6th International Symposium on Advances in Science and Technology
SASTech
Malaysia | Kuala Lumpur
24 - 25 March, 2012
Scope of the Symposium
Organised by:
Khavaran Institute of Higher Education
Hosted by:
Geospatial Association of South East Asia

Attitude Dynamics of Floating Bodies with Irregular Configurations as Determined by a Computational Model

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Reference Number: 6-11-22-158
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Abstract

This study acquires the attitudes of floating bodies with irregular configurations using a computational model, that has been theoretically verified and can confirms these values by experiment. First, a simple correlation is described to predict inclinations for floating slender bodies where the lateral bias of the center of gravity is negligible. Then a computational model is employed to account for bodies with attitudes in more general situations. In addition, a case similar to a submarine is simulated to reveal that the inclinations vary abruptly around certain longitudinal locations of center of gravity. The property variations during water ingress are also presented numerically. Finally, the computational model is used to build a numerical data bank of properties for a specific floating body, by which the position of its center of gravity can be obtained by interpolation from known attitudes in the data tables.

Key words: Computational Model, Floating Body, Attitude, Submersible

1. Introduction

The magnitudes and locations of weight and buoyancy in marine vehicles are important factors in their motion or floating characteristics. By adjusting them, static and dynamic stability, in both transverse or longitudinal direction, can be established (Clayton and Bishop, 1982; Burcher and Rydill, 1999). In fact, some vehicles have been designed to be operational for certain particular requirements by virtue of the movement of their centers of gravity. Papoulias and McKinley (1994) analyzed the steady-state vertical ascent of a submarine with excess buoyancy. Light and Morison

(1989) considered the attitude of the Mobile Target MK38 as the driving force to actively adjust the pendulum inside it for positioning its elevators and rudders to heave. Woolsey and Leonard (2002) used a movable weight as an actuator to control the motion stability of underwater vehicles. Another case for taking advantage of the inclinations of a body is the FLoating Instrument Platform (FLIP), as described by Fisher and Spiess (1963). This was the American research ship. It was designed to float not only like a conventional surface vessel with its keel horizontal but also with its keel vertical after suitable flooding. The attitudes of a floating cylinder with uniform material were investigated by Dugdale (2004), who showed that a cylinder having a length less than 0.707 of its diameter will float with its axis vertical, and when the length exceeds its diameter it will float with its axis horizontal. Obviously, the relations among weight, buoyancy and their locations are strongly related to bodies' states of equilibrium statically and dynamically (Barlow and Nicholson, 1983; Zubaly, 1996). Nevertheless, the measurement of physical properties of a general body, e.g. the floating attitude and center of gravity (CG), is not an easy task. A method and device for determining the CG by virtue of the test body floating in the tank was proposed by Buyanov (1993). Moreover, a system to obtain the CG of a body by basic statics and standard trigonometry was proposed by providing a balance arm and adding a disturbance weight (Schechter and Leyenaar, 1992). But those devices were somewhat complicated and not suitable for heavy vehicles such as torpedoes and submarines.

The motivation of this study came from the deploying and retrieving problems of an exercise submersible in sea trials (Chen and Wu, 2001). That submersible was a prototype of a heavy torpedo in its configuration of body of revolution. In recent decades, with more powerful computers and advanced softwares, the technique of computer-aided engineering (CAE) has enhanced the process of reverse engineering (Marzi, 2006), and can be applied to obtain the properties of present floating bodies of interest. Moreover, numerical simulation for real applications is cost-effective and accurate if the computational model has been validated. In this study, a practical correlation expression is first stated for inclinations of a floating slender body, which was modeled mathematically by Chen and Chen (2006). Then, a verified and validated computational model is demonstrated to account for attitudes of bodies floating quasi-unsteadily, including a submarine-like submersible with ingress of water (Chen et al., 2010). Finally, a proposed numerical water tank for acquiring the CG of a vehicle from a numerical data bank is addressed.

