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Effect of wing form on the hydrodynamic characteristics and dynamic stability of an underwater glider

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Abstract

We are developing a prototype underwater glider for subsea payload delivery. The idea is to use a glider to deliver payloads for subsea installations. In this type of application, the hydrodynamic forces and dynamic stability of the glider is of particular importance, as it has implications on the glider's endurance and operation. In this work, the effect of two different wing forms, rectangular and tapered, on the hydrodynamic characteristics and dynamic stability of the glider were investigated, to determine the optimal wing form. To determine the hydrodynamic characteristics, tow tank resistance tests were carried out using a model fitted alternately with a rectangular wing and tapered wing. Steady-state CFD analysis was conducted using the hydrodynamic coefficients obtained from the tests, to obtain the lift, drag and hydrodynamic derivatives at different angular velocities. The results show that the rectangular wing provides larger lift forces but with a reduced stability envelope. Conversely, the tapered wing exhibits lower lift force but improved dynamic stability.

Keywords: Underwater glider; Hydrodynamic characteristics; Dynamic stability

1. Introduction

An Underwater Glider (UG) is a self-propelled unmanned underwater vehicle with wings that convert vertical motion into horizontal motion. The wing form of these gliders influenced their hydrodynamic characteristics. The hydrodynamic characteristics may be obtained experimentally or numerically. Experimental studies are expensive and tedious, as it entails among others, availability of test facilities, fabrication of a prototype, calibration, experimental setup, etc. On the other hand, numerical simulation does not have these drawbacks and is a proven alternative to experimental studies. Nevertheless, an effective model, appropriate boundary conditions and selection of correct mesh size are needed to achieve good results (Stern et al., 2013). The hydrodynamic forces and moments acting on the glider in turn affect its dynamic stability. Stability is important, as the glider's external control surfaces such as its wings typically operate in a low-speed environment, and as such are unable to make quick corrective actions.

Zhang et al. (2014) evaluated the lift to drag ratio of a fish-like robot with a simple non-standard trapezoidal wing at different wing aspect ratio. They found that larger wings result in shallower gliding paths i.e. longer horizontal travel, but slower total speed compared to smaller wings. Liu et al. (2014) investigated the effect of wing layout on the maneuverability of a hybrid underwater vehicle Petrel-II, specifically the influence of chord length, aspect ratio, sweep back angle and axial position. They found that chord length has a

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significant impact on the lift to drag ratio, while sweep angle has a significant impact on the movement of the vehicle. In this work, we investigated the effect of wing form on the lift to drag ratio and stability, by replicating both a straight-line resistance test and a rotating arm test using Computational Fluid Dynamics (CFD) in three dimensions.

The layout and dimensions of the newly developed glider, the UTP glider, are provided in Fig. 1 and Table 1, respectively. The glider consists of an elliptical hull and vertical rudder, with an interchangeable tapered and rectangular wing. Both wings have a NACA 0016 airfoil shape. The lift, drag, pitching moment, rotating arm normal forces and pitching moment of the glider with both the rectangular and tapered wing were compared. Additionally, the dynamic stability of both wing forms was evaluated analytically.

In Section Two, a dynamic model of the UTP glider along the vertical plane and its corresponding dynamic stability equations are described. Section Three describes the detailed CFD simulation methodology. In the last section, we present and discuss the results of the straight-line resistance test and rotating arm test for the UTP glider with rectangular and tapered wings.

2. Dynamic equations of motion

The motion of the UTP glider is based on the six Degrees of Freedom (DOF) body fixed coordinate, the origin of which is the Center of Buoyancy (CB), as shown in Fig. 2. Table 2 lists the respective motion parameters and the corresponding axes in the body fixed coordinate system.

