

Study on Floating Motion Characteristics and Stability of Unpowered Underwater Carrier (UUC)

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Abstract. The water-exit velocity and attitude of UUC are crucial for underwater launching aircraft-like payloads. To ensure that the design of the UUC is reasonable, the investigation on motion characteristics and stability of the UUC in vertical floating process are carried out. Firstly, a computational model of the UUC has been established. Then, a combination method of theoretical calculations and CFD simulations has been used to study the relationship between model parameters and hydrodynamics parameters. Finally, stability analysis has been conducted for initial heading angle of 3° and 6°. The results show that increasing the net buoyancy can allow the UUC to obtain a larger water-exit velocity, while to reduce accelerated time and distance. The designed UUC can achieve stably convergence under the disturbance of initial heading angle, indicating that the UUC has a good motion stability in vertical rising process.

Keywords: Water-exit velocity and attitude; Floating motion characteristics; Stability; UUC.

1. Introduction

How to get out of the water is one of the key technologies for underwater launching aircraft-like payloads. Underwater carriers are important underwater vehicles for achieving this purpose, which are used to isolate the payloads from the ocean environment. The main function of underwater carriers are to transport aircraft-like payloads from the sea-bottom or deep-sea to the sea-surface and launch them. And it requires underwater carriers to meet the launch conditions of aircraft-like payloads, such as the water exit velocity and the water-exit attitude stability, so that the payloads can adapt the complexity of the actual sea environment.

In order to reduce the resistance in water, the shape of underwater carriers is usually designed as a torpedo-like hydrodynamic shape. And the underwater carriers usually adopt a powerless rising method so as to save energy consumption. According to the underwater carrier with or without propulsor, it can be divided into two categories: The Unpowered Underwater Carrier (UUC) and the Powered Underwater Carrier (PUC). Among them, the UUC must have a positive net buoyancy. On the premise of shape design, it mainly depends on the initial velocity and the difference between its own buoyancy and gravity to affect the floating motion characteristics of UUC.

Currently, research on the free-floating motion characteristics has become one of the hot topics among scholars. Liang Li [1] modeled and simulated the floating motion process of the buoy. Tianjian Zhang [2] proposed a fast motion prediction method of floating and diving for the buoyancy-driven vehicle's based on numerical simulation. Haiyang Zhang [3] conducted dynamic simulation of the inclined climbing floating process of UUC by using CFD method. Zhichao Zhao [4] has established a space motion simulation model of unpowered deep-sea vehicles, and explored the effect of initial launch conditions on the trim ascent motion. Qiaosheng Zhao [5] presented a stability analysis method for pure floating bodies of an arbitrary shapes. Xuejing Zhang [6] studied the floating stability of pontoon launcher. Yujin Lu [7] drawn a conclusion that tail fin can increase the stability of UUC.

Taking the above research technologies into account, the paper studied the floating motion characteristics and stability of the UUC with already determined design features, such as shape and tail fin. The influence rules between the model parameters and the rising motion characteristics parameters were obtained. The research findings can not only be used to guide UUC design but also to assess whether the design meets the engineering application requirements.

1.1 Model Parameter

The research object is an UUC, which consists of the main body with four crisscross-type tail wings, as shown in Fig. 1. The main body of the UUC has a symmetrical cross-section shape with a length-diameter ratio $L/D=12:1$, and it can be divided into three parts (as exhibited in Fig. 2): The entrance segment $L1$, the parallel middle segment $L2$ and the run segment $L3$, and their length ratio is $L1:L2:L3=1.5:8:2.5$. The wet surface area and volume of the UUC is S and V respectively, and that of the parallel middle segment is $S2$ and $V2$ respectively, then there is $S/S2=1.44:1$ and $V/V2=1.27:1$. The neutral point and center of gravity of the UUV are both located on its axis, with the neutral point ahead and the center of gravity behind, and the distance between the neutral point and the center of gravity is ΔL , which meets that $\Delta L/L=1:20$. The four tail wings of the UUC is identical, with the average extend length and average chord length being 2:5 and 7:10, respectively, of the maximum cross-section diameter D . The UUC is designed with a positive net buoyancy ($B_N > 0$) to ensure that it can quickly float to the sea-surface after being released underwater in a vertical stance.

