Ocean Engineering 108 (2015) 648–661

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Study on the control methods of a water hydraulic variable ballast system for submersible vehicles

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ARTICLE INFO

Article history:
Received 13 January 2015
Accepted 25 August 2015
Available online 18 September 2015

Keywords:
Variable ballast system
Seawater hydraulics
Generalized predictive control
Pump-controlled hydraulic system
On–off valve controlled hydraulic system
Energy saving

ABSTRACT

The water hydraulics is a competitive mechanism to adjust the ballast water and also is the only choice for ultra-deep sea applications. In order to improve the control performance and reduce the energy consumption of the water hydraulic variable ballast system (WHVBS), a novel type WHVBS, which introduces a servo motor to drive the pump and uses four fast response direct-acting solenoid valves to control the water flow direction, has been proposed. The proposed WHVBS has two novel flow control modes: changing the speed of servo motors (pump controlled mode) or changing the opening time of solenoid valves (valve controlled mode). The mathematical model of WHVBS was built up for the purpose of predicting the flow rate under both control modes. A generalized predictive controller with forgetting factor recursive least square (FFRLSGPC) was proposed for WHVBS to improve the control performance. Finally, based on the tracing experiments performed on a WHVBS experiment platform, the comparative discussion of control performance and the analysis of energy efficiency were presented. The experimental results show that the mean tracing error can be maintained within 0.27% by the proposed FFRLSGPC in valve controlled mode and the pump controlled mode is an energy-efficient control method.

1. Introduction

With the development of industry and the expansion of our population, more and more countries have focused their attention on ocean exploitation in recent years. The submarine environment is crucial for human beings to investigate; therefore submersible vehicles, such as manned deep-sea submersibles and autonomous underwater vehicle (AUVs), are very useful tools in exploring and utilizing the resources in oceans.

For the submersible vehicles used in deep sea applications, such as submarine survey, rescue (Bovio et al., 2006; Grob, 2007) and cable laying (Balasuriya and Ura, 2002), depth and pitch angle control is a key aspect of its the control systems (Lee and Singh, 2012). A fin deflection controller, which uses bow plane and stern plane to control the depth and pitch angle, is frequently used in submersible vehicles (Kim and Shin, 2007; Liceaga-Castro et al., 2008). Although this method has been successfully applied in many submersible vehicles, it suffers from the following drawbacks: 1) it performs inefficiently with low forward velocity, 2) it cannot work with the propeller off, 3) it limits weight and placement of the payload, 4) it reduces the amount of fin authority available when used to compensate for changes in buoyancy or own weight of submersible vehicles. Furthermore, the fin deflection controller cannot meet certain special application requirements. *Seahorse*, for example, due to a combination of surface capture and lift forces on the nose, is unable to dive under the surface using the fins alone even when it has neutrally buoyant and sufficient forward speed (Tangirala and Dzielski, 2007). Accurate underwater hovering, which is an invaluable function for submersible vehicles, cannot be achieved by fin deflection controller as well (Fairfield et al., 2010; Liu et al., 2010).

In order to overcome the shortcomings of fin deflection controllers, several methods such as position movable mass (Hussain et al., 2011), oil bladder type variable buoyancy system (Aoki et al., 2008) and variable ballast system (VBS) (Schneider and Sasse, 1973) have been presented. With its advantages of environmental friendliness, simple mechanism, easy disposal of working media and cleanliness, VBS is the most popular mechanism which changes the total weight of submersible vehicles by adjusting the water mass in ballast tank. 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 (Min and Smith, 1994; Wasserman et al., 2003; Font and Garcia-Pelaez, 2013). Because it is restricted by the total compressed air volume and pressure drop in a compressed air bottle, a blowing/venting

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http://dx.doi.org/10.1016/j.oceaneng.2015.08.045
0029-8018/

system is not a good choice for long mission submersible vehicles. A novel variable ballast mechanism presented by Sumantr et al. has a movable plate in the ballast tank and ensures that the water always fulfill the space in the variable volume ballast tank (2008). Even though the novel mechanism is shown to be feasible and efficient by simulation results, it still faces challenges of reliability and availability for deep water 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 combined effect of pneumatics and hydraulics, a complex control strategy was required and 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 submersible vehicles, for example the variable ballast system in *Seahorse* (Tangirala and Dzielski, 2007). The water hydraulic variable ballast system (WHVBS) has advantages of simple construction, environmentally friendliness and simple seal. Furthermore, it is the only choice for deep-sea manned submersibles like 'ALVIN' and 'Jiao Long' (Schneider and Sasse, 1973; Worall et al., 2007; Liu et al., 2010).

However, the existing literature always focuses on depth and pitch angle control when studying WHVBS and few of them pay attention to the transient performance of VBS. For those operations needing underwater hovering, the ballast water in submersible vehicles needs to accurately track the changes of buoyancy and payload. Moreover, proportionally synchronous control of ballast water, which needs to focus on the transient performance of VBS, must be applied to eliminate the torque effect for those submersible vehicles equipped with two asymmetry ballast tanks. In other situations like soft grounding (Riedel et al., 1999), accurate compensation of variable sea water density and accurate net buoyancy control, the transient flow rate of WHVBS must be taken into account. In general, there are two ways to control the flow rate in a hydraulic system: valve controlled mode which uses a servo flow valve (Yao et al., 2014) or a proportional flow valve to control flow rate (Mohanty and Yao, 2011), and pump controlled mode which uses a variable displacement pump to adjust flow rate (Wang et al., 2012). However, those two methods are not suitable for those WHVBSs with on–off valves and a fixed displacement pump.

