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Dynamic modeling and motion control strategy for deep-sea hybrid-driven underwater gliders considering hull deformation and seawater density variation

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ABSTRACT

Operating in the depth-varying oceanic environment, the buoyancy of deep-sea underwater gliders (UGs) will change with depth due to pressure hull deformation and seawater density variation. As the buoyancy variation caused by these two factors is of the same order of magnitude as the nominal net buoyancy, hull deformation and seawater density variation will accordingly affect the dynamic behaviors of deep-sea UGs. In this paper, a full dynamic model was established using Newton-Euler method for a deep-sea UG, PETREL-II. The hull deformation and seawater density variation, fitted as the functions of depth, are considered in the model. Comparisons of results obtained by sea trials, the full dynamic model and the simpler dynamic model without considering hull deformation and seawater density variation showed that the proposed full dynamic model can more truly reflect dynamic behaviors of the glider. Comparisons of simulation results for the full and simpler dynamic models showed hull deformation and seawater density variation have great effect on pitch angle and velocity of the gliders. Through analysis of motion control strategy, a buoyancy compensation scheme was proposed to reduce the negative effect of hull deformation and seawater density variation, and was validated to be effective by sea trials.

1. Introduction

Since underwater gliders (UGs) are of long-range, high-endurance, low-energy consumption, and low cost without expensive supporting vessels, they are widely used in oceanic observations, such as monitoring oceanic activities and collecting data for oceanic research. After the concept of underwater glider was first proposed by Henry Stommel in 1989 (Stommel, 1989), some outstanding gliders, such as Spray (Sherman et al., 2001), Seaglider (Eriksen et al., 2001), Slocum (Simonetti et al., 2001), ALBAC (Kawaguchi et al., 1993), XRay (Gerald et al., 2005), Deepglider (Osse and Eriksen, 2007), STERNE (Moitie et al., 2001) and USM (Ali Hussain et al., 2010), have been developed and widely applied in various fields.

The conventional underwater gliders are usually pure buoyancy-driven, and can be operated in two classical motion modes: saw-tooth and spiral motions. The diversity of marine tasks requires the underwater gliders to have the ability of depth-keeping cruise and operating in deep sea. The hybrid-driven underwater gliders (HUGs) (Blidberg, 2001; Jenkins et al., 2003) combining actuation of both buoyancy and propeller were then born, such as Slocum AUV (Webb et al., 1999; Webb et al., 2001), AUV-Glider (Wood et al., 2007), PETREL-II (Liu et al., 2014), and Fòlaga III (Alvarez et al., 2009). Compared to conventional gliders, the HUGs are more maneuverable, able to fulfill the depth-keeping cruise besides the saw-tooth gliding and spiral motions, and also can obtain a higher gliding speed with actuation of the propeller.

Dynamic modeling and prediction of motion behaviors, which are essential to maneuverability design and motion performance optimization of underwater vehicles, are always the focus in study of underwater vehicles. The most famous and commonly used dynamic model of underwater vehicles was derived by Fossen (1991, 1994, 2011). Fossen's model was derived in ideal ocean environment and in the forms of Newton-Euler and Euler-Langrange (Fossen et al., 1995) with nonlinear 6-DOF, which has been widely applied in design of controller for AUVs (Sarkar et al., 2016), motion planning of HUGs (Wehbe et al., 2014), and motion prediction (Isa et al., 2013; Nakamura et al., 2013). Another famous nonlinear dynamic model was derived by Leonard and Graver (2001) for a laboratory-scale underwater glider. This model has been widely used in feedback control (Leonard and Graver, 2001), parameter identification (Ali Hussain et al., 2011; Graver, 2005; Graver

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et al., 2003), stability analysis (Bhatta, 2006; Bhatta and Leonard, 2002, 2008) and controller design (Isa et al., 2014) of underwater gliders. Besides, Zhang et al. (2013) derived the equations of the steady spiraling motion by using Leonard's dynamic model. Wang and Wang (2009) established a nonlinear dynamic model for a thermal underwater glider by use of Gibbs function and Appell equations. Wang et al. (2014) established a dynamic model of HUG from the viewpoint of energy by using the Riemannian differential geometry and affine connection. In order to improve the prediction accuracy, Thomasson and Woolsey (2013); Woolsey (2011) developed a nonlinear dynamic model of a vehicle in an unsteady, nonuniform flow. Fan and Woolsey (2014) extended the derivation of Woolsey (2011) and Thomasson and Woolsey (2013) to incorporate the multibody dynamics of an underwater glider, and investigated the effect of a nonuniform flow on the dynamics of the underwater glider.

Although hull deformation and change of seawater density with depth can be considered in the above mentioned dynamic models, volume of the hull and seawater density are generally treated as environmental and vehicle-specific constants in the applications of these models to underwater vehicles. The main reason is that most of the vehicles are operated in shallow water or that some of the UGs have nearly neutral pressure hulls (Eriksen et al., 2001; Osse and Eriksen, 2007). However, in deep sea, the buoyancy variation caused by the hull deformation and change of seawater density is of the same order of magnitude as net buoyancy (driving force) of the gliders. For example, for PETREL-II descending from the sea surface to 1500 m underwater, the buoyancy variation caused by the hull deformation and change of seawater density is 3.02 N, which is comparable with the maximum net buoyancy (7 N) of glider. The buoyancy variation will have effect on net buoyancy of the UGs in dynamics, and then affect dynamic behaviors of the UGs. Therefore, it is essential to establish a more accurate dynamic model for deep-sea UGs considering the hull deformation and change of seawater density.