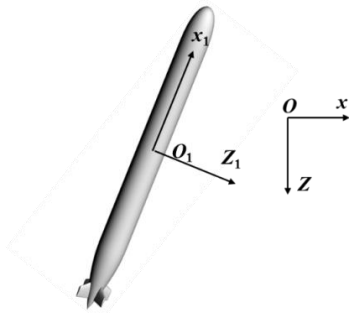


Fig. 1 The 3D model of UUC

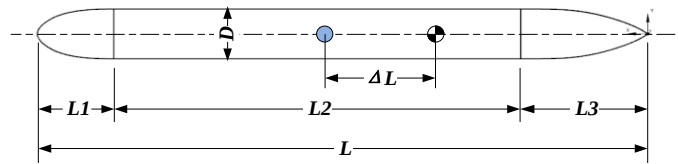


Fig. 2 The main line type of UUC

1.2 Definition and Transformation of Coordinate System

1.2.1 Definition of coordinate systems

To describe the motion characteristics of the UUC in rising process, motion equations needs to be established through the introduction of an inertial coordinate system $O-xyz$ and a body-fixed coordinate system $O_1-x_1y_1z_1$. The inertial coordinate system $O-xyz$ is coupling with the Earth and has a fixed origin O on the ground. The Ox axis is located in any direction within the horizontal plane; The Oz axis is within the vertical plane of the ground and has the positive direction towards the center of the Earth; The Oy axis is determined according to the right-hand rule. While the body-fixed coordinate system $O_1-x_1y_1z_1$ is fixed with the UUC and has the origin O_1 as the mass center of the UUC. The O_1x_1 axis is the symmetric axis of the UUC and points to the head of the UUC; The O_1z_1 axis is within the longitudinal plane of the UUV; The O_1y_1 axis is also determined according to the right-hand rule.

1.2.2 Transformation of coordinate systems

The UUC has three kinds of attitude changes in the free floating process, and they can be described as: The roll angle φ (Positive by rolling to the right), the pitch angle θ (Positive with upward pitch) and the yaw angle ϕ (Positive by yawing to the right). Moreover, to facilitate the solution of the kinematics equations, the motion parameters of the UUC need to be transformed from the inertial coordinate system to the body-fixed coordinate system. And the coordinate transformation equation is:

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = T \begin{bmatrix} x \\ y \\ z \end{bmatrix}. \quad (1)$$

In the expression above, the coordinate transformation matrix T can be expressed:

$$T = \begin{bmatrix} \cos \theta \cos \phi & \sin \theta & -\cos \theta \sin \phi \\ -\cos \varphi \sin \theta \cos \phi + \sin \varphi \sin \phi & \cos \varphi \cos \theta & \cos \varphi \sin \theta \sin \phi + \sin \varphi \cos \phi \\ \sin \varphi \sin \theta \cos \phi + \cos \varphi \sin \phi & -\sin \varphi \cos \theta & -\sin \varphi \sin \theta \sin \phi + \cos \varphi \cos \phi \end{bmatrix}. \quad (2)$$

1.3 Dynamic Equations

During the rising process, the UUC is mainly affected by the combined action of three forces: Gravity G , Buoyancy B and Resistance R . And its gravity G as well as buoyancy B can be considered as fixed values, while the rising resistance R changes with the rising velocity U . The rising process of the UUC can be divided into two phases: Acceleration phase and constant velocity phase. In the acceleration phase, the rising velocity U increases continuously, and the rising resistance R also increases continuously, while the rising acceleration a will reduce with them. When the resistance R reaches the value of the net buoyancy B_N of the UUC, the acceleration a will reduce to zero, and the rising velocity U will reach its maximum value, named terminal velocity U_T , at which the floating process turns from acceleration motion to constant velocity motion. So there are:

$$\begin{cases} ma = B_N - R = B - G - R \\ R = \frac{1}{2} \rho S U^2 C_d = \frac{1}{2} \rho S U^2 (C_f + C_p + \Delta C_f) \end{cases} \quad (3)$$

Where: m and ρ represent mass and density of the UUC; C_d represents friction coefficient; C_p represents shape friction coefficient; ΔC_f represents roughness added friction coefficient; C_f represents friction coefficient, and $C_f = \frac{0.075}{(\lg \text{Re} - 2)^2}$; Re represents Reynolds number, and $\text{Re} = UL/\gamma$; γ represents water viscosity.