In general, the dynamic behavior of an underwater glider is highly complex due to nonlinear coupling of forces and moments in 6-DOF. The 6-DOF equations of motion of the glider were simplified along the horizontal and vertical plane, with the assumption that the forces and moments are functions of velocity and acceleration. The linearized model of the glider in the vertical plane (Fossen, 2011) are expressed as follows:

$$-X_u U + (m - X_{\dot u})\dot U = 0 \qquad (1)$$

$$(m - Z_{\dot w})\dot w - Z_w w - (m x_G - Z_{\dot q})\dot q - (mU + Z_q)q = 0 \qquad (2)$$

$$-(m x_G + M_{\dot w})\dot w + (I_{yy} - M_{\dot q})\dot q - M_w w + (m x_G U - M_q)q = 0 \qquad (3)$$

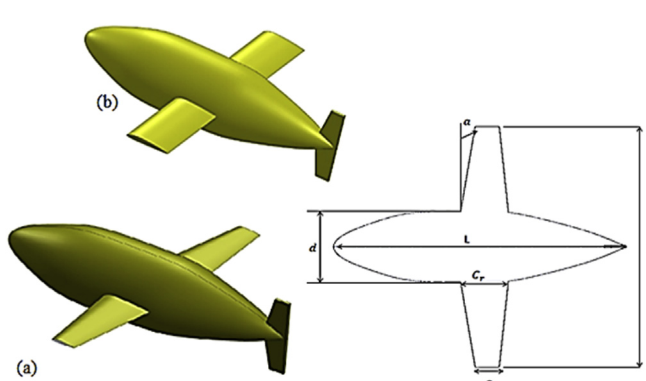

Fig. 1. Underwater glider with (a) tapered wings (b) rectangular.

2.1. Dynamic stability

Vertical and horizontal stability are important to ensure good path stability and turning performance. A highly maneuverable glider requires dynamic stabilities in both horizontal and vertical directions. While a stable glider without any control input may have straight line stability in the horizontal plane, hydrostatic restoring forces and moments are prone to destabilize the glider in the vertical plane. The stability of a glider is controlled by a moving internal mass or. Alternatively, the dynamic stability of a glider may be controlled by external fixed wings and a vertical rudder. The Routh stability criteria for dynamic stability in heave and pitch are given in Eqs. (4) and (5).

$$Z_w M_q - M_w (y_r + mw) > 0 \qquad (4)$$

$$\frac{Z_w}{(Z_q + mw)} - \frac{M_w}{M_q} > 0 \qquad (5)$$

Table 1
UTP glider dimension.

Dimension	Rectangular wings glider	Taper wings glider
Total wing span (b)	0.97 m	0.97 m
Root chord length C_r	0.17 m	0.17 m
Glider diameter d	0.28 m	0.28 m
Glider length (L)	1.04 m	1.04 m
Taper ratio C_r/C_t	–	1.89
Sweep angle (a)	–	8.5°

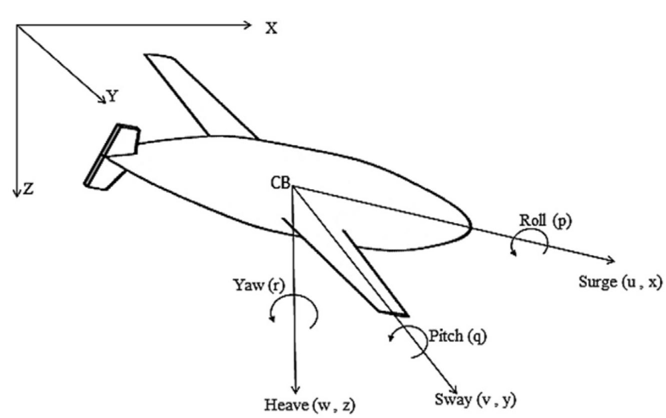

Fig. 2. Glider body fixed coordinate system.

Table 2
Motion parameters and their corresponding axes.

DOF	Displacement	Force & Moment	Velocity	Acceleration
1-surge	x	X	u	$\dot u$
2-sway	y	Y	v	$\dot v$
3-heave	z	Z	w	$\dot w$
4-roll	ϕ	K	p	$\dot p$
5-pitch	θ	M	q	$\dot q$
6-yaw	ψ	N	r	$\dot r$

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