2. Modelling

2.1 Correlation for Slender Bodies

The general slender body configuration depicted in Fig. 1 represents a floating torpedo. Due to the body's slenderness, it can be assumed that positions of centers of gravity (W), buoyancy with the body submerged totally (B), and the net force (B-W) are collinear longitudinally. That is, the biased CG is negligible laterally in this problem of interest. Thus by manipulating equations for moment balance, we introduce the inclination factor K and obtain the following expression,

$$\mathrm{K} = \frac{\mathrm{B} - \mathrm{W}}{\mathrm{X_G} - \mathrm{X_B}} = \frac{\mathrm{W}}{\mathrm{X_B} - \mathrm{X_S}} = \mathrm{f}\,(\theta, \mathrm{W}) \tag{1}$$

where X_G, X_B and X_S are the distance from the reference point to the CG, the distance to the center of buoyancy (CB) and the distance to centroid of the body's portion above water plane, respectively. Equation (1) indicates that the behavior of K depends on the magnitude, W, as well as the location of CG, X_G, which is straightforward because B and X_B are fixed values for a given body's configuration. Computationally, by keeping the body of interest floating in the water plane at a given inclination angle, θ, one can obtain the relations of B-W versus X_G-X_B by varying the magnitudes of weight and locations of CG. A correlation can be deduced by the curve-fitting technique as

$$\mathrm{K} = \mathrm{a}\theta^3 + \mathrm{b}\theta^2 + \mathrm{c}\theta + \mathrm{d} \tag{2}$$

where a is -0.01153, b is 0.7769, c is -18236 and d is 638.316 with inclination angles θ not greater than 30 degrees for the present case. The above expression was successfully used to predict the inclination angles of a specific exercise torpedo floating in several sea trials. However, this correlation expression is only valid for slender bodies, in which the biased CG is negligible laterally.

2.2 *Benchmark for a floating cylinder*

Figure 2 shows the sketch of a floating cylinder at rest in a liquid, with diameter D, length L and other notations. Based on the calculus and hydrostatics, the governing theoretical formula from our previous work takes the form of (Chen and Chen, 2006):

$$\Theta^3 - 32\left(\delta\omega - {\omega^2}/{2} - {1}/{16}\right)\Theta = -32\eta'_w\omega \tag{3}$$

where $\Theta = cot\theta$, $\delta = (L - \xi_w)/D$, $\eta'_w = \eta_w / D$. The value of ω is defined as the weighting of gravity force W/τ, and τ is equal to $\pi D^3\gamma_f/4$, where γ_f indicates the specific weight of the present liquid. Accordingly, the constraints for valid parameters, such as $0 < \eta' < 0.5$, $1 < \omega < L/D$, and $0 < \delta < 0.5L/D$, are prescribed following our simplified physical model. Equation (3) clearly shows that inclination angle θ is a function of dimensionless terms, δ, η'_w and ω, which represent the longitudinal location of the CG from the end, the biased location of the CG in radial direction, and the weight magnitude, respectively. In addition, the corresponding experiment has been carried out in a water tank and compared with the theoretical data, shown in Fig. 3. Overall, the comparison is satisfactory and indicates a successful validation. Figure 3 reveals that it is difficult to accurately measure the location of the CG of a body, especially in a radial direction. Obviously, minor errors could cause significant deviations between theoretical and experimental data in regions with steeper slope. To remedy it, the following computational model has been employed to obtain the attitudes of bodies with irregular configurations.

