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Stability analysis of a positively buoyant underwater vehicle in vertical plane for a level flight at varying buoyancy, BG and speeds

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ABSTRACT

This paper studies the dynamic stability of a positively buoyant Autonomous Underwater Vehicle (AUV) in vertical plane for a level flight. Dynamic stability of underwater vehicles is estimated by using the linearized equations of motion about an equilibrium position. AUV is a slow moving and positively buoyant vehicle that enhances the stabilizing effect of the restoring forces. Hence a more general approach is required for the evaluation of stability. A 3 dof model for trajectory simulation for level depth trajectories is used to study the effect of positive buoyancy on vehicle trajectory at different speeds. The relative importance of the damping, restoring and control forces acting on the vehicle is established. The stability analysis is undertaken using linearized equations of motion considering the nonlinearities due to positive buoyancy. Numerical studies are carried out to estimate the fixed points of the system and eigenvalues at different forward speeds, metacentric heights and positive buoyancy for a level depth. The study shows that the stability changes from oscillatory to a steady node at a transition speed that depends on the metacentric height. The positive buoyancy has marginal effect on the transition speed but influences the sternplane angles and pitch of the vehicle.

1. Introduction

The dynamic stability of an underwater vehicle in level flight is evaluated based on linearized equations of motion and the eigenvalues of the system. The conditions for the stability of an underwater vehicle with controls fixed, (Spencer, 1968), are

$$BG > 0 \tag{1a}$$

$$Z'_w < 0 \tag{1b}$$

$$M'_q < 0 \tag{1c}$$

$$M'_w\left(m' + Z'_q\right) - Z'_w M'_q < 0 \tag{1d}$$

Autonomous Underwater Vehicle (AUV) present new challenges in stability evaluation as they are reconfigurable, slow moving and positively buoyant. Many AUVs have freely floodable spaces enabling reconfiguration of the vehicle for different mission-specific payloads. These results in variation of buoyancy and metacentric height of the vehicle. Further, they move at very low speeds of 0.5–6 knots. This makes the velocity related damping forces smaller, making the contribution of the buoyancy dependent restoring forces important. Hence, any stability evaluation has to account for the restoring forces due to positive buoyancy and variation in metacentric height. Further, the practical limitation of the angle of incidence of the sternplanes for depth control limit the maximum control forces available in the system to compensate for the positive buoyancy. Eqn (1), derived based on the linearized equations of motion assume neutral buoyancy, thus, the effect of both the restoring forces and control forces are not considered. Thus, the use of Eqn (1) for the study of the effect of the metacentric height and buoyancy for a slow moving vehicle is limited. A more general approach by estimating the system states and control parameters is required for evaluating the dynamic stability of a positively buoyant AUV.

Detailed analysis of dynamic stability is undertaken by modelling the vehicle dynamics in 6 degrees of freedom using the principles of Newtonian mechanics eg. (Abkowitz, 1964; Feldman, 1979; Fossen, 1994; Gertler and Hagen, 1967). The practical use of these equations requires the estimation of hydrodynamic coefficients representing the relationship between the forces, states and control variables (Feldman, 1987; Roddy, 1990). present the experimental techniques for the determination

