VORTEX DYNAMICS IN THE SPHERE WAKE AT MODERATE RE

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Summary For the investigation of the formation mechanisms of vortices in the sphere wake for different fluid flow regimes (for $270 < Re < 3000$) the direct numerical simulation and the Hussain's $-\lambda_2$ vortex-eduction technique have been used. Two different types of the formation mechanisms of vortices for $270 < Re < 400$ and for $Re > 400$ are demonstrated. All stages of the extraction of the hairpin-shaped vortices from an edge of the cylindrical shear layer and the recirculating zone of the wake are shown in detail.

INTRODUCTION AND METHODOLOGY

The understanding of the dynamics and kinematics of the 3D unsteady separated fluid flows around the bluff bodies is very important both from theoretical and from practical point of view. Detailed investigations of the structure of the sphere wake have been initiated in [1] and prolongated in [2-4] and other papers. In spite of these papers the detailed formation mechanism of vortices in the sphere wake is still unclear.

For the investigation of 3D separated homogeneous viscous fluid flows around a sphere the direct numerical simulation is used (the Splitting on physical factors Method for Incompressible Fluid flows (SMIF) with hybrid explicit finite difference scheme: second order of accuracy in space, minimum scheme viscosity and dispersion, capable for work in wide range of Reynolds numbers and monotonous) [5]. The Poisson equation for the pressure was solved by the Preconditioned Conjugate Gradients Method. For the identification of a vortex cores in the sphere wake the Hussain's $-\lambda_2$ vortex-eduction technique is used [6] (see fig. 1).

At the present paper the classification of the 3D separated homogeneous viscous fluid flow regimes around the sphere at $Re < 3000$ is refined and the formation mechanisms of vortices in the sphere wake for different flow regimes are described in detail ($Re = Ud/v$, where U is the free-stream velocity, d is the diameter of the sphere, and v is the kinematic viscosity). The O-type grid is used: (180 x 90 x 180).

CLASSIFICATION OF THE FLUID FLOW REGIMES AROUND A SPHERE

For $200<Re<270$ the flow is steady but not axisymmetrical with non zero lift/side and torque moment coefficients (double-thread wake). For $270 < Re < 400$ the periodical separation of the hairpin-shaped vortices is observed from one edge of the cylindrical shear layer (surrounding the recirculating zone of the sphere wake) and the time-average lift/side and torque moment coefficients are equal to zero. For $Re>400$ the periodical separation of the hairpin-shaped vortices is observed from opposite edges of the shear layer alternatively and the time-average lift/side and torque moment coefficients are equal to zero. Besides the regular and irregular rotation of the cylindrical shear layer are observed for $360 < Re < 400$ and for $Re > 600$ correspondingly. The Strouhal numbers St calculated here for $270 < Re < 3000$ ($0.125 < St < 0.193$) are in a good agreement with experimental and numerical results of the other researchers [2-3] ($St = fd/U$, where f is the frequency of the separation of the hairpin-shaped vortices).

FORMATION MECHANISMS OF VORTICES IN THE SPHERE WAKE

The detailed formation mechanism of vortices in the sphere wake for $270 < Re < 400$ is shown in fig. 1, where the periodical separation of the hairpin-shaped vortices from the top edge of the cylindrical separated shear layer (vortex sheet) is observed at $Re = 350$ during the period ($893<t<908$, $St=0.135$). In fig. 1 one half of the vortex structure has been removed for clarity. This formation mechanism can be divided in two main stages. At the first stage (fig. 1 (a-e)) the nascent hairpin-shaped vortex (facing upwards) is extracting from the recirculating zone of the wake. In fig. 1 (a) you can see the recirculating zone (in the vicinity of the sphere surface), the cylindrical vortex sheet (at the periphery of the recirculating zone) and the deformed vortex loop (facing upwards). The left part of this deformed vortex loop belongs to the lower part of the recirculating zone. In fig. 1 (b-e) this left part is extracting from the lower part of the recirculating zone and the side parts of the deformed vortex loop induce the rolling up of the side parts of the vortex sheet around them. As a result the deformed vortex loop (facing upwards) is transforming into the separated hairpin-shaped vortex (facing upwards) and an additional vortex loop (facing downwards) is induced by the interaction of the near wake flow and the outer flow (see fig. 1 (c-e)).

At the second stage (fig. 1 (f-h)) the additional vortex loop (facing downwards) is extracting from the recirculating zone of the wake. In fig. 1 (g-h) the left part of this additional vortex loop is extracting from upper part of the recirculating zone, shifted closer to the sphere and connected with the top part of the vortex sheet. As a result the new vortex ring arise in the recirculating zone and the top edge of the vortex sheet is rolling up cylindrically and detached from the vortex sheet in the form of the nascent deformed vortex loop (facing upwards) which then undergoes a stretching process (fig. 1 (h-a)) and so on.