3. Numerical Simulations

For bodies other than regular configurations such as cylinders, a robust program (BDM, Body Decomposition Method) has been developed to simulate their attitudes (Chen et al., 2010). A submarine-like submersible was used to show the feasibility of the BDM program to investigate such consequences. Any submersible that puts to sea is at risk of taking on water, and the most common causes of flooding are collision, grounding and underwater attack (Zubaly, 1996). Figure 4 shows the configuration and mesh system of the submersible with the ratio of length to diameter of 9.5 and the propeller modeled by a disk. Dimensionless densities were assigned to be 7.8 for its elements of the half sphere, cylinder, cone and disk; 0.8 for sail and two fins at sail; 0.9 for four fins at tail. The water ingress length is indicated by L_f as shown in Fig. 4. By employing the BDM computational model to simulate a flooding situation, variations of the corresponding properties are depicted in Fig. 5. In this figure, the square symbols represent the relation of attitudes (inclinations) in degree versus ingress lengths divided by D. It is noteworthy that there is a steep variation around $L_f/D = 1.5$, which indicates a phenomenon similar to the cylinder flotation described above. The submersible appears nearly level or vertical for most of its range of ingress length, which means the longitudinal position of CG is very important to the trim angle of a surfaced submersible. Moreover, the circle symbol represents the proportion of distance between centers of buoyancy and gravity, BW, in relation to D in gravitational direction while the submersible is taking on water. In practice, the typical submarine proportion for BW in relation to the diameter of the pressure hull is 3% to 4%; and the CG might effectively rise in the transition from submerged to surface conditions (Burcher and Rydill, 1999). In Fig. 5, the CG is above the CB before ingress of water, which is indicated by the circle symbol with a negative value around -15. Nevertheless, the CB becomes further above the CG as more water enters the sinking submersible. Physically, it is more stable when the CB is above the CG because a small inclination of heel or trim produces a restoring couple. But normally W lies above B in the intended attitude for surface vessels like ships. The reasons are (i) it would be easier to contrive, and (ii) the vessels concerned would not be uncomfortably ‘stiff’ and would sustain small inertial forces in its upper works as a consequence (Clayton and Bishop, 1982). The triangle and diamond symbols represent the shift over diameter in percentage for the CB after ingress of water in longitudinal and transverse directions, respectively. Clearly, the shift of the CB in lateral direction is not obvious as expected. However, the shift of the CB in longitudinal direction is abrupt over $L_f/D = 1.5$. This means the attitudes of a flooding submersible are strongly related to the buoyancy-center shift longitudinally rather than in lateral direction. A basic issue in the design of a submarine is the provision of high strength bulkheads to isolate selected parts of the hull and so limit the extent of flooding throughout the hull in the event of an accident. The present simulated results may suggest the preliminary concept for escape policy in the early stages of this submarine design.

4. Numerical Water Tank

It is desirable to simulate the water tank experiment for body floatation by a numerical model so that numerical experiments can be performed without a real tank, and the body's properties can be systematically changed for parametric studies (Marzi, 2006). The attitude θ of a cylinder related to parameters ω, η', δ and L/D of equation (3) has been thoroughly investigated in our previous work (Chen and Chen, 2006). It implies that the data bank can be established without difficulty. The inclinations of a floating cylinder can be illustrated or tabulated in terms of other parameters; that is, varying parameters by fixing another one. The properties of a floating cylinder thus can be constructed by numerical tables. Figure 6 shows one of the results, which illustrates the relations between the attitude angle and the weight magnitude for various radial positions of CG at a specific position of longitudinal CG (L/D=9.279, δ =4). Thus, when the floating attitude angles of a cylinder in the tank have been obtained, the corresponding CG can be determined by interpolating among known parameters, such as θ and ω. Table 1 displays the results from several examples and demonstrates the feasibility of applying this concept, which is similar to the reverse engineering process. In Table 1, θ and ω are measured from numerical experiment for given L/D and δ (L/D=9.279, δ =4, ω =8.3 for this case), then the corresponding η', which are required, can be obtained by linear interpolation from the data sheet in Fig. 6. In other words, this process can avoid the difficulty of experimentally obtaining the distance of CG in a radial direction, that is, η'. In principle, as the computational model has been theoretically verified and experimentally validated, it can be used to build a data bank, including various attitudes and locations of CG et al., without the need of costly experiments. Once we know the locations of CG for a specific body, conversely we can obtain the attitude angle by using interpolation techniques in the data bank. Therefore, the data bank can be numerically tabulated without difficulty. With the longitudinal direction specified on the body, for instance, the CG variation can be achieved for fixed weight magnitude by longitudinally varying the density value element by element. The whole data table thus can be constructed numerically by individually changing either density value or changing fixed weight magnitude. Generally speaking, a real body can be decomposed to components, which then can be numerically defined as objects and given individual properties. After completing the numerical data bank, the relevant properties of a body, such as the coordinates of CG, can be acquired by applying 2D linear interpolation techniques to other known properties in the data tables. Obviously, the accuracy of the required property depends on how fine is the mesh system for the computational model. Moreover, a finer mesh system also helps to locate which region in the data table is more appropriate for applying the interpolation to quickly get the required property. Furthermore , the computing time of each parameter run by the present computational model is very short since powerful personal computers can be employed. The present method could thus play a role in acquiring properties for a floating body instead of using costly experiments.

