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Practical Estimation of the Longitudinal and Lateral Hydrodynamic Coefficients of Underwater Vehicle by Free Decay Pendulum Motion

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Abstract: A good dynamics model is essential and critical for dynamic analysis of underwater vehicle. However, it is difficult to determine the hydro-dynamics forces, especially the added mass and the drag coefficients. In this paper, an experimental method has been used to find the hydrodynamics forces for a remotely operated underwater vehicle (ROV). The proposed method is based on the classical free decay test. The experiment was video captured, then processed by a Covariance Tracking MATLAB^{TM} computer program to determine the time history of the swinging angle of the model, then the values were numerically processed by least square method to determine the coefficients values, which compared with the simulation results obtained from well-established computational fluid dynamics (CFX) program. Thus, the proposed approach can be used to find the added mass and drag coefficients for other underwater vehicles.

Keywords: ROV, Hydrodynamic coefficients, Covariance Tracking, CFX, Least Square.

Nomenclature

B	Buoyancy
F_H	Hydrodynamic force
F_{rod}	Tension force from the rod
G	Gravitational acceleration
K_L	Linear damping coefficient
K_Q	Quadric damping coefficient
K_t	Torsion spring constant
M	Mass of the model
M_a	Added mass in single DOF
R	Length of the pendulum (radius)
V	Tangential velocity
Θ	Angle of rotation of the pendulum

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1. Introduction

Water covers 71% of plant earth, this fact leading us to the necessity of exploring this huge area of the plant which will be the future of humanity. Gathering data and studying the underwater environment is the first step to control and have benefits of the ocean's wealth. Human can only dive to the depth near 300 meters without solid suit or vehicle, while man can dive to the depth near 600 using a hard-shell suit.

Oil underwater pipe lines path from country to country through sea must go through depths more than (600 m), these lines need to be maintained and repaired. Catastrophic ship accidents cannot be ensured to happen in shallow water. Oil exploration in seas and oceans also leads to the same result, the necessity of remotely operated underwater vehicles.

In order to establish an ROV model it is necessary to determine the hydrodynamic coefficients of the structure which reflects the effects of the underwater environment on the ROV structure motion. A tow tank tests of the vehicle or a scale model was used by (P. Egeskov and C. Aage) [1,2]. Special equipment called planer motion mechanism (PMM), where the model is forced to move in a tank in a planer motion and a system of force and moment sensors are used to indicate these values while another set of sensors indicates the position in six degree of freedom, which give a complete model identification.

However the tow tank that equipped with a PMM is very costly. In addition, the test procedures are highly time-consuming. A. Alessandri, P. Ridao and D. A. Smallwood [3.4.5] used on-board sensors to indicate the thrust force and position identification, which is very helpful in ROV which vary its shape during mission, this method is also very costly and the repeatability is very high. However most of the works simplify the model to an uncoupled one DOF model, which needs the motion of the ROV to be constrained to a single DOF during identification. This is hard to implement in practice. In addition, it is also hard to model the thruster forces and to measure the vehicle’s responses accurately.

The use of free decay test in finding the hydrodynamics coefficients was reported by Morrison [6] in 1993. In his study, the hydrodynamics coefficients of the ROV Hylas were determined successfully for the heave motion. The ROV Hylas was allowed to oscillate in water by hanging it from an overhead crane by using three springs. The position of the Hylas was determined using Sonic High Accuracy Ranging and Positioning System (SHARPS). Free decay test have also been studied by T. I. F. A. Ross [7] to identify a multiple-DOF model of an UUV. In his proposed experiment, the underwater vehicle is attached to four springs. The method was tested using a computer simulation and the results converge to true values. The proposed free decay tests exhibit a few problems in practice. Firstly, the vehicle’s positions are needed during identification and the main problem is the ability to measure the vehicle states accurately. In Morrison [6], this problem is solved by employing an expensive underwater positioning system (SHARPS). In T. I. F. A. Ross [7], only computer simulation is done. Secondly, all the springs must always be kept in tension during the oscillations. It is challenging for such experiment configuration to constraint the ROV motion within the predefined DOF. As a result, the mathematical model may not represent the motion accurately and thus the identified results might be poor.

