL3,$\cdots$. The sectional flow pattern of the vortex series is very similar to the Karman vortex street whether the section is perpendicular to the body axis or not. Such a vortex series we call a quasi-Karman vortex street.

Here the micro-disturbance is set on the nose tip of the cylinder where the azimuth angle is θ=130°. When the micro-disturbance is set at θ=−130°, a vortex series develops in a sequence of VL1, VR1, VL2, VR2, VL3, VR3,$\cdots$. The two vortex series are in the state of mirror image. In the following sections we take the first vortex series for further analysis.

3.2. Evolution mechanism for quasi-Karman vortex street

3.2.1. Hierarchical structures of vortex system over the cylinder

Integrated structure of sectional flow patterns is given in Fig.2. It shows that three levels of vortical configurations are generated both in the symmetric state (Fig.2(a)) and in the asymmetric state (Fig.2(b)). Vortices VRM and VLM are the main vortices which are located at the right side and left side of the cylinder, respectively. They are developed from the first separation of the boundary layer. That is to say, the leeside boundary layer separates and rolls up into a symmetric vortex pair at incidences of α=18°, which is asymmetric at increasing incidence, say α=28°, and more main vortices are generated at high incidences, say α=58° in Fig.1. Vortices VRS and VLS are the secondary vortices, which are induced by their main vortices VRM and VLM, respectively, after reattachment of the separated shear layer. Vortices VRT and VLT are the tertiary vortices, which are generated inside of their main vortices VRM and VLM. They rotate respectively in the same directions as VRM and VLM do. And they get vorticity basically from vortices VRM and VLM. These three types of vortices comprise a hierarchical structure of vortex system over the cylinder. Often, even a fourth level of vortex is generated in the asymmetric vortices state, see vortex VLF in Fig.2(b).



(a) Symmetric flow pattern at α=18° (b) Asymmetric flow patter at α=58°

Fig.2. Hierarchical structures of vortex system.

The flow around the cylinder and its dynamical characteristics are normally controlled by the main vortex. For instance, the quasi-Karman vortex street VR1, VL1, VR2, VL2, VR3, VL3,$\cdots$ in Fig.1 produced a sinusoidal-like distribution of side force down the cylinder. The coefficient of local sectional side force can exceed the local normal force by a factor as large as 1.5. Such a large side force will result in a high yawing moment on a cylinder-shaped rocket or missile. Therefore, many researchers generally devote attention to the main vortex and ignore the hypo-structure (secondary and tertiary vortices) of the vortex system. As compared with the main vortex, the hypo-structure is normally small both in vorticity and in size, and the aerodynamic effect is not obvious. However, one cannot understand the formation mechanism of vortex system without the hypo-structure.

3.2.2. The origin of a new main vortex

As shown in Fig.1 the fully-developed main vortex sheds off right and left from the body surface of the cylinder, and a new main vortex is generated from the position where the former main vortex breaks away. What is a new main vortex originated from? This question has puzzled investigators for a long time. A generally accepted viewpoint is that the new main vortex directly develops from the continuously separated shear layer when a former vortex is shed off.[4] Thus in many papers in the literature concerning the topological evolution of vortex systems only the developmental process of the main vortex was given and no hypo-structure was shown.[12] Another viewpoint is that the new main vortex develops from a spiral vortex, which forms on the body surface and lifts off on the space where the former main vortex sheds off.[13] Degani *et al* saw the appearance of foci where the oil collects on the surface of an ogive-cylinder in their experiment. They believe that these foci act as the anchor points that allow the stream surfaces containing the castoff vortical structures from the forebody to roll up in the wake and form the forebody's trailing vortex system.[14] They presented a conjectured figure to show the formation mechanism of trailing-vortex system on the cylinder.[13] We also found the foci more clearly and they are regularly distributed on the surface of a 3D cylinder.[15] The focus lifts off in the shape of a small tornado with its axis of rotation nearly normal to the body surface. This spiral vortex rolls into the main vortex on its side and transmits the vorticity gathered from the body surface to the main vortex, and does not develop into a new concentrated vortex.