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Nomenclature

x	Displacement in x direction m
z	Displacement in z direction m
θ	Pitch angle rad
u	Velocity in x direction m/s
u'	Non dimensional form of u = 1.0
w	Velocity in z direction m/s
w'	Non-dimensional form of w $\left(=\frac{w}{u}\right)$
q	Pitch rate in body coordinates rad/s
q'	non dimensional form of q $\left(=\frac{qL}{u}\right)$
$\dot{u}$	Acceleration in x direction m/s^2
$\dot{w}$	Acceleration in z direction m/s^2
$\dot{w}'$	Non dimensional form of $\dot{w}\left(=\frac{\dot{w}L}{u^2}\right)$
$\dot{q}$	Pitch acceleration rad/s^2
$\dot{q}'$	Non dimensional form of $\dot{q}\left(=\frac{\dot{q}L^2}{u^2}\right)$
δs	Sternplane angle rad
L	Length of the vehicle m
x_G	Longitudinal centre of gravity m
x_B	Longitudinal centre of buoyancy m
z_G	Vertical centre of gravity m
z_B	Vertical centre of buoyancy m
x'_G	Non dimensional form of x_G $\left(=\frac{x_G}{L}\right)$
x'_B	Non dimensional form of x_B $\left(=\frac{x_B}{L}\right)$
z'_G	Non dimensional form of z_G $\left(=\frac{z_G}{L}\right)$
z'_B	Non dimensional form of z_B $\left(=\frac{z_B}{L}\right)$
BG	Metacentric height ($=z_G - z_B$) m
ρ	Density of the medium (=1000) kg/m^3
g	Acceleration due to gravity (=9.81) m/s^2
m	Mass of the vehicle kg
m'	Non dimensional mass coefficient $\left(=\frac{m}{\frac{1}{2}\rho L^3}\right)$
b	Positive buoyancy of the vehicle kg
I_y	Mass moment of inertia w.r.t y axis $kg\text{-}m^2$
I'_y	Non dimensional Inertia coefficient $\left(=\frac{I_y}{\frac{1}{2}\rho L^5}\right)$
W	Weight of the vehicle (=mg) N
B	Buoyancy of the vehicle (=(m + b)g N
η	[x z θ]
ν	[u w q]
K_T	Propeller force coefficient
n	Propeller rpm
d	Propeller diameter m
$Z_{\dot{w}}$	Z-Coefficient representing effect due to $\dot{w}$ kg
$Z'_{\dot{w}}$	Non dimensional form of $Z_{\dot{w}}$ $\left(=\frac{Z_{\dot{w}}}{\frac{1}{2}\rho L^3}\right)$
$Z_{\dot{q}}$	Z-Coefficient representing effect due to $\dot{q}$ kg-m
$Z'_{\dot{q}}$	Non dimensional form of $Z_{\dot{q}}$ $\left(=\frac{Z_{\dot{q}}}{\frac{1}{2}\rho L^4}\right)$
$M_{\dot{w}}$	M-Coefficient representing effect due to $\dot{w}$ kg-m
$M'_{\dot{w}}$	Non dimensional form of $M_{\dot{w}}$ $\left(=\frac{M_{\dot{w}}}{\frac{1}{2}\rho L^4}\right)$
$M_{\dot{q}}$	M-Coefficient representing effect due to $\dot{q}$ kg-m
$M'_{\dot{q}}$	Non dimensional form of $M_{\dot{q}}$ $\left(=\frac{M_{\dot{q}}}{\frac{1}{2}\rho L^5}\right)$
Z_w	Z-coefficient representing effect due to w kg/s
Z'_w	Non dimensional form of Z_w $\left(=\frac{Z_w}{\frac{1}{2}\rho u L^2}\right)$
Z_q	Z-coefficient representing effect due to q N
Z'_q	Non dimensional form of Z_q $\left(=\frac{Z_q}{\frac{1}{2}\rho u L^3}\right)$
M_w	M-coefficient representing effect due to w N-m
M'_w	Non dimensional form of M_w $\left(=\frac{M_w}{\frac{1}{2}\rho u L^3}\right)$
M_q	M-coefficient representing effect due to q N-m
M'_q	Non dimensional form of M_q $\left(=\frac{M_q}{\frac{1}{2}\rho u L^4}\right)$
$Z_{\delta s}$	Z-coefficient representing effect due to δs N
$Z'_{\delta s}$	Non dimensional form of $Z_{\delta s}$ $\left(=\frac{Z_{\delta s}}{\frac{1}{2}\rho u^2 L^2}\right)$
$M_{\delta s}$	M-coefficient representing effect due to δs N-m
$M'_{\delta s}$	Non dimensional form of $M_{\delta s}$ $\left(=\frac{M_{\delta s}}{\frac{1}{2}\rho u^2 L^3}\right)$

of the hydrodynamic forces (Aage and Smitt, 1994; Guo and Chiu, 2001; Praveen and Korulla, 2008). have used planar motion mechanism techniques for the determination of the hydrodynamic forces of a flat fish AUV. Numerical methods are also used for determining the hydrodynamic forces, particularly for simpler axisymmetric shapes eg. (Nahon, 1996).

(Fossen, 1994) presents a condition for stability analysis of underwater vehicle dynamics using Lyapunov's methods. The Lyapunov candidate function is derived as an energy function of potential and kinetic energies and the necessary condition for stability is that both added mass and damping matrices should be positive. This derivation assumes that the inertial state variables and their first order derivatives are zero and the control surface forces are not present (Papoulias and Papadimitriou, 1995). undertake a stability analysis for an axisymmetric underwater body based on the Routh-Hurwitz criterion and establish that the stability depends on the metacentric height and the vehicle is stable up to a certain critical speed. The study considers the stabilizing effect of the quadratic drag forces. The study further indicates that as the vehicle crosses the critical speed, the system leaves its steady state in an oscillatory manner, which is a Hopf bifurcation (Leonard, 1997). studies a case of stability of neutrally buoyant vehicle with non-coincident centres of gravity and buoyancy in vertical plane. The study uses rigid body dynamic theory and represents the underwater vehicle dynamics as a Lie-Poisson system using a Hamiltonian. (Palmer, 2009) investigated the stability of a survey style AUV and provided a formula for the critical speed above which the AUV can maintain a constant depth trajectory. The formula was applied for an AUV with neutral buoyancy and near zero BG.

This paper attempts to answer the following: What would be the effect of positive buoyancy, speed and BG on the vehicle stability for level depth trajectories. As the AUVs are slow moving vehicles, during constant depth runs in straight line, the sway forces and yaw moments are absent in calm water manoeuvres. So, a 3 dof nonlinear model with surge, heave and pitch is considered adequate for simulation of level depth trajectories in straight line at different speeds and positive buoyancies. Trajectory simulation is undertaken for a 'flat-fish' AUV developed at the Naval Science and Technological Laboratory (NSTL) for level depth conditions at constant speed for different positive buoyancies. The