5. Concluding Remarks

Based on the theoretical and numerical results, several conclusions are drawn below:

(1) A correlation for predicting the inclinations of floating slender bodies, with biased center of gravity negligible, has been described.

(2) As a benchmark, the inclinations of a floating cylinder in wide range of angles were demonstrated theoretically and experimentally. For a floating slender body, such as a cylinder or a submersible vessel, the inclination is sensitive to the longitudinal movement of its center of gravity around certain critical locations.

(3) For a flooding submersible that is taking on water, there exists an abrupt inclination angle variation at the point where a certain amount of water has entered. Furthermore, the center of gravity becomes further below the center of buoyancy as more water enters the submersible. During flooding, the shift of the center of buoyancy in lateral direction is not obvious and the longitudinal shift of the CB is abrupt near certain points.

(4) The analytical data bank of a floating cylinder was demonstrated. In addition, a numerical data bank can be constructed by virtue of the present computational model. As the bank of properties for a specific floating body is built, its position of center of gravity may conversely be obtained by interpolations from known attitudes in data tables.

Acknowledgements

The authors gratefully acknowledge support of this work by the National Science Council of Taiwan through Grant NSC100-2221-E-214-039.

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Figures and Tables

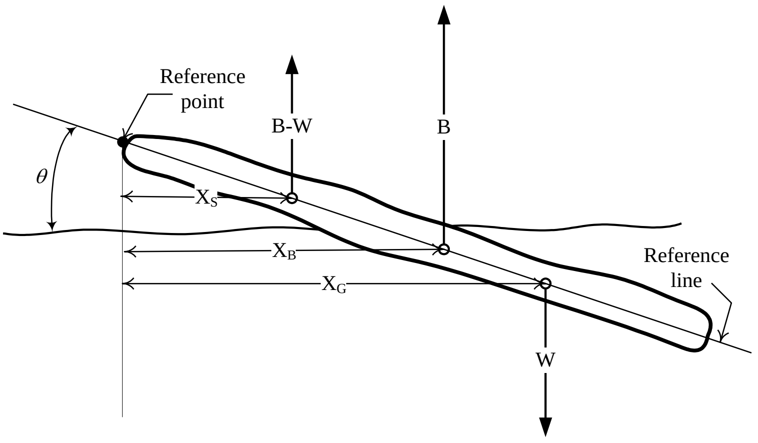

Fig. 1: General sketch for a slender floating submersible.

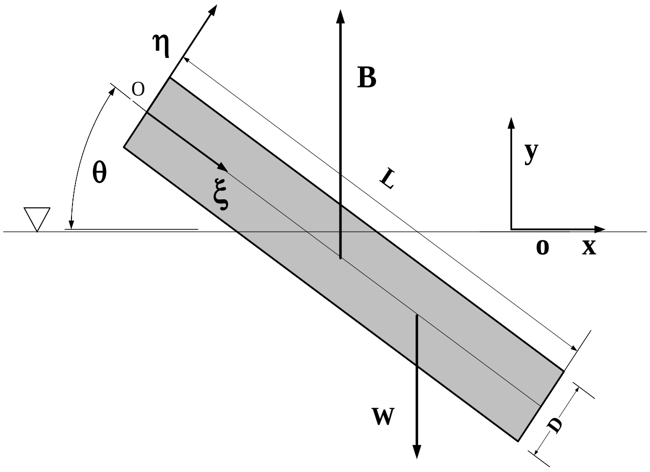

Fig. 2: Physical model of the floating cylinder.