In this paper, the hydrodynamics added mass and drag forces will be determined experimentally using a model (Fig 1) of the ROV. The model is set to oscillate in water when it is displaced from its equilibrium position and due to the hydrodynamics forces that resist the motion, the amplitude of the swing will decay over time. The hydrodynamics parameters can then be extracted from the time history of the motion, Eng YH, Lau WS, Low E., Seet

GGL and C S Chin [8]. As the model is allowed to oscillate freely in the water tank, the experiment is classified as a free decay test. Then, verification is performed by comparing the experimental values obtained with that predicted by CFX for the ROV. The proposed method has few advantages. Firstly, the motion of the pendulum is restricted in a plane and has only one DOF. The position of pendulum is fully described by variableθ. The motion is appropriately constrained and hence, the dynamics equation of motion could represent the motion correctly. Therefore, the result will be more accurate. Secondly, the variableθ can be measured easily using a potentiometer or an encoder. However, in this experiment, the angleθ is obtained through visual sensing using a digital camera, , then processed by a Covariance Tracking MATLAB$^{\text{TM}}$ computer program to determine the time history of the swinging angle of the model, then the values were numerically processed by least square method to determine the coefficients values. The method is very simple and reasonably accurate. As a whole, the experimental setup is simple and is very low cost compared with the building cost of a water tunnel facility with PMM equipment.

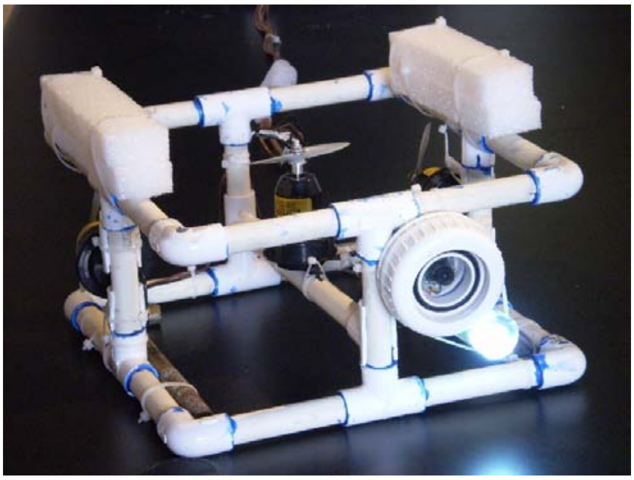

Fig. 1 ROV model

2. Dynamics Equation

Consider an object of interest attached at the end of the pendulum and fully submerged in the water. The object moves in a circular path with radius r as shown in Fig 2.

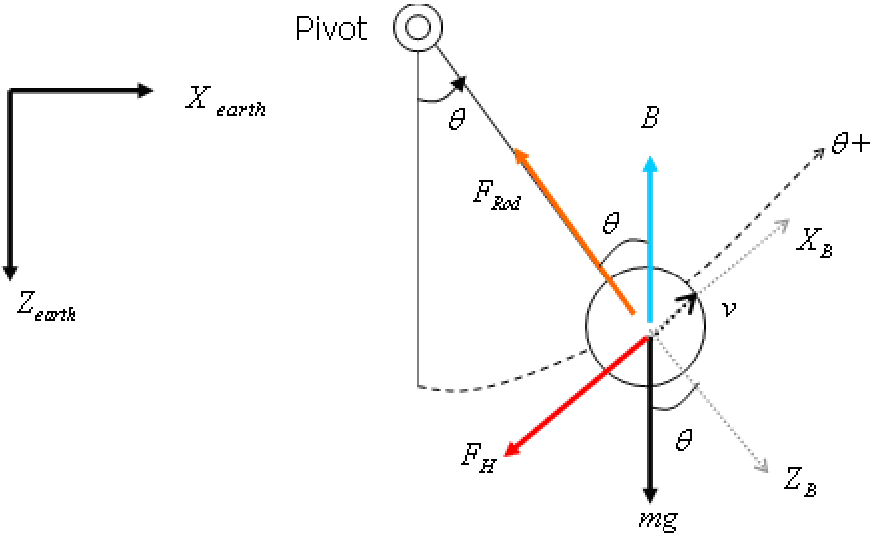

Fig. 2 Free Body Diagram of the Pendulum under Hydrodynamics Forces

In the earth-fixed frame, the object is rotating about the pivot point. However, in the body-fixed frame, the object only moves in the surge direction at any instance; the object has only velocity component in surge direction.

