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Fluid dynamics and motion simulation of underwater glide vehicle

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1. Introduction

As a underwater vehicle with new thrust mode, the underwater glide vehicle had shown some enormous advantages. When it is moving, it changes its motion trajectory through changing the gravity, buoyancy and location of gravity, lateral wing. The underwater glide vehicle had many advantages, such as simple structure, low resistance, low noise, high utilize ratio of energy, and it can fit the need of manufacture cost, energy expend, and long time navigation, so it can be used as a kind of long time auto underwater carry platform or surveillant platform [1].

This paper presents a dynamics model of underwater glide vehicle. The underwater glide vehicle has a compressed body and a pair glide hydrofoil, and it is propelled and controlled through changing the gravity and location of gravity. Section 2 introduces the dimensional dynamics model of underwater glide vehicle. Section 3 presents the model for fluid dynamics of underwater glide vehicle. Section 4 provides the simulation results of the glide motion of the underwater glide vehicle. Finally, Section 5 draws conclusions.

2. Dimensional dynamics model

First, the kinematics equations of the underwater glide vehicle can be built.

We can commonly select two coordinate systems that are used to describe the underwater glide vehicle kinematics (Fig. 1): earth-fixed frame, which can be regarded as an inertial frame, and body-fixed frame. The position and orientation of the vehicle are described relative to the earth-fixed frame, while the linear and angular velocity and the control forces/moments are described in the body-fixed frame. The vector form of these expressions is [2 - 4]:

$\boldsymbol{R} = [x_0, y_0, z_0, \theta, \psi, \varphi]^{\mathrm{T}}$ position and orientation vector in earth-fixed frame.

$\boldsymbol{V} = [v_x, v_y, v_z, \omega_x, \omega_y, \omega_z]^{\mathrm{T}}$ velocity vector in body-fixed frame.

$\boldsymbol{f} = [F_x, F_y, F_z, M_x, M_y, M_z]^{\mathrm{T}}$ force/moment vector in body-fixed frame.

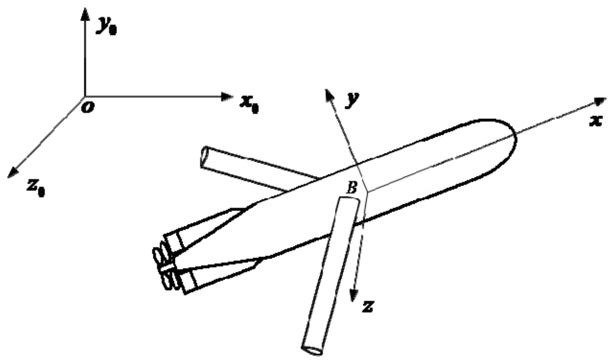

Fig. 1 Underwater glide vehicle frames

The velocity vectors in body-fixed frame and in earth-fixed frame can be described as [3, 4]

$$\dot{R} = J(R)V \tag{1}$$

where $J(R)$ is the rotation matrix, which is shown in equation (2)

$$J(R) = \begin{bmatrix} (C_E^B)^{-1} & 0 \\ 0 & T^{-1} \end{bmatrix} \tag{2}$$

where

$$C_E^B = \begin{bmatrix} cos\theta\, cos\psi & -sin\theta\, cos\psi\, cos\varphi + sin\psi\, sin\varphi & sin\theta\, cos\psi\, cos\varphi + sin\psi\, cos\varphi \\ sin\theta & cos\theta\, cos\varphi & -cos\theta sin\varphi \\ -cos\theta\, sin\psi & sin\theta\, sin\psi\, cos\varphi + cos\psi\, sin\varphi & -sin\theta\, sin\psi\, sin\varphi + cos\psi\, cos\varphi \end{bmatrix}$$

$$T = \begin{bmatrix} 1 & 0 & sin\theta \\ 0 & sin\varphi & cos\theta\, cos\varphi \\ 0 & cos\varphi & -cos\theta\, sin\varphi \end{bmatrix}.$$

Second, the dynamical equations of the underwater glide vehicle can be built.

