Ocean Engineering 119 (2016) 125–134

Contents lists available at ScienceDirect

Ocean Engineering

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

Design and analysis of folding propulsion mechanism for hybrid-driven underwater gliders

Zhier Chen [a,b], Jiancheng Yu [a,*], Aiqun Zhang [a], Fumin Zhang [c]

[a] State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, No. 114, Nanta Street, Shenyang, Liaoning 110016, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form
15 December 2015
Accepted 20 March 2016
Available online 6 May 2016

Keywords:
Hybrid underwater glider
Foldable propellers
Mechanical design
CFD analysis

ABSTRACT

This paper presents a design of foldable propellers for a hybrid-driven underwater glider. The design ensures that the propellers are fully closed when the glider is working in buoyancy-driven gliding mode, and become fully open to provide propulsion when necessary. The hydrodynamical moments during the folding and unfolding processes is analyzed and computed using computational fluid dynamics (CFD) methods. Torsion springs are used as key components in the folding and unfolding mechanism. The stiffness of the torsion springs are designed to achieve balance between the mechanical and hydrodynamical moments acting on the propellers. It is shown that comparing to a conventional unfoldable design, the foldable propellers may achieve a significant reduction in drag force when the glider is operating in the gliding mode. Pool experiment results demonstrate the effectiveness of the folding mechanism when installed on an underwater glider.

1. Introduction

In the past decade, Autonomous Underwater Gliders (AUGs) are widely used in oceanographic research (Eriksen et al., 2001; Claus et al., 2012). AUGs are a class of underwater vehicles that change their volume and buoyancy to cycle vertically in the ocean and use lift forces generated by a pair of symmetrical wings attached to the glider hull to convert this vertical velocity into forward motions (Sherman et al., 2001; Yu et al., 2011, 2013). As a result, the glider usually follows a sawtooth motion pattern in the vertical plane. AUGs can also generate helical motion using a rudder or a rolling mass system (Graver, 2005; Zhang et al., 2013; Hussain et al., 2011). AUGs have an excellent endurance up to a few months or more (Webb et al., 2001). In comparison, the autonomous underwater vehicles (AUVs) in common use today perform missions measured by days (Paull et al., 2013; Hyakudome et al., 2002). However, the speed of existing AUGs is lower than that of AUVs (Wang et al., 2011). Thus the slow speeds of AUGs present challenges for navigation in areas of strong current. The vehicle maneuverability will be greatly affected leading to failure in performing observational operations (Merckelbach et al., 2008). In addition, the zigzag trajectory does not allow leveled flight hence preclude observation of dynamic processes in horizontal plane or in shallow water column (Hobson et al., 2012; Zhu et al., 2012; Tian et al., 2014).

Hybrid-driven underwater glider (HDUG) combines the strength of conventional buoyancy-driven AUGs with the propeller-driven AUVs, thus may offer a relatively higher endurance and a better capability to overcome strong current. Some work (Caffaz et al., 2010; Claus et al., 2010b; Isa and Arshad, 2012). Claus et al. (2010a) developed a HDUG with aeronautical foldable propeller placed in the stern of a Slocum glider to achieve leveled flight. Vehicle Control Technologies, Inc. (VCT) has developed a lower-cost, expendable glider (xGlider) that will last sufficiently longer so that recovery is not required. It is worth mentioning that this kind of underwater glider can be easily upgraded to be an AUV with a maximum speed of 2 knots by using modular design method. The ALCEN company have developed a SeaExplorer glider that can operate in hybrid 'AUV/glider' mode if necessary . Designs of HDUG have also been reported by other researchers (Wang et al., 2011).

Most existing HDUGs use conventional fixed-blade propellers. This design is simple, but has drawbacks. The vehicles will experience parasitic drag due to trailing propellers and associated appendages when operating in the glider buoyancy-driven mode, leading to reduced efficiency in operation (MacKenzie and Forrester, 2008; Tian et al., 2012). In order to reduce the impact of drag by the propellers, some researchers have proposed a foldable propeller design (Claus et al., 2010a). If the increase is taken as a

---

* Corresponding author.
E-mail addresses: chenze@sia.cn (Z. Chen), yjc@sia.cn (J. Yu), zaq@sia.cn (A. Zhang), fumin@gatech.edu (F. Zhang).

http://dx.doi.org/10.1016/j.oceaneng.2016.03.034

percentage of the overall glider drag, it would add to the drag force of a glider by 15–18% when the folding propulsion module is not in use (Claus, 2009). But the blades of the folding propeller are unable to close entirely if not in use in water. An improved folding propeller must require the blades fully folded in when the propeller is not in use, and unfolded out when the propeller is in use. Foldable propellers have been used on sailing yachts to reduce drag while under sail for improved performance in competitions (MacKenzie and Forrester, 2008). However, the blades resetting mechanism of the foldable propellers in sailing boats have a large size which does not fit in underwater vehicles. Foldable propellers are also used on model sailplanes to reduce air drag when the power is turned off (Patel et al., 2008). Since the propellers are usually installed in vertical direction, the blades can be easily folded by the force of gravity without any resetting mechanism. So far foldable propellers are rarely used in autonomous underwater vehicles, because the propellers are usually installed at the stern in horizontal direction. The blades cannot be perfectly folded together without enough resetting force when not in use. A foldable propeller applied in HDUG will greatly improve vehicle maneuverability and endurance. Folding propulsion mechanism dedicated for HDUG will be designed and analyzed in the paper. Similar work has not been found in published literature.