Since rising velocity U and the acceleration a are functions of time t , there is:

$$a(t) = (B/G - 1)g - \frac{1}{2} \rho g S (U(t))^2 \left(\frac{0.075}{(\lg(LU(t)/\gamma) - 2)^2} + C_p + \Delta C_f \right) / G \quad (4)$$

Therefore, we can get:

$$\int_{t=0}^{t=t1} a(t) dt = U(t) - U(0), \quad \int_{t=0}^{t=t1} U(t) dt = H(t) \quad (5)$$

Where: $t1$ represents the rising time; $H(t)$ represents the rising depth.

And the corresponding boundary conditions are:

$$U(0) = 0, \quad a(0) = (B/G - 1)g \quad (6)$$

1.4 Kinematics Equations

The kinematics equations of the UUC in the rising process mainly include the translational motion equations and rotation movement equations. If the angular velocity component of the UUC around the origin O_1 of the body-fixed coordinate system $O_1-x_1y_1z_1$ is (p, q, r) , and the component of the

rising velocity U at the origin O_1 of the body-fixed coordinate system $O_1-x_1y_1z_1$ is (u, v, w) ; The rotation moment is I , and the rudder angle is δ ; The coefficient corresponding to the main fluid momentum vector and the main torque vector of the UUC are (X', Y', Z') and (K', M', N') respectively. Based on the momentum and moment theorems, we can obtain the kinematics equations of the UUC.

The axial motion equation is:

$$\begin{aligned} & m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] \\ &= \frac{1}{2}\rho L^4(X'_{qq}q^2 + X'_{rr}r^2 + X'_{rp}rp) + \frac{1}{2}\rho L^3(X'_u\dot{u} + X'_{vr}vr + X'_{wq}wq) + \frac{1}{2}\rho L^2(X'_{uu}u^2 + X'_{vv}v^2 + X'_{ww}w^2) \\ &+ \frac{1}{2}\rho L^2u^2(X'_{\delta_r\delta_r}\delta_r^2 + X'_{\delta_s\delta_s}\delta_s^2) - (G - B)\sin\theta \end{aligned} \quad (7)$$

The transverse motion equation is:

$$\begin{aligned} & m(\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(pq + \dot{r})) \\ &= \frac{1}{2}\rho L^4(Y'_i\dot{r} + Y'_{p|p}|p| + Y'_{pq}pq + Y'_{qr}qr + Y'_{r|r}|r|) + \frac{1}{2}\rho L^3(Y'_v\dot{v} + Y'_{ur}ur + Y'_{wp}wp + Y'_{wr}wr + Y'_{v|v}|\frac{v}{|v|}\sqrt{v^2 + w^2}|r|) \\ &+ \frac{1}{2}\rho L^2(Y'_{uv}uv + Y'_{uw}uw + Y'_{v|v}|v|\sqrt{v^2 + w^2}) + \frac{1}{2}\rho L^2Y'_{\delta_r}u^2\delta_r + (G - B)\cos\theta\sin\varphi \end{aligned} \quad (8)$$

The vertical motion equation is:

$$\begin{aligned} & m(\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rp - \dot{q}) + y_G(rq + \dot{p})) \\ &= \frac{1}{2}\rho L^4(Z'_q\dot{q} + Z'_{pp}p^2 + Z'_{qq}q^2 + Z'_{rp}rp + Z'_{q|q}|q|) + \frac{1}{2}\rho L^3(Z'_w\dot{w} + Z'_{uq}uq + Z'_{wq}wq + Z'_{w|w}|\frac{w}{|w|}\sqrt{v^2 + w^2}|q|) \\ &+ \frac{1}{2}\rho L^2(Z'_{vv}v^2 + Z'_{uw}uw + Z'_{u|w}|u||w| + Z'_{w|w}|w|\sqrt{v^2 + w^2} + Z'_{ww}w^2) + (G - B)\cos\theta\cos\varphi \end{aligned} \quad (9)$$