In the present work, focused on the deep-sea HUG PETREL-II developed by Tianjin University, a full dynamic model (hereinafter referred to as the F-Model) was built using the Newton-Euler method. In the F-Model, the buoyancy variation due to hull deformation and seawater density variation, modeled as a function of depth, was considered into the restoring forces and moments. The hydrodynamic forces, considered as a function of seawater density, captured the change of seawater density with depth. In order to verify accuracy of the F-Model, dynamic behaviors of PETREL-II predicted by the F-Model and those predicted by the simpler dynamic model (hereinafter referred to as the S-Model) without considering hull deformation and seawater density variation were compared with those from sea trials. Effects of the hull deformation and seawater density variation on dynamic behaviors of the glider were also discussed. Finally, an effective buoyancy compensation control strategy was proposed to reduce effects of the hull deformation and seawater density variation on motion behaviors of the glider.

2. Buoyancy of deep-sea gliders

Buoyancy of the submerged underwater gliders mainly depends on two parts: the pressure hull and external bladder. Generally, it is believed that buoyancy provided by these two parts is constant in shallow water based on the assumptions that there is no change of seawater density, and that volumes of the pressure hull and external bladder are not affected by water pressure. But in fact, both volume of the glider and seawater density are changing with the increasing depth of seawater. For example, volumes of the pressure hull and external bladder will be smaller in deep sea than in shallow water, seawater density will also be larger, and vice versa. The decrease/increase of the buoyancy caused by deformation of the pressure hull and external bladder cannot counteract the increase/decrease of the buoyancy caused by change of seawater density. That is to say, buoyancy variation of the glider is nonzero, which will result in change of the net buoyancy and then have effect on dynamic behaviors of the gliders.

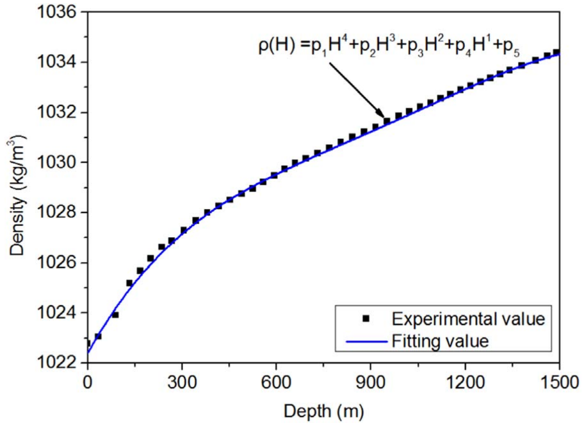

Fig. 1. Seawater density versus depth in South China Sea.

2.1. The density of seawater

The density of seawater varies with temperature, salinity and pressure, which vary with different seas. In the present work, the relevant data was from South China Sea. According to data of the conductivity, temperature and salinity, density of the seawater with depth was obtained (Fig. 1). The maximum and minimum densities of the seawater are 1034.5 kg/m^3 at the depth of 1500 m and 1022.7 kg/m^3 on the surface of seawater, respectively.

According to Fig. 1, a quartic polynomial can be used to describe the seawater density related to depth,

$$\rho_h = p_1 H^4 + p_2 H^3 + p_3 H^2 + p_4 H + p_5 \tag{1}$$

where H is depth of the seawater, and the values of fitting coefficients p_i (i = 1,...,5) are -5.083×10^{-12}, 1.95×10^{-8}, -2.75×10^{-5}, 0.02248, and 1022.7, respectively. The coefficient of determination (R-square) is 0.99.

2.2. Deformation of the pressure hull

The hull of PETREL-II is a sealed tank-like structure with the cylindrical main section and hemispherical ends (Liu, 2014). Volume of the hull under standard atmospheric pressure in air is $V_s = \pi R^2 (4R/3 + L_b)$, where R and L_b are radius and length of the cylindrical part of the hull, respectively. Volume of the hull V_h under a given depth can be expressed as

$$V_h = V_s - \Delta V_h \tag{2}$$

where ΔV_h is volume reduction of the pressure hull. It was obtained through pressure test experiment (Liu, 2014), and found to be a linear function of depth

$$\Delta V_h = K_{vh} H \tag{3}$$

where H is the depth, K_{vh} is compressibility of the hull, and K_{vh} = 0.27172 ml/m.

2.3. Buoyancy variation of the hull

Buoyancy variation of the hull is given

$$\Delta B_h = B_h - B_0 = \rho_h V_h g - \rho_0 V_0 g \tag{4}$$

where B_h is the current buoyancy of the hull under a certain depth when the glider descends or ascends, ρ_h and V_h are the corresponding current density of seawater and current volume of the hull, respectively, B_0 is the buoyancy of the hull when the glider is on the surface,