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Research on the motion characteristics of a trans-media vehicle when entering water obliquely at low speed

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Abstract

This paper proposes a single control strategy to solve the problem of trans-media vehicle difficult control. The proposed control strategy is just to control the vehicle's air navigation, but not to control the underwater navigation. The hydrodynamic model of a vehicle when entering water obliquely at low speed has been founded to analyze the motion characteristics. Two methods have been used to simulate the vehicle entering water in the same condition: numerical simulation method and theoretical model solving method. And the results of the two methods can validate the hydrodynamic model founded in this paper. The entering water motion in the conditions of different velocity, different angle, and different attack angle has been simulated by this hydrodynamic model and the simulation has been analyzed. And the change rule of the vehicle's gestures and position when entering water has been obtained by analysis. This entering water rule will guide the follow-up of a series of research, such as the underwater navigation, the exiting water process and so on.

Keywords: Water-enter movement; Dynamic model; Theoretical model; Ballistic trajectory; Gesture

1. Introduction

Nearly, more and more countries start to study a kind of vehicle which can not only flight in the air, but also navigate underwater. For instance, the detailed design objective of submersible aircraft is proposed in two reports (Goddard and Eastgate, 2010; Willan, 2010). The process of the vehicle's air−water medium alternating repeated movement will accompany the forces and moments mutation, gas−liquid disturbance and complicated collision phenomenon. It can cause adverse effect on the control of vehicle, which seriously affects vehicle's stability. At present, there is not a integration of control strategy to apply to the vehicle's cross-medium movement. And the control strategy which using air and underwater subdivision control, increases the complexity and reduces the reliability of the system. This strategy also exists the problem of the air and the air and underwater controller switch. So this paper proposes a single control strategy which only controls the air navigation, and doesn't control underwater navigation. Through the control of vehicle's posture, speed and so on in the air, the single control strategy makes it in the uncontrolled condition be able to complete a series of movement including entering water, underwater navigation and exiting water. And after it out of the water, make it can meet the requirements of the air control take-off initial state. This paper is aimed to study the water-entry process of trans-media vehicle in the uncontrolled condition.

As the development of trans-media vehicle's trajectory in air and outset underwater, the process of water-entry has the characteristics of integrity and typicality. This subject, that involves the problem of unsteady motion and interaction of air, water and elastic objects, is very complex (Yan, 2002). It is a fluid dynamics problem of free surface and special cavitation,

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which may also involves structure damage caused by high-speed slamming and the dynamics of elastic objects. In order to study and solve these problems, the experiment is about to be necessary. Waugh and Stubstad, 1975 has introduced the knowledge and technologies about water-entry trajectory simulation systematically, also observed and recorded many water-entry experiment methods, process and result. May (1975) collected many valuable knowledge and experiment data as well as information about water-entry, and systematically analyzed many reasons that may affect water-entry trajectory. He et al. (2012a, 2012b, 2012c) and Ma et al. (2014) studied the water-entry problem of sphere and cylinder under different conditions, and analyzed the phase of open, development, closure and collapse of water-entry cavities. Hu (2014), Zhang et al. (2011) and Gu et al. (2012) drew the conclusion that head is very important to cavities and water-entry stabilization by studying the water-entry process of objects with different head styles.

With the development of computer numerical technology, there are more and more numerical simulation methods (NSM) about water-entry movement of the vehicle. Chen et al. (2011) and He et al. (2012a, 2012b, 2012c) used the volume of fluid (VOF) method coupled with the dynamic mesh method to simulate the movement of the vertical water-entry body. And the validity and effectiveness was verified in the numerical simulation. Wei et al. (2010) explored high-speed oblique water-entry impact of an underwater vehicle. Wang and Shi (2012) built the oblique water-entry numerical model of airborne missile to simulate the initial water-entry hydroballistics. Park and Jung (2003) utilized numerical analysis method to study the impact force and ricochet behavior of high speed water-entry bodies.

Concerning the study of process of water-entry, numerical simulation and experiment are the main approaches. Moreover, most of attention was put on the study of some fixed work conditions and special phenomenon, lacking of comprehensive theory research about the whole process of water-entry and trajectory characteristics. With theoretical analysis methods, a trans-media vehicle is taken to be the research object. Under the circumstance of slow velocity, omitting change of free surface, water jet, cavity and so on, the object's force mechanism is analyzed to established water-entry dynamics model. Finally, the object's motion rule and trajectory of water-entry is studied.

2. Build the dynamical model

2.1. Shape model

In the paper, peaked arch shape whose vertex angle is 30° and length is $L = 5.33$ m is used. And the peaked arch shape is uniform mass distribution and is designed as a Linear cutting tail. The physics model of the vehicle is shown as the Fig. 1. The computational formula of the radius is shown as the Eq. (1).

$$R(x) = \begin{cases} 0 & x \le 0,\ x > 5.33 \\ 0.2221x + 0.13325 & 0 < x \le 0.6 \\ 0.2665 & 0.6 < x \le 5.33 - \dfrac{0.2665}{\tan 15^\circ} \\ 0.2665 + \sqrt{r_t^2 - \left(x + \dfrac{0.2665}{\tan 15^\circ} - 5.33\right)^2} - r_t & 5.33 - \dfrac{0.2665}{\tan 15^\circ} < x \le 5.33 \end{cases} \quad (1)$$

In the Eq. (1), $r_t = \frac{0.2665}{2 \cdot \sin 15^\circ \cdot \sin 15^\circ}$.

2.2. Force analysis

As shown in Fig. 2, the body axes coordinate system which is selected as reference coordinate system, is built with the origin at the center of mass. The water-entry angle is θ. Because of less affection of air force, the vehicle is only in the interaction among the gravity G, the buoyancy B and the fluid force F during the water-entry process. The gravity G remains unchanged, the buoyancy B and the fluid force F change along with x_a which is the entering water distance of the vehicle.

(1) the gravity **G**

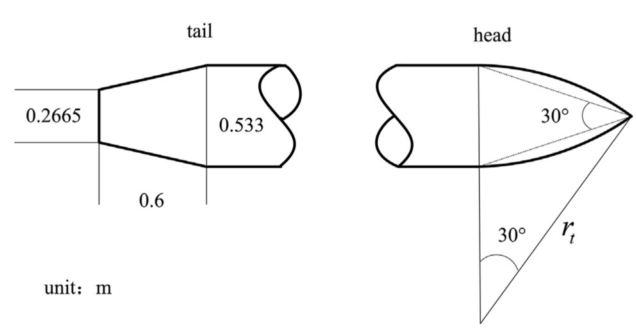

Fig. 1. Contour of the vehicle (unit: m).

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