The rolling motion equation is:

$$\begin{aligned} & I_x\dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} + m(y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp + ur)) \\ &= \frac{1}{2}\rho L^5(K'_p\dot{p} + K'_i\dot{r} + K'_{qr}qr + K'_{pq}pq + K'_{p|p}|p| + K'_{r|r}|r|) + \frac{1}{2}\rho L^4(K'_{vq}vq + K'_{wp}wp + K'_{wr}wr) \\ &+ (y_GG - y_BB)\cos\theta\cos\varphi - (z_GG - z_BB)\cos\theta\sin\varphi \end{aligned} \quad (10)$$

The pitching motion equation is:

$$\begin{aligned} & I_y\dot{q} + (I_x - I_z)rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{zx} + (qp - \dot{r})I_{yz} + m(z_G(\dot{u} - vr + wq) - x_G(\dot{w} - uq + vp)) \\ &= \frac{1}{2}\rho L^5(M'_q\dot{q} + M'_{pp}p^2 + M'_{rr}r^2 + M'_{rp}rp + M'_{q|q}|q|) + \frac{1}{2}\rho L^4(M'_w\dot{w} + M'_{vr}vr + M'_{vp}vp) \\ &+ \frac{1}{2}\rho L^4(M'_quq + M'_{q|q}|u||q|\delta_s + M'_{w|q}\sqrt{v^2 + w^2}q) - (x_GG - x_BB)\cos\theta\cos\varphi - (z_GG - z_BB)\sin\theta \end{aligned} \quad (11)$$

The yawing motion equation is:

$$\begin{aligned}
 & I_z \dot{r} + (I_y - I_x) pq - (\dot{q} + rp) I_{yz} + (q^2 - p^2) I_{xy} + (rq - \dot{p}) I_{zx} + m(x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)) \\
 &= \frac{1}{2} \rho L^5 (N'_i \dot{r} + N'_p \dot{p} + N'_{|p|} p |p| + N'_{qr} qr + N'_{pq} pq + N'_{r|r|} r |r|) + \frac{1}{2} \rho L^4 (N'_v \dot{v} + N'_{wr} wr + N'_{wp} wp + N'_{vq} vq) \\
 &+ \frac{1}{2} \rho L^4 (N'_p up + N'_r ur + N'_{|r|\delta_r} u |r| \delta_r + N'_{|v|r} \sqrt{v^2 + w^2} r) + \frac{1}{2} \rho L^3 (N'_o u^2 + N'_v uv + N'_{v|v|} v \sqrt{v^2 + w^2}) \\
 &+ \frac{1}{2} \rho L^3 (N'_{vw} vw + N'_{\delta_r} u^2 \delta_r) + (x_G G - x_B B) \cos \theta \sin \varphi + (y_G G - y_B B) \sin \theta
 \end{aligned} \tag{12}$$

And the kinematics equations are:

$$U^2 = u^2 + w^2 + v^2 \tag{13}$$

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 1 & -\tan \theta \cos \varphi & \tan \theta \sin \varphi \\ 0 & \sin \varphi & \cos \varphi \\ 0 & \cos \varphi / \cos \theta & -\sin \varphi / \cos \theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{14}$$

1.5 Simulation Model

See Fig. 3, the zoom ratio of the numerical simulation model is 1:1. The computational domain is a circular cylinder with a length of $5L$ and a diameter of $12D$, which includes the entire UUC model. The head and tail of the UUC model are separated by a distance of $1.5L$ and a distance of $2.5L$ with the left and right boundaries of the computational domain. The RNG k- ϵ turbulent model is used for steady-state calculations. The boundary layer of the computational grid has a thickness of 1mm, and the wall y^+ distribution satisfies the requirements $y^+ < 300$ of the turbulent model.

