Ocean Engineering 72 (2013) 441–447

Contents lists available at ScienceDirect

Ocean Engineering

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

On a submarine hovering system based on blowing and venting of ballast tanks

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ARTICLE INFO

Article history:
Received 27 July 2012
Accepted 27 July 2013
Available online 19 August 2013

Keywords:
Manned submarines
Underwater hovering
Variable buoyancy
Sliding control

ABSTRACT

A submarine hovering system based on the blowing and venting of a set of dedicated tanks is investigated. We review the mathematical models involved and propose a sliding mode controller for the input–output linearized system. Numerical simulation results support the idea that this could be a promising hovering strategy for manned submarines, autonomous underwater vehicles or other platforms.

1. Introduction

Underwater hovering, the ability to statically keep a desired depth, is at the same time a challenge, due to many uncertainties associated with the underwater environment, and a very important feature for both small size autonomous underwater vehicles (AUVs) and large manned submarines. In the last years several hovering AUVs have been developed (see Vasilescu et al., 2010 for a survey on the subject). The hovering facility expands the capabilities of AUVs allowing them to perform more complex missions that previously could only be carried out through Remotely Operated Vehicles (ROVs). For manned submarines, accurate hovering can be an invaluable tool, for example, for safe swimmer delivery, cover supply replacement or the deployment and recovery of AUVs, a subject that has recently raised an extraordinary interest (see for example Hardy and Barlow, 2008; Martínez-Conesa and Oakley, 2011).

From the technological point of view, AUVs usually hover by using thrusters (Choi et al., 2003; Li et al., 2011). Due to the large energy requirements of this approach, however, buoyancy control by pumping seawater in or out of ballast tanks can be used to save energy (Vasilescu et al., 2010) or in larger designs (Tangirala and Dzielski, 2007). In manned submarines, hovering is traditionally performed using hydraulic pumps (Yang and Hao, 2010; Ying and Jian, 2010), although not very much information about hovering systems is available in the literature due to the military nature of these vehicles.

The aim of this work is to investigate the feasibility of a hovering system in which dedicated tanks are blown and vented similarly to the way the main ballast tanks are traditionally operated in manned submarines.

In these vehicles, a variable number of main ballast tanks are distributed along the hull. In case of emergency the main ballast tanks can be emptied by blowing into them air from high pressure bottles. This way the water is expelled from the tanks, the vehicle gains buoyancy and can rise more quickly. To fill the tanks with water, air is vented out of the ballast tanks. In the previous works (Font et al., to appear, 2013) we proposed mathematical models for the blowing and venting of ballast tanks and showed that the implementation of a control system for these processes, usually performed manually, can improve in a significant way the performance and stability in emergency rising manoeuvres. Our objective is to extend the approach used with the main ballast tanks to a set of dedicated hovering tanks (see Section 2 for details) in order to test the feasibility of a hovering system based on blowing and venting of tanks. Although throughout this paper we will use a manned submarine as test platform, it is worth noting that the use of blowing and venting of tanks as hovering control is not limited to these vehicles nor is our intention to carry out the discussion of conceptual designs for the compromise between efficiency and stealth in a hovering system ready for military applications. Indeed, this technology could be applicable to manned submarines, AUVs, ROVs or any offshore platform requiring variable buoyancy control.

The rest of the paper is organized as follows. In Section 2 we formulate the problem and describe the mathematical models

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http://dx.doi.org/10.1016/j.oceaneng.2013.07.021

for blowing and venting processes, vehicle motion and external disturbances. In Section 3 we propose a feedback control scheme for the hovering submarine consisting of a sliding mode controller acting on a previously input–output exactly linearized system. Section 4 is devoted to the results of numerical simulations testing the performance of the proposed hovering system. Finally, in Section 5 we discuss the obtained results and present some conclusions.

2. Problem formulation. Mathematical models

As we said above, we will consider a manned submarine, particularly the Navantia P-650 design, as the test platform for our hovering system. Details about the hydrodynamic characteristic and the blowing/venting system can be found in García et al. (2011) and Font et al. (to appear) respectively.

Our objective is to maintain a desired depth with no propulsion (and thus without any help from the control surfaces) in the face of external disturbances like changes in water density or forces induced by the sea state. In the next sections we review the mathematical models for the blowing/venting system, vehicle motion and external disturbances.

2.1. Blowing/venting system

The blowing and venting system is composed of the tank, the pressure bottle, the blowing and venting valves and the outlet/inlet hole located at the bottom of the tank. When the blowing valve is opened, air flows into the tank from the bottle increasing the pressure and forcing the water to flow out through the outlet hole. When the venting valve is opened, air can flow out from the tank letting the water flow back into the tank. Fig. 1 shows a schematic view of these processes. The subindex F denotes conditions in the bottle, the subindex B denotes conditions in the tank, $\dot{m}_F$ and $\dot{m}_v$ are respectively the mass flow rates through blowing and venting valves, q_B is the water flow through the tank hole, h_{wc} is the height of the water column in the tank and p_{SEA}, p_{ext} are respectively the hydrostatic pressures outside the flood port and venting outlet (they differ in the depth at which each one is evaluated). We will use 3 variables for each tank to completely describe its state: mass of air in the bottle, m_F, mass of air in the tank, m_B, and pressure in the tank, p_B. We refer the reader to Font et al. (to appear) and Font and García (2011) for a more detailed description of the model presented below. The symbols introduced in this section are summarized in Table 1.

