

Impact of folding propeller spinning position for the transit efficiency of a hybrid-driven underwater glider

Zhier Chen^{*†}, Jiancheng Yu^{*}, Aiqun Zhang^{*}

^{*}Shenyang Institute of Automation, Chinese Academy of Sciences
Shenyang, 110016, P.R.China.

Email: chenze@sia.cn

[†]University of Chinese Academy of Sciences
Beijing, 100049, P.R.China.

Abstract—A hybrid underwater glider(HDUG) is developed based on a folding propeller. The blades of the propeller can fold and unfold according to the motor work or not. When it stop spinning, the blades will come to a rest position. The hydrodynamic performance will vary with the position of the blades, thus the transit efficiency of the HDUG will also vary. So there must be an optimal transit efficiency for the propeller spinning position. Thus to investigate this problem, this paper presents a thorough approach characterizing the transit efficiency for different folding propeller spinning position of the HDUG. This paper employ first-principle analysis that concludes the effect of efficiency for spinning position of the blades. This result implies that the spinning position can effect the transit efficiency of a hybrid-driven underwater glider based on the mathematical model.

Index Terms—Transit efficiency; glider; AUV

I. INTRODUCTION

In the past few years, Autonomous Underwater Gliders(AUGs)are widely used in oceanographic research [1][2][3][4][5]. AUGs are a class of underwater vehicles that can change their gravity center and net buoyancy to periodically navigate in the ocean[6][7][8]. Therefore, the AUGs usually follow a zigzag trajectory in the vertical plane. AUGs can also generate helical motion using one or more vertical rudders or a rolling mass system instead[9][10][11]. AUGs have an excellent endurance up to a few months or more[12]. However, the autonomous underwater vehicles(AUVs)have endurance just several hours or few days[13][14], and the speed up to several knots that is much faster than that of AUGs[15]. We know that the slow speeds of AUGs present challenges for navigation in areas of strong current. So the AUGs maneuverability will be greatly affected leading to failure observational operations[16].In addition, the zigzag trajectory does not allow leveled flight hence preclude observation of dynamic processes in horizontal plane or in shallow water column [17]. According to the above description in above, we find that both the AUGs and the AUVs have their own advantage and disadvantage. This may really limit their application in daily life. So

many researchers around the world perform a new concept underwater vehicle which combine the two kind vehicles characters together, we mean it hybrid-driven underwater glider (HDUG)[18][19][20]. Due to the new design of the HDUG, it can navigate in three different modes in water, that is AUV propeller-driven mode, glider buoyancy-driven mode, and hybrid-driven mode. So the HDUG can obtain a faster velocity and a long endurance. And at the same time, the HDUG can navigate not only in zigzag trajectory but also in line trajectory.

The HDUG navigates in glider mode by the buoyancy without the propeller. So we hope the auxiliary propulsion module can bring drag as smaller as possible when the HDUG gliding underwater. We present a folding propulsion mechanism at the stern of the HDUG to generate thrust in AUV mode and hybrid-driven mode and to reduce drag during gliding motion. The folding propulsion mechanism has been designed in this paper as shown in Fig. 1. The HDUG features high efficiency penetrating in ocean like conventional underwater gliders and high maneuverability when the folding propulsion is in use. For long-range survey, the HDUG should have high transit efficiency. Some works have been carried on the transit efficiency of the HDUG. We can see from Fig. 2 that the folding propeller spinning position is not fixed at a same position each time when the motor stop spin. So our work in this paper is to find out the impact of the folding propeller spinning position for the transit efficiency of the HDUG. This is important to the maximum survey range of the HDUG.

In this paper following, we first introduce the HDUG design. In section three, we built the transit efficiency model of the HDUG. In section four, we analyze the effect of the spinning position to the transit efficiency. Lastly, we give some summary and conclusions.

II. HYBRID-DRIVEN UNDERWATER GLIDER DESIGN

We put the pitch adjustment mechanism and buoyancy adjustment engine of traditional AUGs into the AUVs in order to obtain the HDUG. In order to reduce the drag on the hull

of the HDUG, we develop a folding propulsion mechanism for the HDUG (see Fig.1). The illustration of the HDUG control system is in Fig.3. From Fig.3 we can find the upper parts are the mechanism own to AUVs, and the lower parts are the mechanism own to traditional AUGs. Because of this new concept design, the HDUG can fly in three modes in water. And each mode will have its own hydrodynamic characteristics.

