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Experimental investigation on roll stability of blunt-nose submarine in buoyantly rising maneuvers

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ABSTRACT

The roll stability of submarine buoyantly rising is investigated by means of kinematics model test in this paper. The physical model design, similarity criteria and experimental procedures are presented in detail for simulating emergency rising of the real submarine with similar properties. Experimental results reveal that the roll and yaw are strongly coupled and interacted. In addition, excessive roll occurs inevitably when underwater drift angle is larger than 5°. In other words, the yaw instability is the most key coupled factor of increasing drift angle as well as generating snap roll, which eventually aggravates the excessive roll. Furthermore, the rising sternplane angle is essential to pitch up nose because a larger pitch rate is conducive to maintain stable heading angle. In summary, by keeping yaw deviation as low as possible helps to limit the increase of drift angle, and further delay the onset of snap roll. Therefore, the excessive roll can be avoided through optimal control of initial speed, blown ballast longitudinal centroid and sternplane angle. The experimental results can provide manipulations recommendations for the emergency rising of the real submarine.

1. Notes

The body fixed axis system is given in the figure [1]. The origin, O, is taken on the centerline at the position of longitudinal centre of gravity. The positive linear distances, velocities, accelerations and forces are all in the positive direction of the relevant axes, and the positive rotational values are all in the clockwise direction looking along the positive direction of the axes from the origin.

2. Introduction

It is vital that a submerged submarine which experiences the system failure be able to carry out emergency rising to the surface. This invariably means blowing some or all of its main ballast tanks. Generally speaking, a submarine usually experiences the temporary hydrostatic instability on the surface. This hydrostatic instability results from a sudden reduction in the center of buoyancy as the superstructure emerges and a delay in the reduction of the center of gravity while floodwater drains out of the superstructure. However, sometimes the surface instability can be aggravated by a large underwater roll angle which is the result of a submerged roll instability. For instance, Itard.X conducted a free running model test that present a dead leaf ‘flutter’ ascent phenomenon with 60° roll angle during underwater rising process [2]. Therefore, more and more attentions have been taken to the mechanism of submerged roll instability. In this paper, the submerged roll instability refers to the excessive roll state that maximum submerged roll angle larger than 20° or maximum roll angle on the surface larger than 50°.

With regard to roll stability of emergency rising and the coupled stability of other degrees of freedom motions, the UK scholar Booth carried out a stability analysis by introducing nonlinear flow incidence angle to conventional coefficient model [3]. The lateral stability of submarine with forward rising motion was analyzed and a qualitative analysis of model test was given in his research. His tests presented a strong coupling effect between roll and yaw motions. Based on full scale trials data from real boats and wind tunnel test data of a submarine model, George D. Watt studied stability problems within the range of 30° flow incidence angle. Watt initially proposed the 1-DOF criterion of roll stability in terms of the balance between stabilizing static moment and destabilizing moment [4]. He pointed out the hydrodynamic forces generated by sail is the main source of causing excessive roll. Furthermore, Watt argued that the unsteady viscous effect between shedding vortex and tail planes increases significantly at very high flow incidence, making roll angle inherently unsteady. Based on 6-DOF analysis, Watt further considered the coupling of yaw and sideslip motion, and analyzed the yaw stability of buoyantly ascending [5].

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D	maximum hull diameter
L	overall length of the hull
$s = L_m/L_f$	scale ratio, L_m, L_f are length of model and full scale boat respectively
T_m, T_f	roll, pitch periods of model and full scale boat respectively
$\overrightarrow{\mathrm{BG}} = z_G - z_B$	height of the CB above the CG
CB, CG	centers of buoyancy and gravity
m, m_{blown}	mass of the submarine, the blown mass
$W = mg$	weight within ∇
$B = \rho g\nabla$	buoyancy
ρ	density of water
∇	volume of the external hydrodynamic envelope, including main ballast tanks
$\Delta = \rho g\nabla$	total submerged displacement
x, y, z	body fixed axes, with origin on the centroid of the gravity
x_B, y_B, z_B	coordinates of the centroid of the buoyancy in body axes
x_G, y_G, z_G	coordinates of the centroid of the gravity in body axes
x_{blown}, y_{blown}, z_{blown}	coordinates of the centroid of blown mass in body axes
X, Y, Z	body axis forces
K, M, N	body axis moments
I	moments of inertia in body axes
I_{xx_Δ}, I_{yy_Δ}, I_{zz_Δ}, I_{xz_Δ}	total underwater displacement moments of inertia about the body axes
$I_{xx_{\mathrm{blown}}}, I_{yy_{\mathrm{blown}}}, I_{zz_{\mathrm{blown}}}, I_{xz_{\mathrm{blown}}}$	the blown mass moments of inertia about the body axes
u, v, w, u_0	body axis velocities, initial axis velocities
p, q, r	body axis angular velocities
ψ, θ, ϕ	yaw, pitch, and roll Euler angles giving body axes orientation relative to inertial axes
$\dot{z}_0$	rising velocities($= usin\theta + v\ cos\theta sin\phi + w\ cos\theta cos\phi$)
$U = \sqrt{u^2 + v^2 + w^2}$	overall speed of vehicle
$\alpha = \tan^{-1}(w/u)$	angle of attack
$\beta = \tan^{-1}(-v/u)$	angle of drift
$\Theta = \tan^{-1}(\sqrt{v^2 + w^2}/u)$	flow incidence, always positive
$\Phi = \tan^{-1}(-v/-w)$	flow orientation
δ, δ_r, δ_s, δ_b	appendage deflection angle, rudder, sternplane and bowplane deflections respectively; direction is found from the right hand rule using body axes, e.g., when $\delta_s < 0$, the boat woule pith up nose
$Re = UL/\upsilon$	Reynolds number
υ	kinematic viscosity of water
t, t_e, t_o	time, time of emergence, time of surfacing