Due to the high pressure difference between bottle and tank, the flow from the bottle will usually be supersonic. As the bottle empties, however, this difference decreases and the flow can become subsonic if the pressure ratio is below the critical pressure

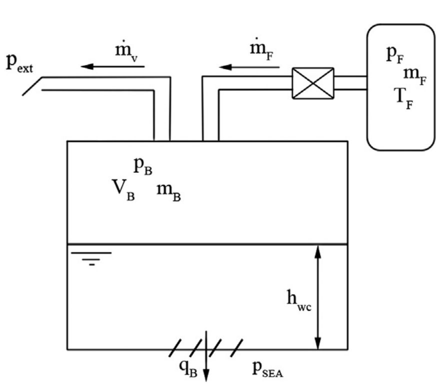

Fig. 1. Blowing and venting processes.

Table 1
Summary of symbols introduced in Section 2.1.

A_v	Vent pipe cross-section (m^2)
$h_{wc}(t)$	Height of water column in the tank (m)
$m_B(t)$	Mass of air in ballast tank (kg)
$m_F(t)$	Mass of air in pressure bottle (kg)
m_{F0}	Initial mass of air in pressure bottle (kg)
$\dot{m}_F(t)$	Mass flow rate from pressure bottle (kg/s)
$\dot{m}_v(t)$	Mass flow rate through venting valve (kg/s)
$p_B(t)$	Pressure in ballast tank (Pa)
$p_{ext}(t)$	Pressure outside the venting valve (Pa)
$p_F(t)$	Pressure in bottle (Pa)
p_{F0}	Initial pressure in bottle (Pa)
$p_{SEA}(t)$	Pressure outside the outlet hole (Pa)
$q_B(t)$	Water flow through outlet hole (m^3/s)
R_g	Gas constant for air (J/kg K)
T_B	Water temperature (K)
V_{B0}	Initial air volume in ballast tank (m^3)
$V_B(t)$	Volume of air in ballast tank (m^3)
V_F	Pressure bottle volume (m^3)
γ	Isentropic constant
ρ	Density of water (kg/m^3)

ratio $P_c = ((\gamma+1)/2)^{\gamma/(\gamma-1)}$, with γ the isentropic constant. Let s denote the variable aperture of the blowing valve, the equation for the mass of air in the bottle in both the supersonic and the subsonic cases is

$$\dot{m}_F(t) = s(t)A\left(\frac{m_F(t)^{\gamma+1}p_{F0}}{m_{F0}^{\gamma}V_F}\right)^{1/2}\mu(p_B(t), m_F(t)) \tag{1}$$

where $A = \dot{m}_{Fmax}((2/(\gamma+1))^{-(\gamma+1)/(\gamma-1)}V_F/\gamma p_{F0}m_{F0})^{1/2}$, with $\dot{m}_{Fmax}$ the maximum mass flow rate from the bottle, experimentally measured, V_F is the bottle volume, p_{F0}, m_{F0} are respectively the initial pressure and mass of air in the bottle and

$$\mu(p_B, m_F) = \begin{cases} \sqrt{\gamma\left(\dfrac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}, & P_c \le \dfrac{p_F}{p_B} \\ \sqrt{\dfrac{2\gamma}{\gamma-1}\left(\left(\dfrac{p_B}{p_{F0}\left(\dfrac{m_F}{m_{F0}}\right)^{\gamma}}\right)^{2/\gamma} - \left(\dfrac{p_B}{p_{F0}\left(\dfrac{m_F}{m_{F0}}\right)^{\gamma}}\right)^{(\gamma+1)/\gamma}\right)}, & 1 < \dfrac{p_F}{p_B} < P_c \\ 0, & \dfrac{p_F}{p_B} \le 1. \end{cases}$$

The mass flow through the venting valve is obtained similarly. The variation in the mass of air in the tank is the difference between the mass flow rate from the bottle and the mass flow rate through the venting valve. Let $\overline{s}$ denote the aperture of the venting valve. Then, the equation for the mass of air in the tank is

$$\dot{m}_B(t) + \dot{m}_F(t) = -\overline{\mu}\left(\frac{p_{ext}(t)}{p_B(t)}\right)\frac{\overline{s}(t)A_v p_B(t)}{\sqrt{R_g T_B}}, \tag{2}$$

where A_v is the venting pipe system cross-section, R_g is the gas constant for air, T_B is the temperature in the tank and $\overline{\mu}(p_{ext}(t)/p_B(t))$ is a function of the tank and outside pressures obtained by curve fitting from experimental measures.

Finally, the variation in the tank pressure is obtained from the perfect gas equation as

$$\frac{m_B(t)}{p_B(t)}\dot{p}_B(t) - \dot{m}_B(t) = -\frac{p_B(t)q_B(t)}{R_g T_B}, \tag{3}$$

where $q_B(t)$ is the water flow through the flood port.

We will consider two hovering tanks, bow and aft, with their respective bottles and blowing and venting valves. The geometric characteristics of the blowing and venting system have been adapted from the characteristics of the main ballast tanks blowing and venting system which can be found in Font et al. (to appear).