Using the momentum theorem and the angular momentum theorem, the dynamical equations of underwater glide vehicle can be given by [5, 6]

$$M_{RB}\dot{V} + C_{RB}(V)V = f \tag{3}$$

where

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & mz_c & -my_c \\ 0 & m & 0 & -mz_c & 0 & mx_c \\ 0 & 0 & m & my_c & -mx_c & 0 \\ 0 & -mz_c & my_c & J_{xx} & J_{xy} & J_{xz} \\ mz_c & 0 & -mx_c & J_{yx} & J_{yy} & J_{yz} \\ -my_c & mx_c & 0 & J_{zx} & J_{zy} & J_{zz} \end{bmatrix} \tag{4}$$

$$C_{RB}(V)=\begin{bmatrix} 0 & -m\omega_z & m\omega_y & m(y_c\omega_y+z_c\omega_z) & -mx_c\omega_y & -mx_c\omega_z \\ m\omega_z & 0 & -m\omega_x & -my_c\omega_x & m(z_c\omega_z+x_c\omega_x) & -my_c\omega_z \\ -m\omega_y & m\omega_x & 0 & -mz_c\omega_x & -mz_c\omega_y & m(x_c\omega_x+y_c\omega_y) \\ -m(y_c\omega_y+z_c\omega_z) & my_c\omega_x & mz_c\omega_x & 0 & -J_{yz}\omega_y-J_{xz}\omega_x+J_{zz}\omega_z & J_{yz}\omega_z+J_{xy}\omega_x-J_{yy}\omega_y \\ mx_c\omega_y & -m(z_c\omega_z+x_c\omega_x) & mz_c\omega_y & J_{yz}\omega_y+J_{xz}\omega_x-J_{zz}\omega_z & 0 & -J_{xz}\omega_z-J_{xy}\omega_y+J_{xx}\omega_x \\ mx_c\omega_z & my_c\omega_z & -m(x_c\omega_x+y_c\omega_y) & -J_{yz}\omega_z-J_{xy}\omega_x+J_{yy}\omega_y & J_{xz}\omega_z+J_{xy}\omega_y-J_{xx}\omega_x & 0 \end{bmatrix} \quad (5)$$

The right hand term in Eq. (3) is the vector of external forces and moments, such as weight, buoyant, fluid dynamics which produced by the motion of underwater glide vehicle, and disturbed force which produced by the environment. In this paper, we suppose that the underwater glide vehicle motions in the enough deep, enough big and enough quiescent water, so the disturbed force which produced by the environment is ignorable.

And the fluid dynamics which produced by the motion of underwater glide vehicle can be described by the mass forces and drag forces of the main body and the fluid dynamics of the glide hydrofoil. The mass forces and drag forces of the main body can be computed by the model which is detailed described in the literature [3] and [4]. And the model of the fluid dynamics of the glide hydrofoil is built in the next section.

3. Fluid dynamics of underwater glide vehicle

The fluid dynamics of underwater glide vehicle can be calculated by the CFD. In this part, the model of the fluid dynamics was built and the fluid dynamics of underwater glide vehicle was calculated.

The basic of the CFD model is Reynolds-Averaged Navier-Stokes equation [7, 8].

1. Continuity equation

$$\frac{\partial \rho}{\partial t}+div(\rho\mathbf{u})=0 \quad (6)$$

2. Momentum equation

$$\frac{\partial(\rho u)}{\partial t}+div(\rho u\mathbf{u})=div(\mu\ grad\ u)-\frac{\partial p}{\partial x}+\left[-\frac{\partial\left(\rho\overline{u'^2}\right)}{\partial x}-\frac{\partial\left(\rho\overline{u'v'}\right)}{\partial y}-\frac{\partial\left(\rho\overline{u'w'}\right)}{\partial z}\right]+S_u\ \frac{\partial(\rho v)}{\partial t}+$$

$$+div(\rho v\mathbf{u})=div(\mu\ grad\ v)-\frac{\partial p}{\partial y}+\left[-\frac{\partial\left(\rho\overline{u'v'}\right)}{\partial x}-\frac{\partial\left(\rho\overline{v'^2}\right)}{\partial y}-\frac{\partial\left(\rho\overline{v'w'}\right)}{\partial z}\right]+S_v\ \frac{\partial(\rho w)}{\partial t}+div(\rho w\mathbf{u})=$$

$$=div(\mu\ grad\ w)-\frac{\partial p}{\partial z}+\left[-\frac{\partial\left(\rho\overline{u'w'}\right)}{\partial x}-\frac{\partial\left(\rho\overline{v'w'}\right)}{\partial y}-\frac{\partial\left(\rho\overline{w'^2}\right)}{\partial z}\right]+S_w \quad (7)$$