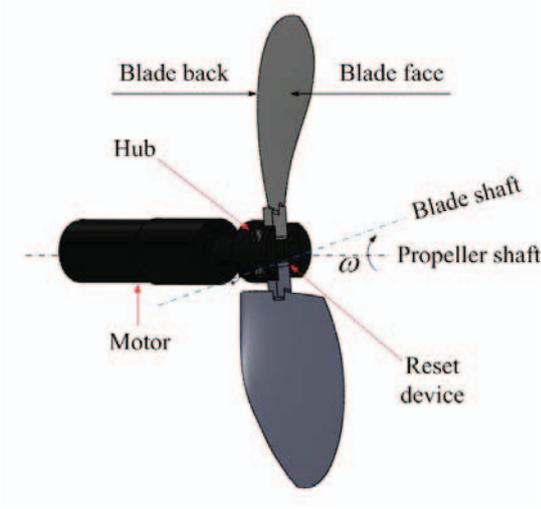


Fig. 1. Illustration of the of the folding propulsion mechanism.

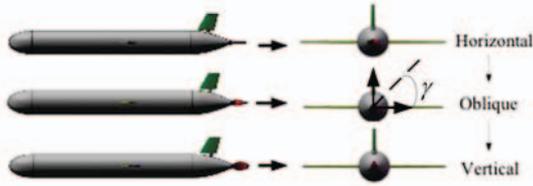


Fig. 2. Different folding propeller spinning position.

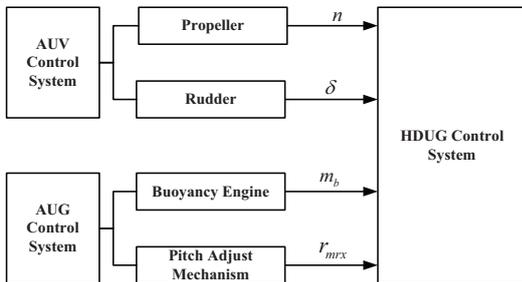


Fig. 3. Illustration of the components of the HDUG control system.

III. TRANSIT EFFICIENCY MODEL

we use a first-principle method to obtain the transit efficiency model in glider buoyancy-driven mode with a folding propulsion mechanism based on the work of Steinberg [21].

Figure 4 and Figure 5 shows the forces acting on the HDUG in the longitudinal plane. The transit efficiency in glider mode η_b is derived in equation (1).

$$\eta_b = \frac{\cot^2 \sigma \cos \sigma (C_{Dh} \lambda_{wh}^{-2} + C_{Dfp\gamma} \lambda_{wp}^{-2})}{2(-1 + \sqrt{1 - (C_{Dh} \lambda_{wh}^{-2} + C_{Dfp\gamma} \lambda_{wp}^{-2}) \cot^2 \sigma}} \quad (1)$$

where σ is the gliding-path angle, $C_{Dfp\gamma}$ ($\gamma \in [0, \pi/2]$) are the propeller drag coefficients with blades in folding at different spinning angle γ when the drive motor stop spin. λ_{wh} is the wing span/hull diameter ratio, λ_{wp} is the wing span/propeller diameter ratio.

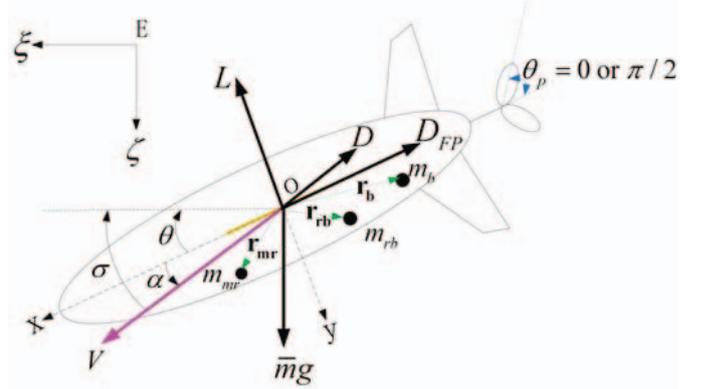


Fig. 4. Variables in the dynamic motion of the HDUG.