Besides, based on the quasi-steady hydrodynamic coefficients, Watt proposed an external force model F_{uvw} (Θ, Φ) [6], which was applicable to emergency rising, and carried out a 6-DOF submarine maneuverability simulation. Nevertheless, these empirical-based coefficients were obtained through approximating unsteady effects with information gleaned from steady state experiments, leading to uncertainty remains in this modeling method.

In order to study excessive roll of submarine at high flow incidence, Booth further analyzed the stability of submarines in near vertical ascent state by replacing relevant coefficients to conventional coefficient-based model [7]. However, the unsteady effects caused by flow separation and shedding vortex at very high incidences were not modeled in his research. Based on the second-order coefficient model, Papoulias and Mckinley also calculated the stability of a submarine-like body throughout the entire flow regime which includes pitch and roll angles of 180° [8]. They also discussed 'inverted pendulum' phenomenon and its corresponding excessive roll at extreme pitch angles. Wicher Schreur investigated the oscillation of a horizontal cylinder which rising vertically with and without simulated decks and appendages respectively [9]. Schreur found that bare cylinders experienced randomly sway and yaw motions due to the influence of unsteady shedding vortices in the wake. He also pointed out that vertical vanes attached atop cylinders would bring about wide rang of roll angles from 30 to 150°. In addition, K.P. Watson conducted submarine maneuverability predictions at high flow incidence angle based on the aerodynamic characteristics of missiles at high attack angles [10]. Watson figured out that at leeward of the main hull, there was a pair of symmetrical flow separation vortex at incidence angles ranging from 5 to 30°, while there was stable asymmetric separation vortexes formed within the range of 30–70°. When the incidence angle exceeded 70°, a completely unsteady turbulence were developed. For submarines that rising with incidence angles exceed 30°, the lateral force produced by asymmetric separation vortexes maybe play a critical role in causing roll. However, there exists another mechanism to produce excessive roll even though incidence angle is below 30°. For instance, rolls occur when the crossflow interacts with the sail, rolling the sail in the direction of the crossflow vector. Moreover, the stability analyses based on the equations of motion show there is a yaw instability at low incidence angles [5]. Anyway, these theories will be verified by means of kinematics model test in this paper, rather than analyzing the equations of motion.

In light of the above information, it can be noticed that establishing hydrodynamic coefficient model of submarine at high incidence angles is an important means to analyze the roll stability. Many of scholars conduct extensive towing tank tests, rotating arm tests or wind tunnel tests to obtain hydrodynamic coefficients as well as theirs derivatives. And then they perform stability analysis and numerical simulation based on standard submarine equations of motion. Many researchers, such as Feldman [11,12], Roddy et al. [13,14] and Seol [15], determined coefficients through tests such as Planar Motion Mechanism (PMM), Rotating Arm, and then analyzed the stability and control characteristics of a submarine. Mackay carried out a series of static hydrodynamic wind tunnel experiments with standard submarine model [16]. He discussed the prediction ability of coefficient-based model at high incidence angles and pointed out that sailplane has a significant influence on vertical plane loads in pitch, but a negligible effect on lateral force in yaw. Jong-Yong Park adopted the combination of towing tank test and wind tunnel test to acquire coefficients [17], and introduced the external force model $F(\alpha, \beta)$ to address the coupled large attack and drift angle. They ultimately proposed a quasi-steady submarine dynamics model which is suitable for high-incidence-angle maneuvers such as hard turning and emergency rising.

On the other hand, experiments are routinely carried out to acquire hydrodynamic force coefficients for use in formulae that quantify both horizontal and vertical plane stability. Researchers such as Mackay [18,16] and Watt G D et al. [19,20] conducted a series of surface flow visualization tests on standard submarine model in wind tunnels. Results of these experiments revealed the flow separation that occurs on hull surface, sail and its junction. Particle Image Velocimetry (PIV) measurements were performed on the Defence Science and Technology Organization (DSTO) axisymmetric submarine model by Kumar et al. in low speed wind tunnel [21]. The horseshoe vortex and sail tip vortex at sideslip angles of 0° as well as 10° were observed. The PIV results provided insight into the vortical systems generated around the submarine model. Ashok and Smits performed a dye flow visualization experiment to exhibit that a weaker secondary vortex is visible in addition to the primary vortex on each side of model [22]. Besides, Saeidinezhad et al. investigated the flow field around the SUBOFF submersible model considering two different nose shapes by employing two visualization methods [23]. The smoke flow visualization was used to study vortex structures around the model for various attack angles and longitudinal locations. The mixture of oil and pigments were utilized to visualize the shear stress line patterns on the model surface. It is