Recently, by elaborate visualization we found that the new main vortex develops from tertiary vortex when the former main vortex breaks away from the body surface of the cylinder.[16] But it is not easy to record the interesting details. Figure 3 shows our numerical results for further validation of the finding. It illustrates the dynamical process of vortex VL1 shedding and VLT developing into VL2. In Fig.3(a), vortex VR1 has already broken away from the body and a new main vortex VR2 has formed on the right side of the body when the flow develops to the section of x/D=4.1. Then the main vortex VL1 on the left side moves into the centre part of the leeside of the cylinder. Vortex VLS is the second vortex and VLT the tertiary vortex. After it crosses the symmetry-plane of the cylinder, vortex VL1 also breaks away from the surface and becomes the shedding vortex when flow develops downstream to x/D=4.9 (Fig.3(b)). Then vortex VLT gets vorticity directly from the continuously separated boundary layer and develops into VL2 along the body axis (Fig.3(c)). Vortex VL2 is just the successor of vortex VL1. Fig.3(d) shows the situation of vortex VL2 keeps developing downstream.

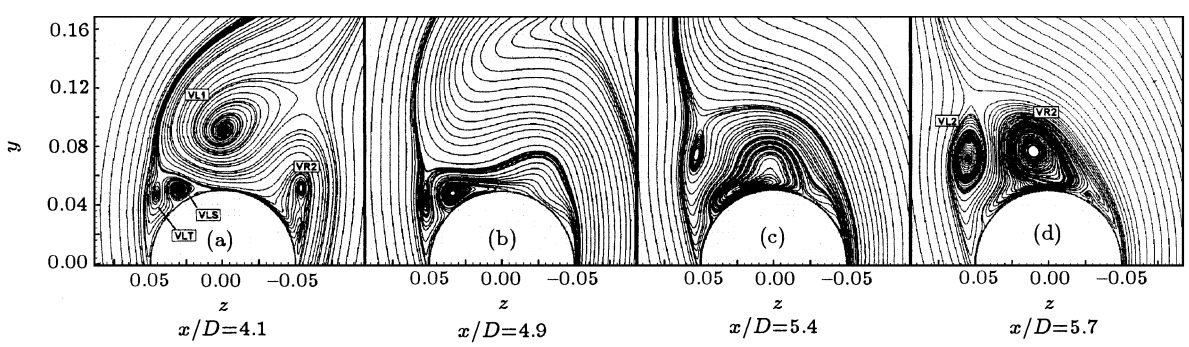


Fig.3. Tertiary vortex develops into a new main vortex.

3.2.3. Spanwise movement of the vortex system and merging of the main vortex and the secondary vortex

Spanwise movement of the vortex system and vortex merger is a very important evolutional process while developing along the axial direction. We have observed this phenomenon in Fig.3 where vortex VR2 on the right side crosses over the symmetry-plane to unite with the secondary vortex VLS on the left side. Here we present Fig.4 for more clarity.

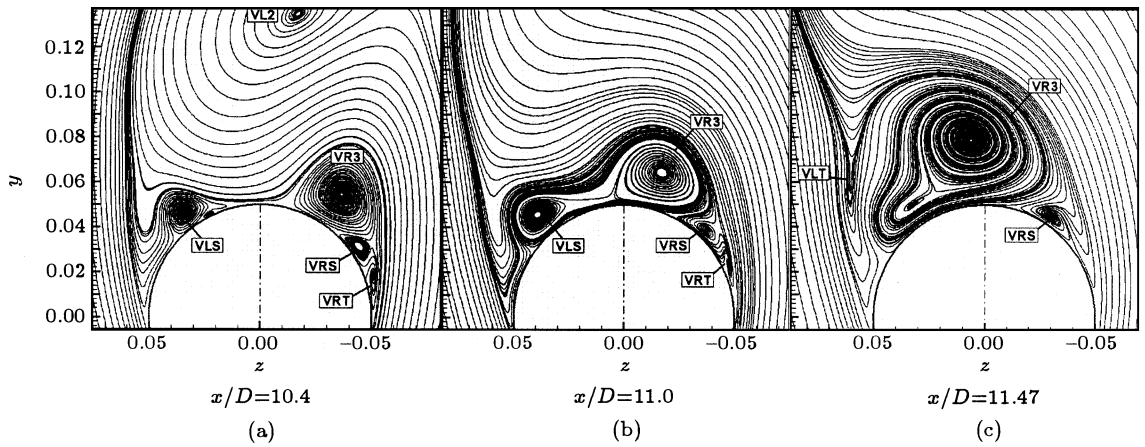


Fig.4. Spanwise movement and vortex merger.