3. Transportation equation of other variable

$$\frac{\partial(\rho\phi)}{\partial t}+div(\rho\mathbf{u}\phi)=div(\Gamma\ grad\ \phi)+\left[-\frac{\partial\left(\rho\overline{u'\phi'}\right)}{\partial x}-\frac{\partial\left(\rho\overline{v'\phi'}\right)}{\partial y}-\frac{\partial\left(\rho\overline{w'\phi'}\right)}{\partial z}\right]+S \quad (8)$$

The RNG $k-\varepsilon$ viscous model which was obtained by Yakhot and Orzag, is ameliorated from the standard $k-\varepsilon$ viscous model.

The RNG $k-\varepsilon$ viscous model includes many assumptions whose basis in physics is not transparent, and considerable controversy surrounds the legitimacy of this formalism. But the its advantage is that the eddy flow of the average flow was included through modifying the turbulent viscosity, and the time average change ratio E_{ij} of the dominating flow was also included through adding a item to the Equation ε. So the adding item in the RNG $k-\varepsilon$ viscous model not only is related with the flow, but also is a function of dimensional coordinate. And the RNG $k-\varepsilon$ viscous model is good at computing the high change ratio and high curve flow. The equation k and equation ε are

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right]+G_k+\rho\varepsilon \quad (9)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right]+$$
$$+\frac{C_{1\varepsilon}^{*}\varepsilon}{k}G_k-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \quad (10)$$

where $\mu_{eff}=\mu+\mu_t$, $\mu_t=\rho C_\mu \frac{k^2}{\varepsilon}$, $C_\mu=0.0845$,

$\alpha_k=\alpha_\varepsilon=1.39$, $C_{1\varepsilon}^{*}=C_{1\varepsilon}-\frac{\eta(1-\eta/\eta_0)}{1+\beta\eta^3}$, $C_{1\varepsilon}=1.42$,

$C_{2\varepsilon}=1.68$, $\eta=(2E_{ij}E_{ij})^{1/2}\frac{k}{\varepsilon}$, $E_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$,

$\eta_0=4.377$, $\beta=0.012$.

The CFD model can be calculated by the numerical procedure, the SIMPLE.

The acronym SIMPLE stems from semi-implicit method for the pressure-linked equations. The SIMPLE algorithm uses a relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field. The SIMPLE algorithm is a comprehensively used algorithm of the flow field in engineering, and it is usually used in computing the incompressible flow.

The calculated results of fluid dynamics.

For simulating the motion of the underwater glide vehicle, we calculated the fluid dynamics, which are shown in the Figs. 2, 3 and the Table.

Table

Calculate results of fluid dynamics

Fluid dynamics parameter	Calculate results
C_{xS}	0.2654
C_y^α	12.112
m_z^α	-0.5324

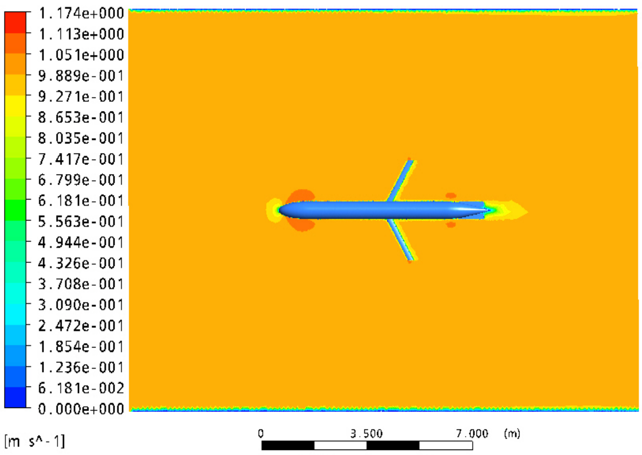

Fig. 2 Velocity contour of underwater glide vehicle

In the Fig. 2, the velocity contour of the underwater glide vehicle was shown, and in the Fig. 3, the surface stress contour of the underwater glide vehicle was shown. Through this two Figs., we can find that the fluid field of the underwater glide vehicle is steady, so the calculation is reasonable.

