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Numerical simulation and control of horseshoe vortex around an appendage–body junction

Liu Zhihua [a], Xiong Ying [a,*], Tu Chengxu [b]

[a] College of Naval Architecture and Power, Naval University of Engineering, Wuhan 430033, China
[b] China Jiliang University, Hangzhou 310018, China

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ABSTRACT

The horseshoe vortex generated around the appendage–body junction of submarines strongly influences the non-uniformity of submarine wakes at the propeller discs. The flow characteristics around the appended submarine body are numerically simulated and analyzed, and a new method on the vortex control baffle is presented. Then, the influence of the vortex control baffle on the horseshoe vortex generated at the sail–body junction is numerically studied, and the flow phenomena caused by the vortex control baffle with different transverse positions is investigated further. Results show that the vortex control baffle can induce a kind of attached vortex in a rotational direction opposite to the horseshoe vortex; these two kinds of vortices undermine each other. Furthermore, when the transverse position of the vortex control baffle is close to the horseshoe vortex, the state of the horseshoe vortex is directly affected, and the flow structure becomes even more complex. We adapt the vortex control baffle for the horseshoe vortex generated at the stern foil–body junction. Results from the numerical simulation of the flow around the fully appended submarine model indicate that the effect of the vortex control baffle greatly improves the performance of the submarine wake. The circumferential non-uniformity of the axial, tangential, and radial velocity components are decreased markedly. The engineering applicability of the vortex control baffle has been well presented.

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1. Introduction

A horseshoe vortex is a typical flow phenomenon around the appendage–body junction. It is typically found in the aerofoil–hull junction of an airplane, the appendage–body junction of a submarine, and the control surface–body junction of a torpedo, among others. The generation and evolution of the horseshoe vortex can strongly influence the hydrodynamic performance of engineering structures. Thus, it has attracted significant interest internationally, especially in the field of fluid dynamics.

As early as the 1960s, flow separation and vortices around surface protuberances have caught the attention of scholars. Since the 1980s, with the development of fluid experimental technology and numerical computation methods, flow measurements, numerical simulations and mechanism analysis on horseshoe vortices have been widely conducted.

Over the years, experiments on horseshoe vortices have been employed using different experimental technologies. Baker (1980, 1985) and Eckerle and Langston (1987) studied plate–cylinder junction flow with the oil stream visualization method, and analyzed the relationship between the generation of horseshoe vortex and flow separation. Using a particle image velocimeter, Pattenden et al. (2005) and Marakkos and Turner (2006) demonstrated the instantaneous flow characteristics of

* Corresponding author. Tel.: +86 27 83442758.
E-mail address: meining1014@sina.com (X. Ying).

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Nomenclature

CFL	Courant–Friedrichs–Lewy number, $dt\|U\|/\Delta$
C_G	correction factor
d	distance from the computational node to the closest wall
dt	time step size
D_i	test results
E_i	comparison error
G_V	production of the turbulent viscosity
k	turbulent kinetic energy
L	the overall length of main body
L_s	the mixing length for sub-grid scales
P_G	order of accuracy
r	distance from the test or calculated point to the axis of the model
r_G	refinement ratio of computational grids
R	maximum radius of main body
R_G	grid converge ratio
Re	Reynolds number
S_i	calculated values
$S_{\tilde{v}}$	source term in Spalart–Allmaras model
u_x	axial velocity
u_i	maximum value of velocity component
u_i	minimum value of velocity component
$u_{i\Delta}$	non-uniform coefficient
U_0	undisturbed inflow velocity
U_G	grid uncertainty
U_I	iterative uncertainty
U_T	time step uncertainty
U_{SM}	modeling uncertainty
U_{SN}	numerical simulation uncertainty
U_{Vi}	validation uncertainty
$\|U\|$	local velocity magnitude
V	volume of computational cell
x	distance from the propeller disc to header point of main body
x_i, x_j, x_k	coordinates in computational flow field
y^+	nondimensional distance
Y_V	destruction of the turbulent viscosity that occurs in the near-wall region
Δ, Δ_i, Δ_j, Δ_k	DES grid length scale
θ	circumferential angle
μ_t	turbulent viscosity
μ_{tL}	sub-grid-scale turbulent viscosity
v	molecular kinematic viscosity
$\tilde{v}$	turbulent kinematic viscosity
ρ	fluid density
τ_{ij}	sub-grid-scale stress
$\\|\ \\|_2$	stands for L2 norm
$\langle\ \rangle$	stands for point variable

horseshoe vortices in the areas where they are formed. Tsutsui (2008) tested boundary layer thickness around junction flows using surface oil stream patterns. Sahin et al. (2008a,b) studied the relationship between flow stagnation point and formation of horseshoe vortices. Braza and Hourigan (2008) investigated the method to control the unsteady separation of three-dimensional flow. Adaramola et al. (2010) showed the main types of time-averaged streamwise vortex pairs in the horseshoe vortex flow field.

With progress in computational fluid dynamics, numerical studies on horseshoe vortices were rapidly developed. Jones and Clarke (2005) studied junction flow based on the experiment carried out by Devenport and Simpson (1990) and compared the computational results. Dijk (2007) demonstrated the influence of Reynolds number on the formation of horseshoe vortices. El-Okda et al. (2008) studied flow separation and horseshoe vortex formation, the results of which showed that primary and secondary flow separations have major effects on horseshoe vortices. Seeta Ratnam and Vengadesan (2008) explored the simulated performance of the turbulence model. All these authors employed numerical simulations in their study of horseshoe vortices.

In dealing with the adverse effects of horseshoe vortices, some scholars explored methods for decreasing the strength and improving the hydrodynamic performance of engineering structures. Batcho (2001) designed a lifting surface based on the body–appendage junction flow. The small lifting surface was set in the upstream area of the appendage, and this induced a tip vortex believed to influence the generation of a horseshoe vortex. Devenport and Dewitz (1988) studied the structure of horseshoe vortices with a time-based method. In the experiment, submarine wakes were improved by adding an arc fillet to the body–appendage junction. Zhang et al. (2005, 2009) calculated the effects of the fillet fit to the sail and stern appendages by using Reynolds-averaged Navier–Stokes (RANS) equations. The fillet flow mechanism was then explained from the perspective of vorticity. Moreover, the fillets were shown to improve wake quality at the propeller discs of a submarine.

This paper takes the submarine geometry as the object of the study. The influence of the horseshoe vortex generated at the appendage–body junction on the submarine wake is investigated by numerical simulation. By analyzing its characteristics, a new method to control horseshoe vortex (i.e., by vortex control baffles) is presented. The effects of the vortex control baffle on the submarine horseshoe vortex and the submarine wake are also employed with numerical simulation. Finally, a set of vortex control baffles that can decrease effectively the circumferential non-uniformity of a submarine wake at the propeller disc is designed.

2. Simulation of horseshoe vortex and submarine wake

The horseshoe vortex is a kind of complex flow phenomenon around the appendage–body junction. Upender (1985) simulated the flow around plate–cylinder junctions with a low Reynolds number, the solutions of which were generated by