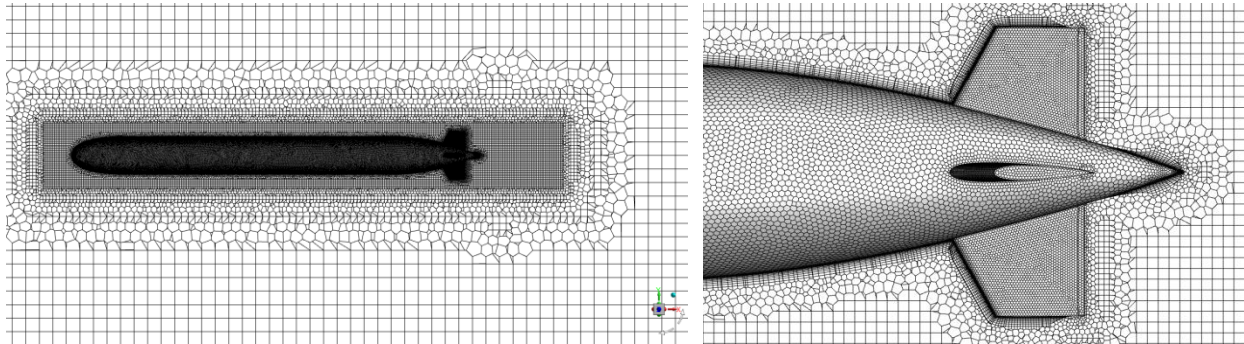


Fig. 3 The UUC meshing model in computational domain

1.6 Calculation of Resistance Coefficient

Before studying the rising process of the UUC, it is necessary to perform numerical simulation calculations to solve the force distribution on the UUC while traveling at a constant speed. Then, the relevant hydrodynamic coefficient can be obtained based on some formulas. In the example case (such as Fig. 4-6), the total resistance force acting on the UUC is 4347.6N when the rising velocity is 0.8 times than the total length L of the UUC per second. And the total resistance coefficient can be calculated as $C_d = 0.002409$. The friction resistance coefficient can be calculated by using the ITTC formula as $C_f = 0.002029$. Therefore, the shape resistance coefficient of the UUC calculated by numerical simulation is $C_p = C_d - C_f = 0.000380$.

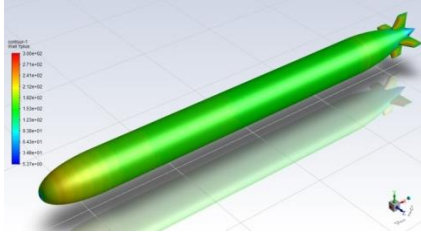


Fig. 4 The wall y^+ distribution

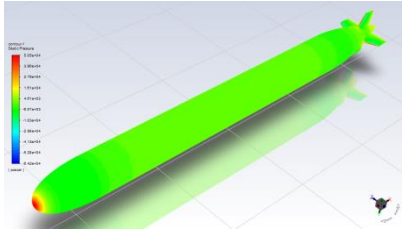


Fig. 5 Pressure cloud map

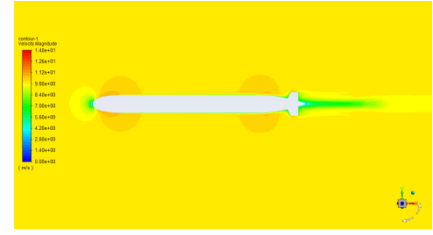


Fig. 6 Velocity cloud map

2. Calculation Results

2.1 Relationship between Terminal Velocity and Net Buoyancy

Through simulation and computation, we can obtain the curves of the rising velocity with time under different net buoyancy conditions for the UUC, as shown in Fig.7. When the net buoyancy is fixed, the rising velocity gradually increases with the change of time, and finally reaches a stable value, which is the terminal velocity. Moreover, the larger the net buoyancy, the larger the corresponding rising velocity at any point in the floating process, and the larger the terminal velocity.

So the curve of the required net buoyancy with the terminal velocity can be gotten, as shown in Fig. 8. As can be seen from the figure, the relationship between the terminal velocity and the net buoyancy of the UUC is described, which shows an approximate linear relationship, and the larger the terminal velocity, and the larger the required net buoyancy.