In Fig.4(a) the main vortex VR2 has shed off the body and VL2 crossed the symmetry-plane, then the new generated vortex VR3 is in the inception state of its development, and it also induced the secondary vortex VRS and tertiary vortex VRT. Down to the section of x/D=11.0 (Fig.4(b)), vortex VL2 has also shed off from the body and VR3 is approaching to the symmetry-plane. When the flow develops to the section of x/D=11.47 (Fig.4(c)), vortex VR3 has crossed the symmetry-plane, vortex VLS joins VR3 with its vorticity transmitting to VR3.

By vorticity transmission, vortex VR3 is rapidly increasing both in size and in vortical strength. It moves through the symmetry-plane again and comes back to the right side of the body. During this process, vortex VR3 gets fully developed and goes up from the body surface gradually. Downstream a little bit of vortex VR3 breaks away from the body and becomes another shedding vortex. After vortex VR3 shedding, the tertiary vortex VRT at the right side will develop into VR4. Down along the body, vortex VLT at the left side will develop into VL3, and approach and cross the symmetry-plane to unite with the vortex VRS on the right side. After the merging of VL3 and VRS, vortex VL3 gets fully developed and will shed too. And then so will VR4, VL4, VR5,$\cdots$. In this way, a shed vortex series forms, and its sectional vortical pattern is similar to a Karman vortex street as shown in Fig.1.

4. Conclusions

By solving the 3D time-dependent compressible laminar Navier–Stokes equations, the flow structure around a 3D cylinder is analysed and its evolution mechanism is presented.

At high incidences, a shed vortex series forms at leeside of a 3D cylinder. Its sectional flow pattern is very similar to the Karman vortex street developed behind a 2D cylinder. This shed vortex series is very complex indeed, its configuration is a hierarchical structure which comprises the main vortex system, a secondary vortex system and a tertiary vortex system, at least. If the dynamical characteristics are mostly controlled by the main vortex system, then we can say that the evolutionary process is dominated by the hypo-structure of the vortex system.

At lower incidence the flow pattern is symmetric over the 3D cylinder. With incidence increasing, the symmetric vortex pair becomes asymmetric. Down along the body the higher vortex get fully developed with the shear layer continuously feeding to it, and breaks away from the body, becoming the first shed vortex. The new main vortex is originated from the tertiary vortex on the side of the shed vortex. The lower vortex approaches and crosses the symmetry-plane to unite with the secondary vortex on its op-

posite side. By vortex merging, the lower vortex gets fully developed and returns back to the side where it originated. And it also breaks away from the body during the process of its return, becoming the second shed vortex. Downstream along the body, the rest of the newly generated vortex follows in the same way. And finally, a quasi-Karman vortex street is developed around the whole 3D cylinder.

We should emphasize that each tertiary vortex will develop into a new main vortex after the shedding of its former main vortex, and will unite with the secondary vortex on its opposite side. This viewpoint on the evolutional mechanism is different from others.

References

[1] Dong P, Feng S D and Zhao Y 2004 *Chin. Phys.* **13** 434

[2] Guo W B, Wang N C, Shi B C and Guo Z L 2003 *Chin. Phys.* **12** 67

[3] Feng S D, Zhao Y, Gao X L and Ji Z Z 2002 *Chin. Phys. Lett.* **19** 814

[4] Telionis D P, Zeiger M D and Vlachos P P 1999 *AIAA Paper* 99-3693

[5] Deng X Y, Wang G, Chen X R *et al* 2003 *Sci. Chin.* E **46** 561

[6] Thomson K D and Morrison D F 1971 *J. Fluid Mech.* **50** 751

[7] Lamont P J and Hunt B L 1976 *J. Fluid Mech.* **76** 519

[8] Thomas J L, Krish S T and Anderson W K 1990 *AIAA J.* **28** 205

[9] Hsieh T and Wang K C 1996 *J. Fluid Mech.* **324** 83

[10] Wang G and Liang X G 2004 *Chin. Phys. Lett.* **21** 2223

[11] Roe P L 1981 *J. Comput. Phys.* **43** 357

[12] Lowson M V and Ponton A J C 1992 *AIAA J.* **30** 1576

[13] Tobak M, Degani D and Zilliac G G 1990 NASA TM-102796

[14] Degani D, Tobak M and Zilliac G G 1992 *AIAA J.* **30** 272

[15] Wang G, Liang X G and Deng X Y 2005 *Acta Aerodynam. Sin.* **23**(2) 167 (in Chinese)

[16] Wang G, Liang X G and Deng X Y 2004 *J. Tsinghua University (Sci. & Tech.)* **44** 1120 (in Chinese)