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Improving the performance of an AUV hovering system by introducing low-cost flow rate control into water hydraulic variable ballast system

Xufeng Zhao, Yinshui Liu*, Mingxing Han, Defa Wu, Donglin Li

State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, 430074 China

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ABSTRACT

Water hydraulic variable ballast system (WHVBS) is a competitive mechanism to realize the hovering system which is one of the most popular ways to expand the maneuvering capability of AUVs. However, the WHVBSs equipped in AUVs almost were on–off type without controlling the flow rate of the in/out ballast water, which limits the hovering performance of the AUVs operated in complex underwater environment. In this paper, three novel types of WHVBS, which supports one or two low cost means to control the flow rate of ballast water, have been proposed to improve the performance of an AUV hovering system. A torpedo-like AUV equipped with WHVBS was used as a simulation platform to verify the effectiveness of the proposed WHVBSs. Numerical simulation results support the idea that compared with the commonly used on–off type WHVBS, the WHVBSs introduced flow rate control can significantly improve the hovering performance of the AUV, especially in the situations with unfavorable sea wave disturbances. Additionally, the statistics on water usage of different WHVBSs in numerical simulation indicated that the novel WHVBSs have the potential to extend the mission duration of AUV.

1. Introduction

Autonomous underwater vehicles (AUVs) are designed to provide scientists and researchers with simple, low-cost, medium and long-range capability to perform underwater missions without placing human lives at risk. In recent years, there are increasing applications for AUVs, including military applications (Bovio et al., 2006), inspection of underwater structures (Maki et al., 2012), exploration of unknown environments(Gupta et al., 2012), oceanographic observations (Pyo et al., 2015), submarine rescue (Grob, 2007), underwater animal behavior research (Kopman et al., 2012), and so on. As the underwater missions of AUVs have become increasingly varied and complex, the AUVs characterized by higher maneuvering capability and longer mission duration are strongly required.

Underwater hovering capability, the ability to reach or keep a desired depth without forward velocity, is one of the most popular ways to expand the maneuvering capability of AUVs (Gao et al., 2015). At present, most AUVs have to actuate bow (or stern) plane to reach or keep a desired depth with satisfying forward velocity so they do not get a complete vertical motion(Li and Lee, 2005). AUVs equipped with hovering system have more maneuverability and can be improved to perform more complex missions that previously could only be carried out through Remotely Operated Vehicles (ROVs). The accurate hovering control of AUVs is usually carried out by a vertical propeller (Li et al., 2011; Pyo et al., 2015). Due to the high energy consumption of using a vertical propeller, however, variable ballast system (VBS), which pumps seawater in or out the ballast tanks to change the vehicle's total weight, is an energy-efficient choice to realize a hovering control system. Additionally, the use of a vertical propeller would generate perturbations in the surroundings, which may impact the reliability of oceanographic measurement result or the behaviors of underwater animal (Gomariz et al., 2015). By contrast, AUVs with VBS can carry out vertical motion with minimal perturbations.

Several different variable ballast mechanisms have been developed by researchers over the past few years. A blowing/venting system using high pressure air to change water volume is the most common form of VBS (Font and Garcia-Pelaez, 2013; Xu and Smith, 1994). Because it is restricted by the total compressed air volume and pressure drop in a compressed air bottle, a blowing/venting system is not a good choice for the AUVs which need execute long duration mission. A novel variable ballast mechanism presented by Sumantr et al. (2008) has a movable plate in the ballast tank and ensures that the variable volume ballast tank is always fully filled with water. Even though simulation results indicate that the novel mechanism is feasible and efficient, this mechanism still faces challenges of reliability and availability for deep water

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* Correspondence author.
E-mail address: liuwater@hust.edu.cn (Y. Liu).

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environments or large ballast volume. A variable ballast system using both a water pump and compressed air is proposed by Woods et al. (2012). With the coupling effect between pneumatics and hydraulics, a complex control strategy is required. Additionally, the drawbacks of the blowing/venting system also exist in the proposed system. The water hydraulics, which is a competitive mechanism to adjust the ballast water volume, has been applied to many AUVs in recent years, for example the variable ballast system in *Seahorse* (Tangirala and Dzielski, 2007). The water hydraulic variable ballast system (WHVBS), whose applications continue to increase, has advantages of simple construction, environmental friendliness and simple seal. Furthermore, WHVBS is the best choice for deep-sea manned submersible vehicles like *New ALVIN*, *SHINKAI6500* and *Jiao Long* (Liu et al., 2010; Nanba et al., 1990; Walden and Brown, 2004; Worall et al., 2007).

However, to the best of our knowledge, the existing WHVBSs equipped in the vehicles almost were on–off type without controlling the flow rate of the in/out ballast water (Liu et al., 2010; Tangirala and Dzielski, 2007; Walden and Brown, 2004; Worall et al., 2007). The main reason for less WHVBS with flow rate control function is that the traditional hydraulic flow rate control ways are hardly possible to be applied into WHVBS. On one hand, the problem was caused by the limited variety, poor performance and inordinately high price of the water hydraulic flow rate control component, such as servo/proportional flow valve and variable displacement pump (Xin et al., 2014). On the other hand, since the WHVBS is an open circuits hydraulic system, the seawater pumped from the ocean through a simple filter is hardly possible to meet the high water quality requirement of the water hydraulic control components. In those complex underwater environments with many uncertainties, these shortcomings would limit the hovering performance of the AUVs equipped with the WHVBS.