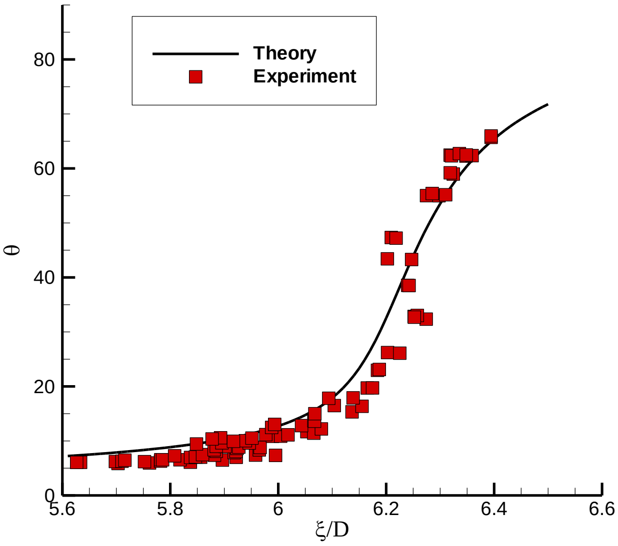

Fig. 3: Comparison of experimental data and theory.

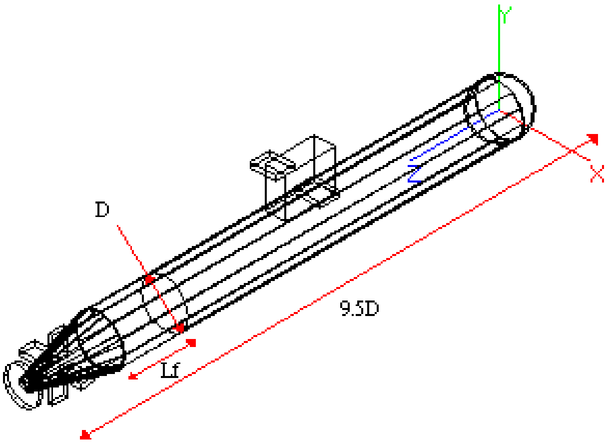

Fig. 4: Physical model for simulating attitudes of the submersible.

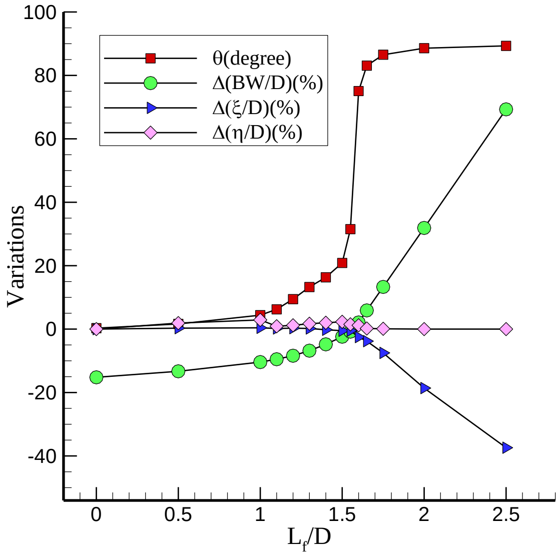

Fig. 5: Property variations for the submersible with various amounts of water admitted.

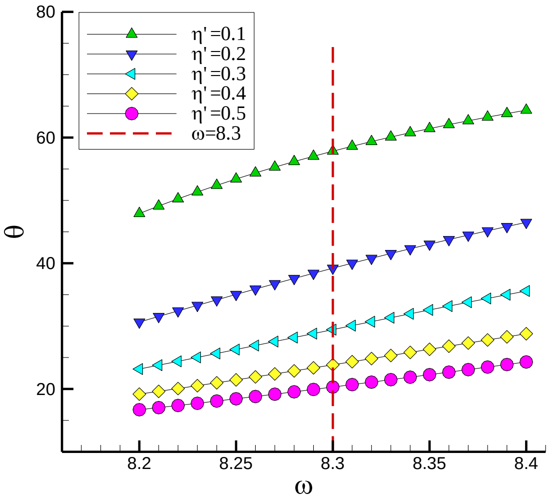

Fig. 6: Comparison of θ against ω for various η' with δ =4 and L/D=9.279.

case	θ (degree) (measured)	ω (measured)	η'_W (interpolated)
1	20.9	8.3	0.48
2	24.5	8.3	0.39
3	35.1	8.3	0.25

4	52.6	8.3	0.14

Table 1: Predicted locations of CG for cases L/D=9.279 and δ =4