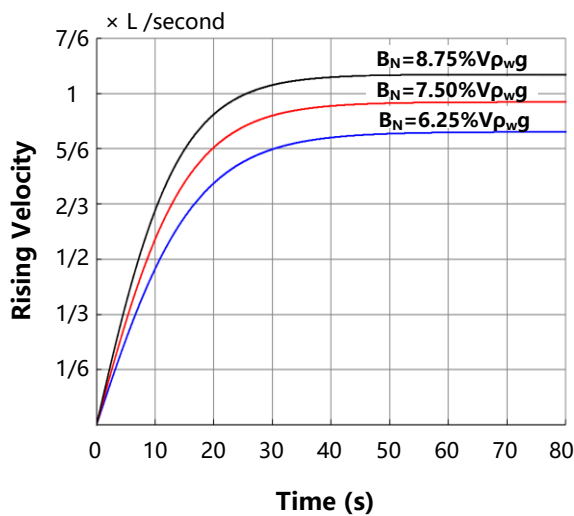


Fig. 7 Curves of rising velocity with time

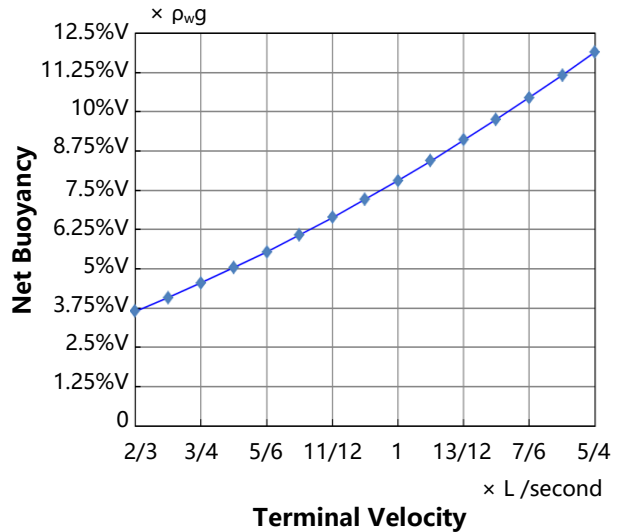


Fig. 8 Curve of the required net buoyancy

2.2 Accelerated Time and Distance at Different Net Buoyancy

As illustrated in Fig. 9, they are the curves of the accelerated time and distance of the UUC at different net buoyancy, and their change trends are basically similar. The greater the net buoyancy, the shorter the accelerated time, and the closer the accelerated time is to the time corresponding to different terminal velocity. Similarly, the greater the net buoyancy, the smaller the accelerated distance, and the closer the accelerated distance is to the distance corresponding to different terminal velocity.