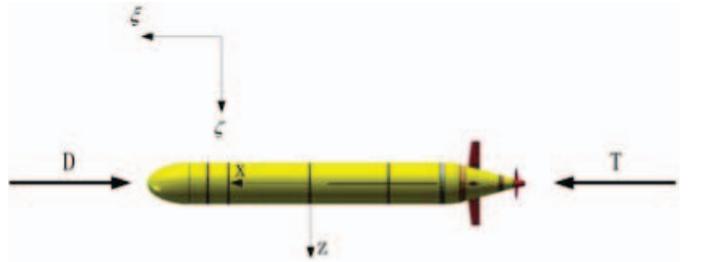


Fig. 5. Illustration of the force acting on the hull body.

IV. CFD CALCULATION AND ANALYSIS OF THE EFFECT OF THE SPINNING POSITION TO THE TRANSIT EFFICIENCY

A computational fluid dynamics (CFD) software package, the CFX, that implements RANS to calculate the hydrodynamic coefficients. The hydrodynamic coefficients $C_{Dfp\gamma}$ acting on the blade shaft generated by the water pressure on the back surface of a blade can be obtained by using CFD software packages. The flow domain is shown in Fig.6.

After obtaining the hydrodynamic coefficients then we can plot the transit efficiency curve as shown in Fig.7. From Fig. 7, we can see that the transit efficiency is decrease with the propeller drag coefficients increasing. So we must calculate the drag coefficients $C_{Dfp\gamma}$ to achieve the minimum value when the propeller spinning position at different spinning angle γ .



Fig. 6. A section of the flow domain of water volume.

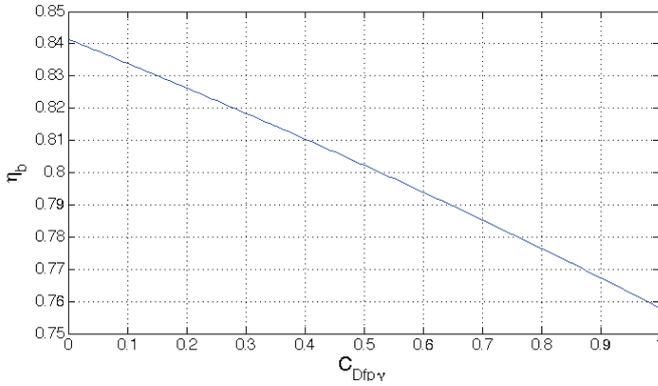


Fig. 7. The transit efficiency in glider buoyancy-driven mode varies with the folding propeller drag coefficients.

So the next task is focused on calculating the foldable propeller drag coefficients when the blades are in folding $C_{Dfp\gamma}$ ($\gamma \in [0, \pi/2]$) based on the Sea-wing glider [?] and the designed propeller (e.g., Table I is the parameters of the propeller).

TABLE I
MAIN PARAMETERS OF THE PROPULSION MECHANISM

List of items	Property
Propeller diameter, D	0.28m
Pitch/propeller diameter ratio, P_p/D	0.786
Hub/propeller diameter ratio, d_h/D	0.14
Blade area ratio, A_D/A_O	0.275

Lastly, based on the previous work we study the effect of propeller spinning angle γ to glider buoyancy-driven mode transit efficiency η_b .

V. CONCLUSION

The last section in this paper presents the preliminary main conclusions, which may be useful for the future manufacture and controller design of the folding propeller. We summarize them as the transit performance of the HDUG is relative to the propeller spinning angle which depends on the parameters of the designed propeller. The results are useful

to conduct the design of the wings, hull, and propeller of the HDUG.

ACKNOWLEDGMENT

The authors acknowledge the support of the National Natural Science Foundation of China under Grants 51179183 and 61233013 and 2015-Z09 of the State Key Laboratory of Robotics in China.