For $Re>400$ the formation mechanism of vortices during the period can be also divided in two identical stages: the extraction of the hairpin-shaped vortices from opposite edges of the vortex sheet and from opposite parts of the recirculating zone of the wake. During a half of the period the lower (upper) part of the recirculating zone is fully separated from the vortex sheet (unlike fig. 1 (a)), shifted closer to the sphere and connected with the bottom (top) part of the vortex sheet. At the same time the nascent hairpin-shaped vortex (facing upwards (downwards)) is extracting from the lower (upper) part of the recirculating zone and the side parts induce the rolling up of the side and bottom (top) edges of the vortex sheet in the form of the next nascent hairpin-shaped vortex (facing downwards (upwards)).

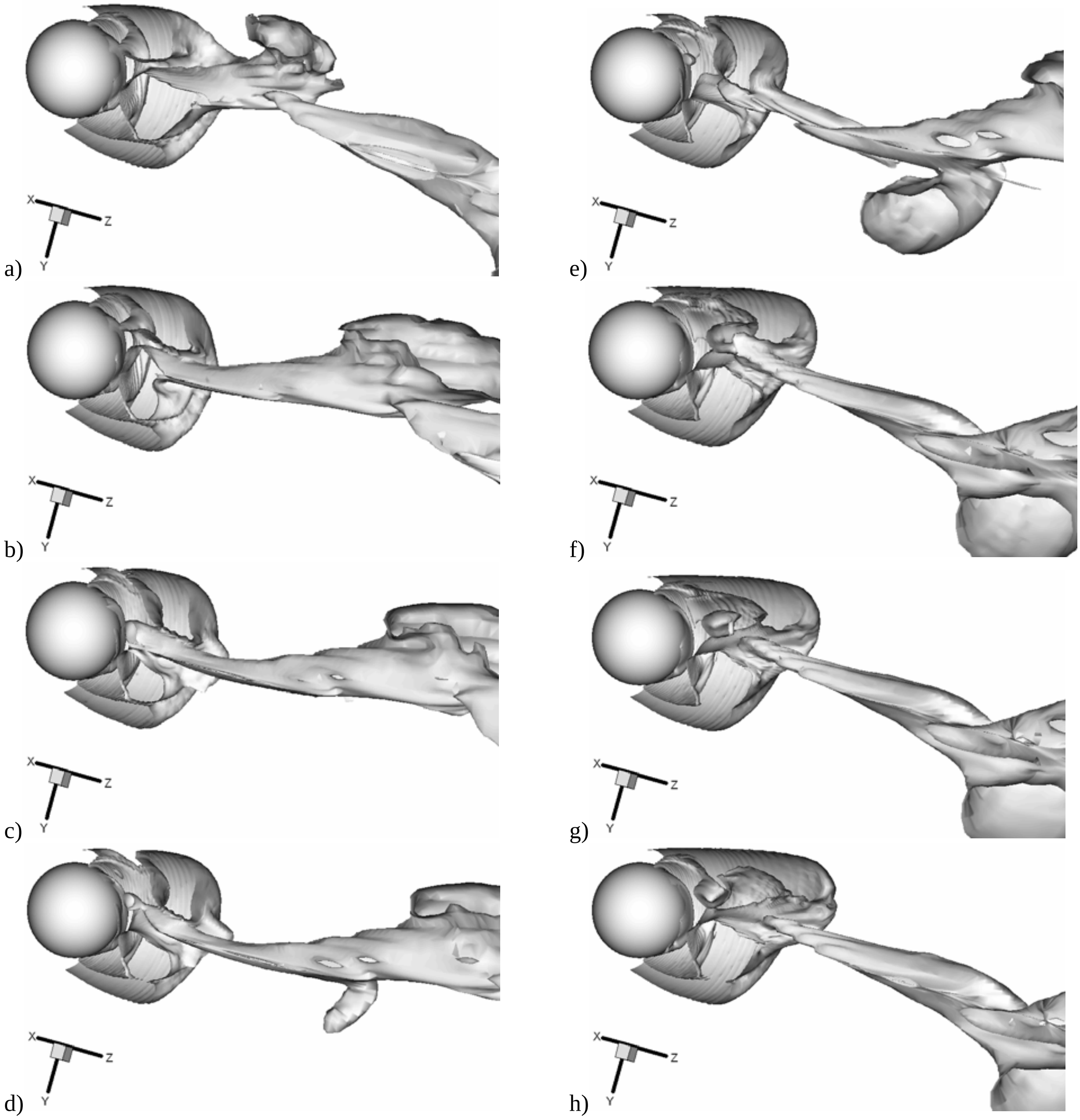

Fig. 1. *Re*=350. Vortex structures during a period ($893<t<908$): a) t=893, b) t=897, c) t=899, d) t=900, e) t=901.5, f) t=904.5, g) t=905, h) t=906 (the zero isosurfaces of the second eigen-values of the $\mathbf{S}^2+\mathbf{\Omega}^2$ tensor [6]).

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