ARTICLE IN PRESS

Ocean Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ocean Engineering

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

Computational fluid dynamics study of the motion stability of an autonomous underwater helicopter

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ARTICLE INFO

Keywords:
Autonomous Underwater Vehicle (AUV)
Autonomous Underwater Helicopter (AUH)
Computational Fluid Dynamics (CFD)
Motion stability
Hydrodynamics

ABSTRACT

In this study, the motion stability of a new type of autonomous underwater vehicle (AUV) named an “autonomous underwater helicopter (AUH)” with a disk-shaped hull was analyzed to better accomplish the complex tasks under the sea, namely, pipeline maintenance, mobile observation network, resources exploration, and isodepth navigation. A Reynolds Averaged Navier-Stokes (RANS) grid for the AUH was created with an ICEM mesh generation tool. The RANS-based computational fluid dynamics (CFD) technique, ANSYS-CFX, was adopted to analyze the AUH's behavior, including its motion stability and maneuverability in the horizontal and vertical planes. Pivotal hydrodynamic technical issues including configurations selection and a trade-off study of the AUH were analyzed with the RANS solver, including computed pressure distribution and comparison of different lengths of aquatic transducers mounted on the AUH for enhanced hydrodynamic performance. The Routh motion stability criterion based on the 6-DOF equations of motion consisting of linear hydrodynamic derivatives was implemented by the RANS solver for the optimized AUH with a service speed in the range of 1–3 knots. The simulation results and experimental tests show that the AUH has ample motion stability for enhanced maneuverability in translational and rotatory motion during under-sea navigation. The results suggest that design configurations of the appended hull can be used on AUVs.

1. Introduction

This study analyzes the motion stability of a new type of underwater vehicle derived from the autonomous underwater vehicle (AUV) family, known as an Autonomous Underwater Helicopter (AUH). Conventionally, AUVs operate from the surface to the deep sea and then return to the surface. However, the AUH uses a new operation mode in which it operates under the sea from seabed to seabed, as shown in Fig. 1. For this adaptive working mode, a disk-shaped AUH was proposed at the Ocean College of Zhejiang University.

With regard to the hydrodynamic shape and configurations to achieve enhanced hydrodynamic performance, motion stability, and trade-off maneuverability, a torpedo-shaped axisymmetric body is the primary design of conventional type of AUVs (Evans and Nahon, 2010), e.g., *REMUS AUV* (Prestero and Timothy, 2001), *MUN Explorer AUV (*Azarsina and Williams, 2010*)*, and *SMAL01 AUV* (Hu and Lin, 2008), etc. However, the torpedo-shaped AUVs have poor maneuverability in sway and yaw situations and motion instability in heave situations owing to control surface inefficiencies under low velocity conditions. However this design does have good linear motion performance owing to its streamlined shape (Phillips et al., 2007a).

New underwater technology applications in the working scope of AUVs, e.g., mobile observation networks (Wu et al., 2014), undersea resources exploration (Kinsey et al., 2011), and isodepth surface navigation demand higher requirements for better maneuverability with trade-off motion stability. A few AUVs can meet these working requirements in deep-sea mobile observation networks (Wu et al., 2014; Alvarez et al., 2009). As shown in Fig. 2, an existing similar network system has already been constructed more than 1000 m below the surface; however, the horizontal deviation of the torpedo-shaped AUV is inefficiently and ineffectively controlled in the docking process (Zhang et al., 2015). The conventional torpedo-shaped AUV, even the novel hybrid underwater glider (Yang et al., 2015), needs a complex docking guidance algorithm for docking transmission between base stations in the network (Yang et al., 2015; Park et al., 2009; Chen et al., 2013a). In addition, once the isodepth surface of the underwater topography in 1000-m deep sea is complex, conventional AUVs find it inefficient to cruise between base stations along the complex topography. Hence, a novel hull form design with a good trade-off between high maneuverability and motion stability is required.

A practical hull form for an AUH must be adapted to perform multi-directional translation, free rotation, and precise hovering and landing

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http://dx.doi.org/10.1016/j.oceaneng.2017.07.020
Received 20 January 2017; Received in revised form 16 May 2017; Accepted 4 July 2017

Please cite this article as: Chen, C.-W., Ocean Engineering (2017), http://dx.doi.org/10.1016/j.oceaneng.2017.07.020