REFERENCES

- [1] C. C. Eriksen, T. J. Osse, R. D. Light, T. Wen, T. W. Lehman, P. L. Sabin, et al., "Seaglider: a long-range autonomous underwater vehicle for oceanographic research," *IEEE J. Oceanic Eng.*, vol. 26, pp. 13, 2001.
- [2] B. Claus, R. Bachmayer, and L. Cooney, "Analysis and development of a buoyancy-pitch based depth control algorithm for a hybrid underwater glider," in *Autonomous Underwater Vehicles (AUV)*, 2012 IEEE/OES, 2012, pp. 1-6.
- [3] M. Arima, H. Tonai, and Y. Kosuga, "Underwater Glider 'SOARER' for Ocean Environmental Monitoring," *2013 IEEE International Underwater Technology Symposium (Ut)*, 2013.
- [4] S. Ruiz, L. Renault, B. Garau, and J. Tintore, "Underwater glider observations and modeling of an abrupt mixing event in the upper ocean," *Geophysical Research Letters*, vol. 39, Jan 13 2012.
- [5] K. Asakawa and M. Nakamura, "Underwater Glider for a Long-Term Virtual Mooring JAMSTEC Glider Able to Monitor Ocean From Seafloor for Over a Year," *Sea Technology*, vol. 53, pp. 15-4, Dec 2012.
- [6] J. Sherman, R. E. Davis, W. B. Owens, and J. Valdes, "The autonomous underwater glider 'Spray'," *IEEE J. Oceanic Eng.*, vol. 26, p. 10, 2001.
- [7] J. C. Yu, A. Q. Zhang, W. M. Jin, Q. Chen, Y. Tian, and C. J. Liu, "Development and Experiments of the Sea-Wing Underwater Glider," *China Ocean Eng.*, vol. 25, pp. 721-736, 2011.
- [8] J. C. Yu, F. M. Zhang, A. Q. Zhang, W. M. Jin, and Y. Tian, "Motion Parameter Optimization and Sensor Scheduling for the Sea-Wing Underwater Glider," *IEEE Journal of Oceanic Engineering*, vol. 38, pp. 243-254, Apr 2013.
- [9] J. G. Graver, "Underwater gliders: Dynamics, control and design," Cite-seer, 2005.
- [10] S. Zhang, J. Yu, A. Zhang, and F. Zhang, "Spiraling motion of underwater gliders: Modeling, analysis, and experimental results," *Ocean Engineering*, vol. 60, pp. 1-13, 2013.
- [11] N. A. A. Hussain, M. R. Arshad, and R. Mohd-Mokhtar, "Underwater glider modelling and analysis for net buoyancy, depth and pitch angle control," *Ocean Engineering*, vol. 38, pp. 1782-1791, Nov 2011.
- [12] D. C. Webb, P. J. Simonetti, and C. P. Jones, "SLOCUM: an underwater glider propelled by environmental energy," *IEEE J. Oceanic Eng.*, vol. 26, p. 6, 2001.
- [13] L. Paull, S. Saeedi Gharahbolagh, M. Seto, and H. Li, "Sensor Driven Online Coverage Planning for Autonomous Underwater Vehicles," *2012 IEEE/Rsj International Conference on Intelligent Robots and Systems (Iros)*, pp. 2875-2880, 2012.
- [14] T. Hyakudome, T. Aoki, T. Murashima, S. Tsukioka, H. Yoshida, H. Nakajoh, et al., "Recent research and development trend on the underwater vehicle in JAMSTEC," *Proceedings of the Fifth (2002) Isopacific/Asia Offshore Mechanics Symposium*, pp. 1-6, 2002.
- [15] S. X. Wang, X. J. Sun, Y. H. Wang, J. G. Wu, and X. M. Wang, "Dynamic Modeling and Motion Simulation for a Winged Hybrid-Driven Underwater Glider," *China Ocean Engineering*, vol. 25, pp. 97-112, 2011.
- [16] L. M. Merckelbach, R. D. Briggs, D. A. Smeed, and G. Griffiths, "Current measurements from autonomous underwater gliders," in *In Proceedings of the Ninth IEEE/OES Working Conference on Current measurement technology*, New York, 2008, pp. 61-67.
- [17] B. W. Hobson, J. G. Bellingham, B. Kieft, R. McEwen, M. Godin, and Y. Zhang, "Tethys-class long range AUVs extending the endurance of propeller-driven cruising AUVs from days to weeks," in *Autonomous Underwater Vehicles (AUV)*, 2012 IEEE/OES, 2012, pp. 1-8.
- [18] K. Isa and M. R. Arshad, "Neural Networks Control of Hybrid-Driven Underwater Glider," *OCEANS, 2012-Yeosu*, 2012.
- [19] B. Claus, "Hybrid Glider Propulsion Module Implementation and Characterization," *Autonomous Underwater Vehicles (AUV)*, 2010.
- [20] J. G. Wu, "System Design and Performance Analysis of Hybrid-driven Underwater glider," Doctor, Tianjin University, Tianjin, 2012.

[21] D. Steinberg, A. Bender, A. Friedman, M. Jakuba, O. Pizarro, and S. Williams, "Analysis of Propulsion Methods for Long-Range AUVs," *Marine Technology Society Journal*, vol. 44, pp. 46-55, 2010.