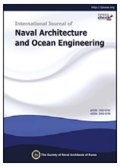
Available online at www.sciencedirect.com
ScienceDirect
Publishing Services by Elsevier
International Journal of Naval Architecture and Ocean Engineering xx (2017) 1−11
http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/



Dynamic modeling and three-dimensional motion simulation of a disk type underwater glider

Pengyao Yu, Tianlin Wang*, Han Zhou, Cong Shen

Transportation Equipment and Ocean Engineering College, Dalian Maritime University, 116026 Dalian, Liaoning, China

Received 17 March 2017; revised 12 July 2017; accepted 1 August 2017
Available online ■ ■ ■

Abstract

Disk type underwater gliders are a new type of underwater gliders and they could glide in various directions by adjusting the internal structures, making a turnaround like conventional gliders unnecessary. This characteristic of disk type underwater gliders makes them have great potential application in virtual mooring. Considering dynamic models of conventional underwater gliders could not adequately satisfy the motion characteristic of disk type underwater gliders, a nonlinear dynamic model for the motion simulation of disk type underwater glider is developed in this paper. In the model, the effect of internal masses movement is taken into consideration and a viscous hydrodynamic calculation method satisfying the motion characteristic of disk type underwater gliders is proposed. Through simulating typical motions of a disk type underwater glider, the feasibility of the dynamic model is validated and the disk type underwater glider shows good maneuverability.

Keywords: Underwater glider; Dynamic modeling; Viscous hydrodynamic modeling; Motion simulation

1. Introduction

Underwater gliders are a type of autonomous underwater vehicle that are driven by changing their buoyancy and position of mass center. They are characterized by low energy consumption, low cost and long range. Nowadays, several commercial gliders have been broadly applied in physical and biological oceanography, such as the *Slocum* (Webb et al., 2001), the *Spray* (Sherman et al., 2001) and the *Seaglider* (Eriksen et al., 2001).

Considering the role played by underwater gliders in ocean observation, much theoretical and experimental work has been carried out to promote the progress of underwater glider design technology. In Graver (2005) and Wang and Wang (2009), dynamic models of underwater gliders were established and the motion of gliders were simulated. In Leonard and Graver (2001), Bhatta and Leonard (2008) and Fan and Woolsey (2013), the nonlinear gliding stability and how to design stabilizing control laws for gliders were discussed. Mahmoudian et al. (2010) applied the perturbation theory to derive an approximate analytical solution for steady spiraling motion. The steady spiraling motion was also analyzed by Zhang et al. (2011, 2013) and a fast solution method for the steady spiraling motion was produced. To improve the maneuverability of gliders, the idea that placing propellers at the stern of original gliders has attracted many researches (Wang et al., 2011; Isa et al., 2014; Chen et al., 2016).

Breaking the shape of traditional underwater gliders, underwater gliders have entered into a diversified development stage. Zhang et al. (2012, 2014) designed a gliding robotic fish combining gliding and fin-actuation mechanisms. This Gliding robotic fish is essentially a hybrid of underwater gliders and robotic fish which is energy efficient and highly maneuverable. And it has been applied in the autonomous sampling of water columns in the Wintergreen Lake, Michigan (Zhang et al., 2016). Referring to air vehicles of circular plan-form,

---

* Corresponding author.
E-mail address: wangtianlin@dlmu.edu.cn (T. Wang).
Peer review under responsibility of Society of Naval Architects of Korea.

http://dx.doi.org/10.1016/j.ijnaoe.2017.08.002
p2092-6782 e2092-6790/

Please cite this article in press as: Yu, P., et al., Dynamic modeling and three-dimensional motion simulation of a disk type underwater glider, International Journal of Naval Architecture and Ocean Engineering (2017), http://dx.doi.org/10.1016/j.ijnaoe.2017.08.002

Niewiadomska et al. (2003) designed a mobile and bottom-resting autonomous underwater glider, whose body was lenticular shape and a tail rudder was fixed at the end of the body. Nakamura et al. (2007) developed a disk type glider for virtual mooring. The concept of virtual mooring refers to the monitoring of local waters by underwater vehicles, as if underwater vehicles were mooring in local waters. When the vehicle deviates from the target position under the external disturbance, it should move back to the designated waters. The shape of the disk type glider (Nakamura et al., 2007) is axisymmetric and it does not have any appendage, such as propellers and rudders. By adjusting the mass center of the glider, it could glide in any directions around the disk. Nakamura et al. (2008) further designed the full-scale disk type glider “BOOMERANG” and the operational tests in the field were carried out. It can be seen that when the glider needs to change the direction of movement, the traditional underwater glider would have to turn the body, while the disk type glider only need to move the internal structure to change the mass center of the glider system, which means the disk type glider is more suitable for virtual mooring tasks.