In the Table, the calculate results of fluid dynamics were shown. Through the table, we can find the lift force parameter is bigger than the normal underwater vehicle. It is because the underwater glide vehicle has a big glide hydrofoil [8].

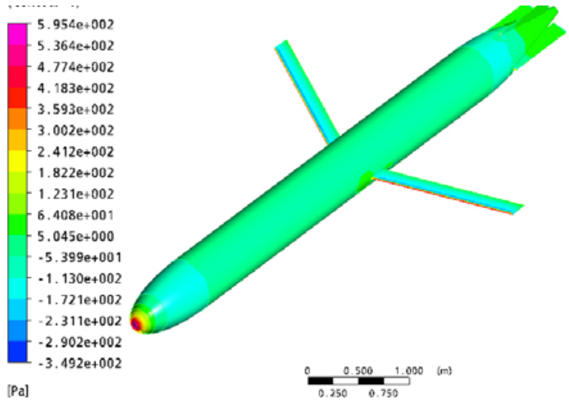

Fig. 3 Surface stress contour of underwater glide vehicle

4. Simulation

For demonstrating the dynamics model of underwater glide vehicle and the model for fluid dynamics of underwater glide vehicle, a numerical example of the

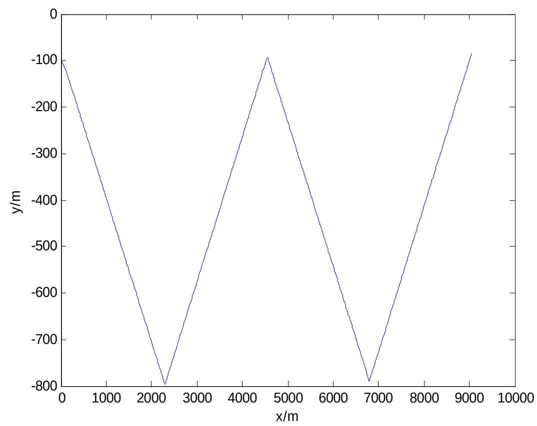

Fig. 4 Trajectory curve

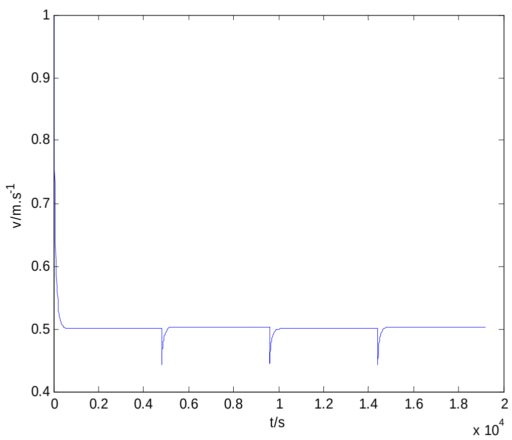

Fig. 5 Velocity curve

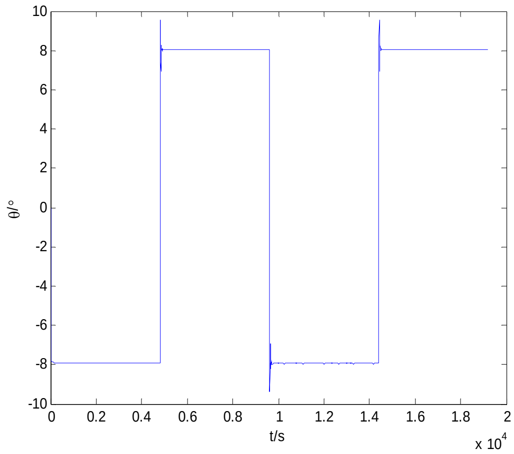

Fig. 6 Pitching angle curve

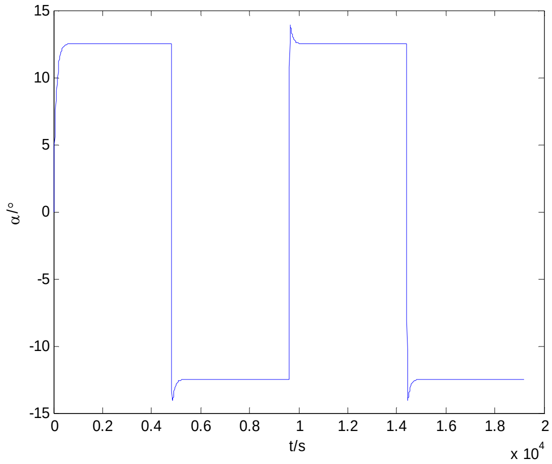

Fig. 7 Attack angle curve

motion of the underwater glide vehicle is presented. The underwater glide vehicle has a compressed body and a pair glide hydrofoil, and it is propelled and controlled through changing the gravity and location of gravity.

The glide motion of the underwater glide vehicle was simulated in this paper, and the results were shown in Figs. 4, 5, 6 and 7. Fig. 4 gives the trajectory curve of the underwater glide vehicle, and Fig. 5 gives the velocity curve. Figs. 6 and 7 give the curves of pitching angle and attack angle.

The simulation results indicate that the underwater glide vehicle can steadily complete the underwater glide motion, and the underwater glide can move forward about 2293 m, when the depth change about 700 m. The results also show that the velocity, pitching angle and attack angle has definite fluctuate when the underwater glide vehicle change the glide mode, and they would get stabilization at a definite time.

5. Conclusions

The dynamics model of underwater glide vehicle and the model for fluid dynamics of glide hydrofoil were presented in this paper for analyzing the dynamics of underwater glide vehicle. The simulation results show that:

1. The underwater glide vehicle can steadily complete the underwater glide motion, and the glide radio achieved 3.27.