In our work, the foldable propeller is aft located on the vehicle hull, its two blades can be opened or closed according to the requirements of operational mission, illustrated in Fig. 1. Results imply that the HDUG with the designed foldable propeller shows advantage in low drag performance over that with fixed-blade propeller.

This paper is organized as follows. Section 2 introduces the foldable propeller design. In Section 3, we built the mathematical model. And in Section 4 presents the verification of the folding mechanism based on CFD data. Section 5 presents the experimental data and analysis. The last section draws conclusions.

2. Mechanical design

A resetting mechanism has been adopted to fold the blades when the HDUG is traveling in the gliding mode at low speed. The mechanism is based on a resetting spring that keeps the blades in folding states when the motor shaft is not rotating. When the drive motor starts to spin the shaft, the blades will experience centrifugal force at high spinning speed to unfold the blades, shown in Fig. 1. The effect of the hydrodynamic forces on the folding mechanism is examined in the next section.

Two or more blades are usually chosen for a ship propeller. It is generally believed that if the plate area and diameter of the propeller is given, when the number of blades increases, the blades interference effect increases, resulting in a lower efficiency. For best efficiency, it is therefore essential to keep the number of blades as low as possible (Bellingham et al., 2010). In addition, propeller with less number of blades has benefit to avoiding vacuoles. Therefore, according to existing AUG's hydrodynamic drag and some other main parameters estimated (Zhang et al., 2012), we chose a two-blade design by applying the propeller atlas design method.

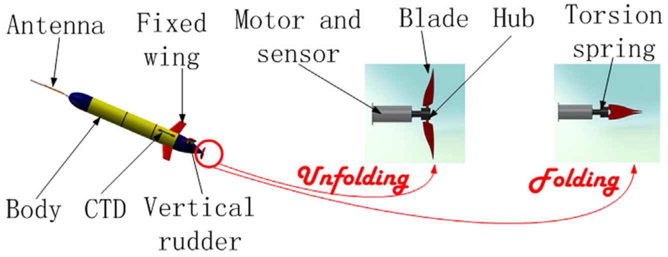

Fig. 1. The external structure of a HDUG whose folding propulsion device is aft located on the hull, the two blades can be completely open or closed.

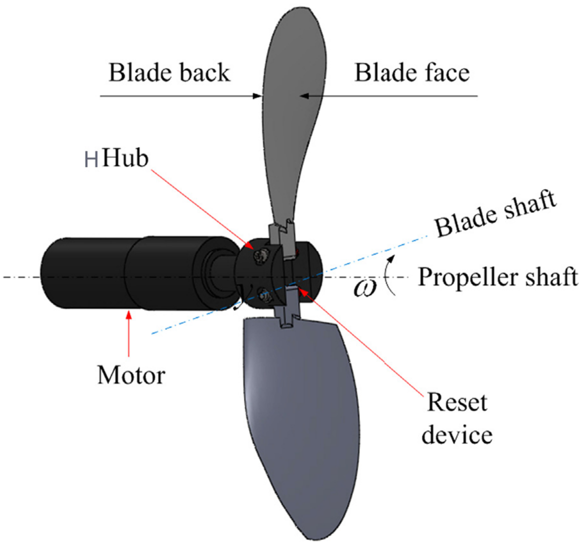

Fig. 2. Illustration of the components of the propulsion mechanism.

The propulsion mechanism designed in this paper includes the following components: a drive motor, a reset unit (torsion spring), two blades, and a hub, shown in Fig. 2. Four torsion strings are installed inside the hub. The stiffness of the torsion string should be designed carefully. The blades cannot successfully unfold from its folding position if the torsion coefficient is too high (i.e., the springs are too stiff). On the contrary, the blades cannot successfully fold completely from its unfolding position if the torsion coefficient is too low (i.e., the springs are too soft). Therefore, mathematical model and analysis are needed to determine the feasible range of torsion coefficient.

3. Balance of moments

Much of our work has been examining the balance of moments during the process of folding and unfolding of the propeller blades. According to this analysis, the required stiffness of the torsion springs has been determined.

3.1. *Balance of moments during blades unfolding*

When the propulsion mechanism needs to work to generate thrust, the drive motor starts to spin and drives the hub to rotate at a constant speed. Then the blades unfold from its folding position due to the centrifugal force and the hydrodynamic thrust force acting on the blades face. Therefore, the blade opening angle θ_p vary approximately from 0° to 90°. The blades will stop at a position where the whole propulsion mechanism reaches a dynamic equilibrium by the action of the centrifugal moment, the hydrodynamic thrust moment, the torsion spring torque, and the gravitational moment on the blades.

Through the above analysis, the moment balance equation is obtained in the blade unfolding process as:

$$-M_C - M_H + M_S + M_G < 0 \tag{1}$$

where M_C is the centrifugal moment, M_H is the hydrodynamic thrust moment, M_S is the torsion spring torque, and M_G is the gravitational moment, all acting on the blade shaft. The positive directions of the moment are defined to follow the right hand rule, as shown in Fig. 3(a).