The objective of this research was to investigate the control performance and energy efficiency of WHVBS based on two novel flow control modes and a new model predictive controller. A novel type water hydraulic variable ballast control system (WHVBS), which introduces a servo motor to drive the pump and uses four fast response direct-acting solenoid valves to control the water flow direction, is proposed in this paper. The proposed WHVBS can employ pulse width modulation (PWM) technology to control the flow rate through the direct-acting solenoid valves (valve controlled mode) or using the servo motor to adjust the flow rate of fixed displacement pumps (pump controlled mode). For the purpose of guaranteeing precision, adaptive ability and robustness, a generalized predictive controller with forgetting factor recursive least square (FFRLSGPC) was designed for WHVBS. In order to predict the flow rate under the two control modes, a simulation model considering the transient performance of a water hydraulic piston pump and water hydraulic solenoid valve was built up. Then, the parameters of different controllers were optimized using an improved particle swarm optimization algorithm, and the tracing experiments were performed in an experimental platform of the WHVBS. Finally, the comparative discussion of control performance and the analysis of energy efficiency were presented.

2. Configuration of the submersible vehicles equipped with WHVBS

The schematic diagram of WHVBS is shown in Fig. 1. Fig. 2 shows the appearance of WHVBS with a rated flow of 25 L/min. In order to accurately control the transient flow rate of ballast water, two novel feasible control methods are introduce in the proposed WHVBS: employing pulse width modulation technology to control the flow rate through an on–off valve (Wang et al., 2013) and using the servo motor to adjust the flow rate of fixed displacement pumps (Ahn et al., 2014). Therefore, a servo motor was introduced to drive the pump and four fast response direct-acting solenoid valves were used to control the water flow direction in the proposed WHVBS. The manifold in Fig. 2 is composed of four solenoid valves (a–d), a pressure-balanced valve and a relief valve (shown in Fig. 1). The switch for injecting ballast water and discharging ballast water is controlled by the solenoid valves. In the injecting process, solenoid valves the (a) and (c) are opened and solenoid valves (b) and (d) are closed. The flow direction of water in the injecting process is: sea to filter to solenoid valve (a) to water pump to flow sensor to pressure-balanced valve to solenoid value (c) to ballast tank. In the discharging process, solenoid valves (b) and (d) are opened and solenoid valves (a) and (c) are closed. The flow direction of water in the discharging process is: the ballast tank to solenoid valve (b) to water

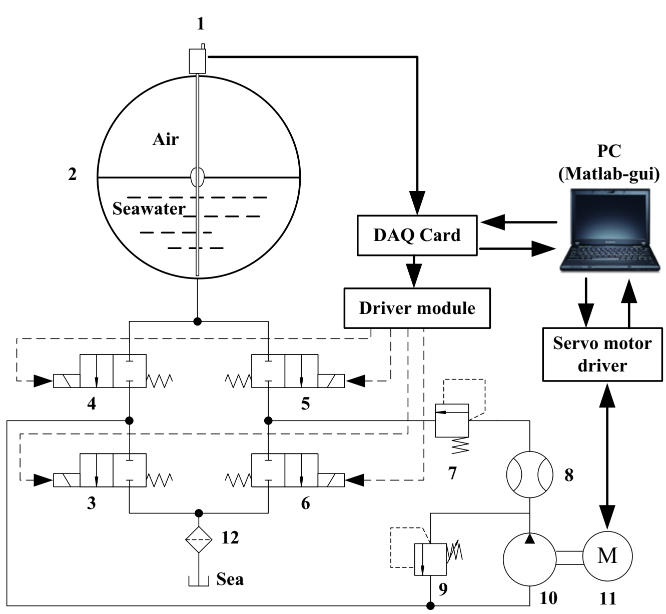

Fig. 1. The schematic diagram of WHVBS. 1-Liquid level sensor, 2-Ballast tank, 3-Solenoid valve a, 4- Solenoid valve b. 5- Solenoid valve c, 6- Solenoid valve d, 7-Pressure-balanced valve. 8-Flow sensor, 9-Relief valve, 10-Water pump, 11- Servo motor, 12-Filter.

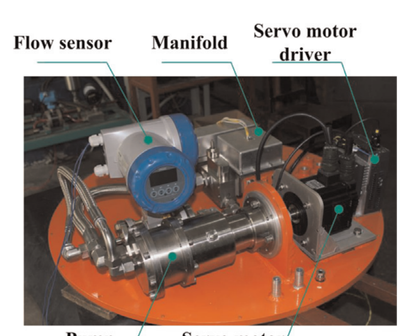

Fig. 2. WHVBS for depth of 320 m.