2. The motion parameter of the underwater glide vehicle, such as velocity, pitching angle and attack angle has definite fluctuate when the underwater glide vehicle change the glide mode, and they would get stabilization at a definite time.

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POVANDENINIO SKLENDŽIANČIO ĮRENGINIO SKYSČIŲ DINAMIKA IR JUDESIO IMITACIJA

R e z i u m ė

Naujos traukos povandeninis sklendžiantis įrenginys turi keletą pranašumų. Judėdamas jis keičia savo trajektoriją keisdamas sunkį, keliamąją jėgą, sunkio centro padėtį bei šoninį sparną. Sklendžiantis povandeninis įrenginys yra paprastos konstrukcijos, pasižymi nedidele trintimi, dideliu energijos naudingumo koeficientu , palyginti nedidelė jo gamybos kaina, jis gali ilgai plaukioti, gali būti panaudotas platformai valdyti ir prižiūrėti.

Straipsnyje aprašomas povandeninio sklendžiančio įrenginio dinaminis modelis. Įrenginys turi siaurą korpusą, du slydimo hidrosparnus ir yra varomas ir valdomas keičiant sunkį ir jo padėtį. Antrame straipsnio skyriuje supažindinama su įrenginio erdviniu dinaminiu modeliu. Trečiame skyriuje pristatytas įrenginio skysčio dinamikos modelis. Ketvirtame skyriuje apžvelgiami įrenginio slydimo judesio imitavimo rezultatai, o penktame pateiktos išvados.

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FLUID DYNAMICS AND MOTION SIMULATION OF UNDERWATER GLIDE VEHICLE

S u m m a r y

As a underwater vehicle with new thrust mode, the underwater glide vehicle had shown some enormous advantages. When it is moving, it changes its motion trajectory through changing the gravity, buoyancy and location of gravity, lateral wing. The underwater glide vehicle had many advantages, such as simple structure, low resistance, low noise, high utilize ratio of energy, and it can fit the need of manufacture cost, energy expend, and long time navigation, so it can be used as a kind of long time auto underwater carry platform or surveillant platform. [1]

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