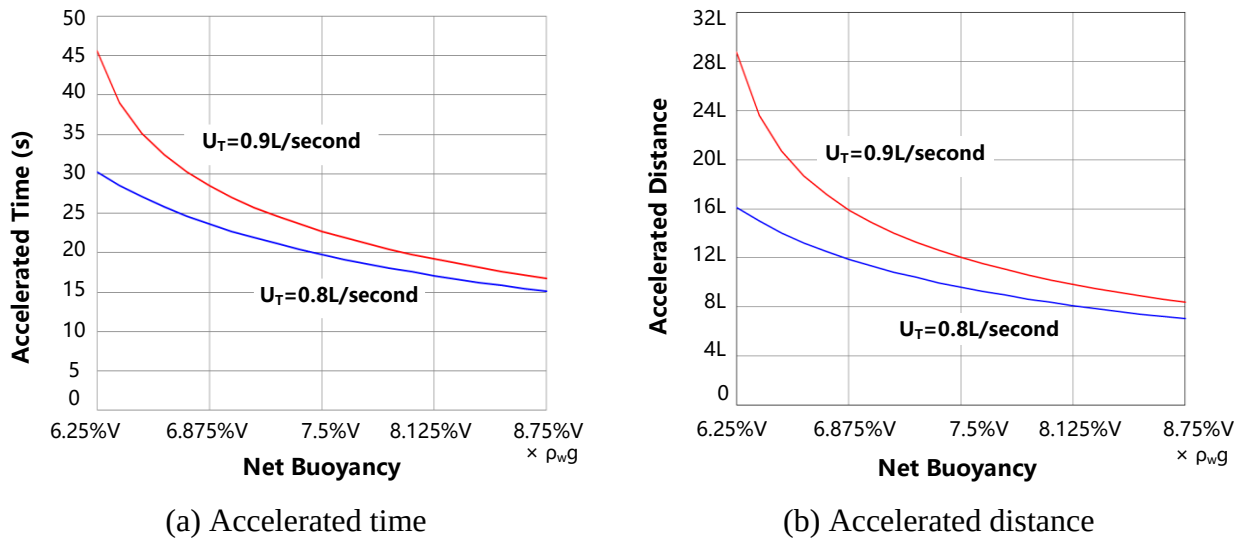


Fig. 9 Curves of accelerated time and distance at different net buoyancy

2.3 Stability Analysis of Vertical Floating Motion

During the vertical floating process of the UUC, the initial heading angle will possibly cause a deviation in the out water angle of the UUC. In order to analyze the influence of the initial state on the rising motion of the UUC, the two cases with initial heading angles of 3° and 6° were simulated and calculated. As can be seen in Fig. 10, the initial heading angles of the UUC will both oscillate over time and gradually convergence to zero due to the moment of buoyancy, meeting the design requirements for floating motion stability.

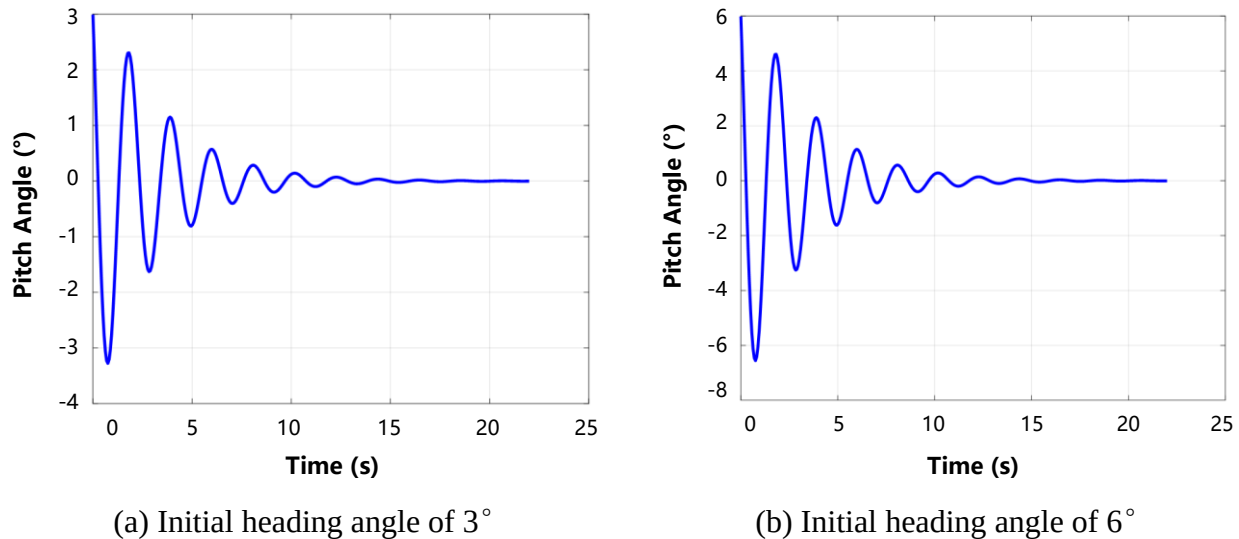


Fig. 10 Variation curves of initial heading angles of the UUC in vertical floating process

3. Summary

The paper focuses on the floating motion behavior of UUC, and numerical simulations were conducted on the UUC model by using CFD software simulation methods and mathematical modeling. The relationship between the terminal velocity and the net buoyancy, as well as the accelerated time and distance at different net buoyancy, were studied. And the stability of vertical floating motion was analyzed, which verified the rationality of the overall design of the UUC. The research results will provide references for determining the overall layout and net buoyancy design of the UUC, along with initial floating position settings.

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