The disk type underwater glider is a new type of underwater gliders and it has better maneuverability than conventional underwater gliders, which makes it potential in marine exploration. A reasonable dynamic model for the disk type underwater glider would be helpful to the prototype development and the design of control system. However, existed dynamic models of conventional underwater gliders often have such limitation that the drift angle cannot be too large, which means they could not satisfy the motion characteristic of disk type underwater gliders. Although the dynamic model of the disk type underwater glider has been discussed by Nakamura et al. (2007), the analytic method is still inadequate, such as effects of internal masses movement is ignored and calculation method of hydrodynamic force do not satisfy the omni-maneuverability of the disk type underwater glider. Therefore, the modeling and simulation of the disk type underwater glider is still a challenge.

Taking a disk type underwater glider as an example, a nonlinear dynamic model is derived in this paper. In the model, the glider was treated as a multi-particle system and the effect of internal masses movement is taken into consideration. Making use of the axisymmetric characteristic of the shape of the disk type underwater glider, a special viscous hydrodynamic calculation method is introduced which satisfies the omni-directional maneuverability of the disk type underwater glider. Based on the dynamic model, typical motions of the disk type underwater glider (sawtooth motion in horizontal direction, sawtooth motion in vertical direction and omni-directional motion) are simulated.

2. Dynamic model

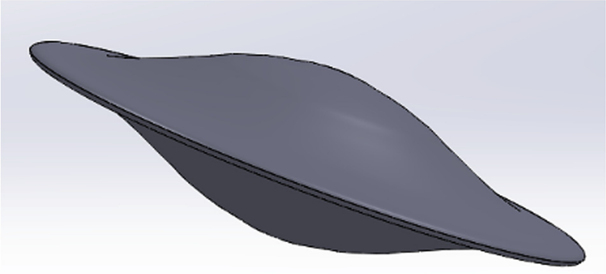


Fig. 1. Appearance of a disk type underwater glider.

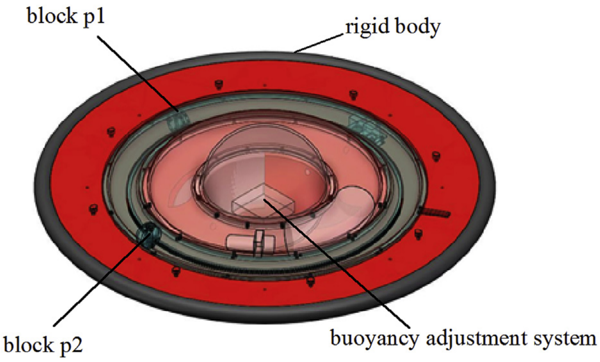


Fig. 2. Internal structures of the glider.

The appearance of a disk type underwater glider is shown in Fig. 1 and internal structures of the glider are shown in Fig. 2. It can be seen that the disk type glider is composed of a rigid body (mass m_{rb}), two moving blocks (mass m_{p1} and m_{p2}), and a variable ballast actuator (mass m_{b}) for buoyancy adjustment. The moving blocks can move along the circle located in the symmetry plane of the upper and lower parts of the glider and they are represented as moving mass particles. The buoyancy adjustment system is represented as a variable mass m_{b} with fixed-position. During the analysis, the volume of the glider V_{dis} is regarded to be constant. Influenced by variable mass m_{b}, the total vehicle mass is variable, which can be expressed in the following equation

$$m = m_{rb} + m_{p1} + m_{p2} + m_b \tag{1}$$

The net weight of the glider can be described as

$$W = mg - \rho g V_{dis} \tag{2}$$

The change rate of the glider mass $\dot{m}_b$ is an input, affected by the buoyancy-powered propulsion. When W is greater than zero, the glider would tend to sink and when W is less than zero, the glider would tend to rise. Through moving blocks p1 and p2, the position of mass center would change, thus the adjustment of motion direction and attitude of the glider is realized. As shown in Fig. 3, Bc and Gc are respectively buoyancy center and mass center of the glider and two different attitudes are described by different colors. The rotation accelerations of two blocks $\ddot{\delta}_{p1}$ and $\ddot{\delta}_{p2}$ are the control inputs, which are used to adjust the positions of blocks.

2.1. Kinematics

Two coordinate frames are used to describe the motion of the disk type underwater glider. One is inertial coordinate frame and the other is body-fixed frame. As shown in Fig. 4, the inertial

Please cite this article in press as: Yu, P., et al., Dynamic modeling and three-dimensional motion simulation of a disk type underwater glider, International Journal of Naval Architecture and Ocean Engineering (2017), http://dx.doi.org/10.1016/j.ijnaoe.2017.08.002