The objective of this work is to improve the hovering performance of an AUV equipped with WHVBS by introducing flow-rate control into on–off type WHVBS. To achieve this goal, three novel types of WHVBS, which can be refitted from on–off type WHVBS at a low cost, have been proposed in this paper. Each of them supports one or both of the following means to control the flow rate of ballast water: (1) employing pulse width modulation (PWM) technology to control the flow rate through four direct-acting solenoid valves; (2) using the servo motor to adjust the flow rate of fixed displacement pumps. Those means have been verified in our previous research (Liu et al., 2015) and it is the first time for those means to be applied in the WHVBS type hovering system in this work.

The rest of this paper is organized as follows. In Section 2, the problem of hovering control is formulated and the mathematical models for the underwater hovering motion of the AUV equipped with VBS are described. The principles and simulation models of traditional on–off type WHVBS and the novel types of WHVBS are described in detail in Section 3. Section 4 focuses on the external disturbances during hovering control in underwater environment. The hovering performance and consumption of the AUVs equipped with different types WHVBS are analyzed and compared in Section 5. In Section 6, conclusions are drawn.

2. Hovering control of an AUV equipped with VBS

The AUV, as a platform to validate the hovering performance of different types WHVBS in this work, has a streamlined torpedo-like body and is propelled by a single thruster (detail diagrams are not available because of its special application background). For vehicle's maneuverability, two stern planes and two stern rudders were installed on the symmetrically round hull at the rear part. The objective of the hovering system is to reach and keep a desired depth with zero propulsion, thus without any help from the above mentioned control planes, in face of external disturbances like variation of seawater density or wave inducted forces. In this section, the configuration of the studied AUV equipped with VBS is introduced and the 2-D AUV model of underwater hovering is formulated.

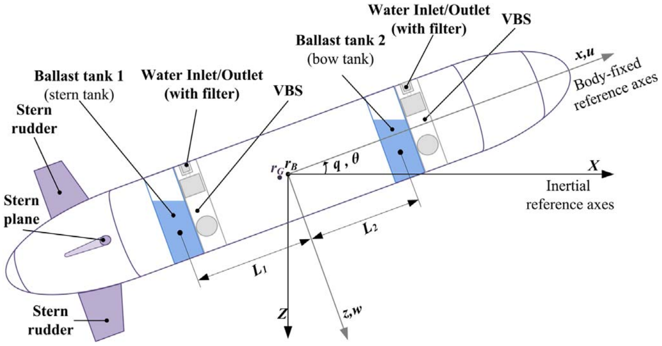

Fig. 1. A typical configuration of an AUV equipped with VBS.

2.1. Configuration of the AUV equipped with VBS

Fig. 1 shows a typical configuration of an AUV equipped with VBS. Two ballast tanks, the bow tank and the stern tank, have been symmetrically installed in the AUV ($L_1 = L_2$). Considering the water volumes in the ballast tanks can be adjusted by VBSs, the total mass of an AUV is controlled by VBS:

$$m_{\text{total}} = \rho_{\text{bal\_wat}} V_{\text{bow}} + \rho_{\text{bal\_wat}} V_{\text{stern}} + m_{\text{init}} \tag{1}$$

where m_{total} is the total mass of the AUV, $\rho_{\text{bal\_wat}}$ is the density of the ballast water, V_{bow} and V_{stern} are the water volume in bow tank and stern tank respectively, and m_{init} is the initial mass of the AUV.

Simultaneously, as the two ballast tanks are not located at the center of gravity r_G, the center of gravity will be shifted with the changes of water volume in the two tanks. During under water hovering, it is important to know the center of gravity of each ballast tank, so that the center of gravity $r_G = [x_G, z_G]$ of the AUV can be calculated from (Woods et al., 2012):

$$r_G = \left(\frac{1}{m_{\text{total}}}\right)[\rho_{\text{bal\_wat}} V_{\text{bow}} r_{G\_\text{bow}} + \rho_{\text{bal\_wat}} V_{\text{stern}} r_{G\_\text{stern}} + m_{\text{init}} r_{G\_\text{init}}] \tag{2}$$

where $r_{G\_\text{bow}} = [x_{G\_\text{bow}}, z_{G\_\text{bow}}]$ represents the center of gravity of the bow tank, $r_{G\_\text{stern}} = [x_{G\_\text{stern}}, z_{G\_\text{stern}}]$ represents the center of gravity of the stern tank, and $r_{G\_\text{init}} = [x_{G\_\text{init}}, z_{G\_\text{init}}]$ represents the center of gravity of the AUV in initial state.

With the ability to change the location of r_G and the total weight $m_{\text{total}}g$ of an AUV, the VBSs can dynamically adjust the hydrostatic forces and moments of the AUV in the body-fixed frame according to the desire (Tangirala and Dzielski, 2007):

$$\begin{cases} F_{\text{hs}\_x} = -(m_{\text{total}}g - B_{\text{AUV}})\sin(\theta) \\ F_{\text{hs}\_z} = (m_{\text{total}}g - B_{\text{AUV}})\cos(\theta) \\ M_{\text{hs}\_y} = -(x_G m_{\text{total}}g + x_B B_{AUV})\cos(\theta) \\ \qquad - (z_G m_{\text{total}}g + z_B B_{\text{AUV}})\sin(\theta) \end{cases} \tag{3}$$

where F_{hs_x} is the axial hydrostatic force, F_{hs_z} is the normal hydrostatic force, M_{hs_y} is the pitching hydrostatic moment, g is the acceleration due to gravity, B_{AUV} is the buoyancy of the AUV, θ is the pitch Euler angles, and $r_B = [x_B, z_B]$ represents the center of buoyancy of the AUV.