Nomenclature

CB, CG	Centers of buoyancy and gravity
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Moment coefficient
D	Drag force, parallel to the direction of flow
H	Maximum hull height
I_{ij}	Moments and products of inertia for the AUH (about the center of gravity)
K, M, N	Components of a resultant total moment acting on the AUH about the x, y and z-axes, respectively; referred to as the rolling, pitching and yawing moments, respectively, $K' = \frac{K}{1/2\rho L^3 V^2}$, $M' = \frac{M}{1/2\rho L^3 V^2}$, $N' = \frac{N}{1/2\rho L^3 V^2}$
L	Maximum hull length (diameter)
m	Mass of the AUH, $m' = \frac{m}{1/2\rho L^3}$
$\mathbf{M}_o$	Moments about the origin of body-fixed coordinate system, relative to the body-fixed coordinate system
p, q, r	Components of resultant angular velocity of the AUH about the x, y and z-axes, respectively, $p' = \frac{pL}{V}$, $q' = \frac{qL}{V}$, $r' = \frac{rL}{V}$
Re	Reynolds number
$\mathbf{r}_G$	Position vector of the center of gravity
S	The area of the body projected on the x-y plane, defined $\pi(L/2)^2$
$\mathbf{u}_o$	Velocity of the origin of body-fixed coordinate system, relative to the body-fixed coordinate system
$\dot{\mathbf{u}}_G$	Acceleration of the center of gravity of the AUH, relative to the body-fixed coordinate system
$\dot{\mathbf{u}}_o$	Acceleration of the origin of body-fixed coordinate system, relative to the body-fixed coordinate system
u, v, w	Components of V along the x, y and z-axes, respectively, $u' = \frac{u}{V}$, $v' = \frac{v}{V}$, $w' = \frac{w}{V}$
$\mathbf{V}$	Translating velocity
x, y, x	Body axis coordinates
x_o, y_o, z_o	Inertial coordinates
x_G, y_G, z_G	The center of gravity in body-fixed coordinate system
X, Y, Z	Components of total force along the x, y and z-axes, respectively, $X' = \frac{X}{1/2\rho L^2 V^2}$, $Y' = \frac{Y}{1/2\rho L^2 V^2}$, $Z' = \frac{Z}{1/2\rho L^2 V^2}$
Y_v	Partial derivative of Y with respect to v, $Y'_v = \frac{Y_v}{1/2\rho L^2 V}$
Y_r	Partial derivative of Y with respect to r, $Y'_r = \frac{Y_r}{1/2\rho L^3 V}$
N_v	Partial derivative of N with respect to v, $N'_v = \frac{N_v}{1/2\rho L^3 V}$
N_r	Partial derivative of N with respect to r, $N'_r = \frac{N_r}{\frac{1}{2}\rho L^4 V}$
Z_w	Partial derivative of Z with respect to w, $Z'_w = \frac{Z_w}{1/2\rho L^2 V}$
Z_q	Partial derivative of Z with respect to q, $Z'_q = \frac{Z_q}{1/2\rho L^3 V}$
M_w	Partial derivative of M with respect to w, $M'_w = \frac{M_w}{1/2\rho L^3 V}$
M_q	Partial derivative of M with respect to q, $M'_q = \frac{M_q}{1/2\rho L^4 V}$
$\boldsymbol{\omega}$	Angular velocity of the AUH, relative to body-fixed coordinate system
$\boldsymbol{\alpha}$	Angular acceleration of the AUH, relative to body-fixed coordinate system
ρ	Density of the water
γ	Coefficient of kinematic viscosity
α	angle of attack (AOA), $\alpha = \tan^{-1}(w/u)$
β	angle of drift (AOD), $\beta = \tan^{-1}(-v/u)$
Φ	angle of orientation (AOO), $\Phi = \tan^{-1}(-v/-w)$

Subscripts/superscripts

G	Indicates the AUH center of gravity in a body-fixed coordinate system
H	the hydrodynamic force or moment acting on the surface of the AUH
CFD	Computational Fluid Dynamics Study in this paper
S	Static stability forces or moments
P	The thrust or torque generated by the propeller
•	Time derivative

on the seabed. A simple practical geometric shape, e.g., sphere, ellipsoidal, disk, or diamond, could be considered as possible designs for an AUH. The disk-shaped AUH has smaller drag in the horizontal plane than the other shapes but the larger drag in the vertical plane than the others. However, our simulation results and experimental tests in this study show that the characteristics of the disk-shaped hull form enable the AUH to land while exercising motion stability in the vertical plane.

Recently, rotatable vectoring thrusters have been incorporated for enhanced maneuverability in conventional AUVs, e.g., Sentry AUV (Kinsey et al., 2011), SIA-4500 AUV (Yi et al., 2013), and ZJU-AUG (Yang et al., 2015), which was integrated with a buoyancy engine, i.e., hybrid vectoring thrusters. The proposed AUH would be equipped with two 360° full-circumferential rotatable vectoring thrusters integrated with a buoyancy engine for enhanced maneuverability with energy saving in the vertical plane and optimized attitude control during navigation. Hence, the AUH mounted with hybrid vectoring thrusters would perform the better maneuverability than torpedo-shaped AUVs, i.e., tactical diameter and/or steady turning radius much smaller than those of the conventional AUVs.

AUV stability can be divided into static stability and dynamic stability (motion stability). A statically stable AUV is easily implemented given an appropriate distance between the *CG* and *CB* in the vertical plane that produces enough restoring forces and moments that oppose an instantaneous perturbation of motion variables from the trimmed state. Static stability is fundamental of motion stability. The concept of motion stability constitutes the concept of stability in both direction and course.

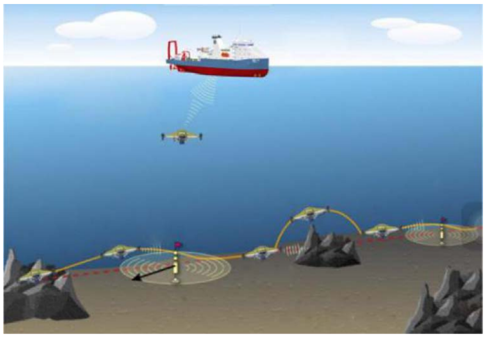

Fig. 1. Working scheme of the AUH.

Motion stability is defined as the tendency of an AUV, without pilot assistance, to return to its initial steady-state trim condition after a disturbance perturbs the trimmed values. Motion stability is concerned with the entire history of the motion, including the rate at which the motion damps out. When an AUV is dynamically and statically stable, it keeps in trim, whereas an AUV is dynamically unstable, the amplitude of the motion variables grow and diverge over time.

An analysis of motion stability is more difficult than analyses of static stability because for a statically stable AUV, there is no guarantee