The added mass and the damping coefficient are defined in body fixed frame such that,

$$F_H = m_a\ddot{x} + K_L\dot{x} + K_Q|\dot{x}|\dot{x} \tag{1}$$

The equation of motion in the srge direction using Newton's second law of motion:

$$\sum F = M\ddot{x} \tag{2}$$

$$-Mg\sin\theta + B\sin\theta - m_a\ddot{x} - K_L\,\dot{x} - K_Q|\dot{x}|\dot{x} = M\ddot{x} \tag{3}$$

Rearranging equation (3) gives:

$$(B - Mg)\sin\theta - K_L\dot{x} - K_Q|\dot{x}|\dot{x} = (M + m_a)\ddot{x}$$

$$\ddot{\mathrm{x}} = \frac{(\mathrm{B-Mg})}{(\mathrm{M+m_a})}\sin\theta - \frac{\mathrm{K_L}}{(\mathrm{M+m_a})}\dot{\mathrm{x}} - \frac{\mathrm{K_Q}}{(\mathrm{M+m_a})}|\dot{\mathrm{x}}|\dot{\mathrm{x}} \tag{4}$$

For rotational motion, $\dot{x} = r\dot{\theta}\ and\ \ddot{x} = r\ddot{\theta}$

$$r\ddot{\theta} = \frac{(B-Mg)}{(M+m_a)}sin\,\theta - \frac{K_L}{(M+m_a)}r\dot{\theta} - \frac{K_Q}{(M+m_a)}r\dot{\theta}\left|r\dot{\theta}\right|$$

$$\ddot{\theta} = \frac{(B-Mg)}{(M+m_a)r}sin\theta - \frac{K_L}{(M+m_a)}\dot{\theta} - \frac{K_Q.r}{(M+m_a)}\dot{\theta}\left|\dot{\theta}\right|$$

Let $\quad \alpha = \frac{(\mathrm{B-Mg})}{(\mathrm{M+m_a})\mathrm{r}}\ ,\beta = \frac{\mathrm{K_L}}{(\mathrm{M+m_a})}\quad \text{and}\ \gamma = \frac{\mathrm{K_Q.r}}{(\mathrm{M+m_a})}$

Then
$$\ddot{\theta} = \alpha.\sin\theta - \beta.\dot{\theta} - \gamma.\dot{\theta}\left|\dot{\theta}\right| \tag{5}$$

3. Least Square

Using least square method [11] to obtain the estimated α, β, γ

$$\underbrace{\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\\ -\\ -\\ -\end{bmatrix}}_{y} = \underbrace{\begin{bmatrix}sin\theta_1 & \dot{\theta}_1 & \dot{\theta}_1\left|\dot{\theta}_1\right|\\ sin\theta_2 & \dot{\theta}_2 & \dot{\theta}_2\left|\dot{\theta}_2\right|\\ - & - & -\\ - & - & -\\ - & - & -\end{bmatrix}}_{H(x)}\underbrace{\begin{bmatrix}\alpha\\ \beta\\ \gamma\end{bmatrix}}_{\theta} + error \tag{6}$$

Subscript i = 1, 2, 3…. represent the number of samples collected from the experiment

Result, $$\acute{\theta}_{LS} = (H^T H)^{-1}H^T y \tag{7}$$

4. Experimental Setup

The experimental setup is simple and the costs involved are minimal. The setup is shown in Fig. 3. The model of the ROV is attached to one end of a pendulum in the water tank (1mx2mx1m) and the other end of the pendulum was equipped with an indicator so that the motion can be captured by a digital camera.

Fig. 3 Experiment setup

First, put a small white mark on the indicator. Next, attach the fixture to the structure of the water tank with a ball bearing as shown in Fig. 3. Set the camera up to capture the trajectory of the white mark when pendulum is swinging. The white mark must distinguish itself from its background for ease of image processing. After that, displace the pendulum from its equilibrium, up to approximate 30 degrees and then release it to swing freely in the water. Record the trajectory of the white mark using the video camera. Then, download the recorded video into PC and use a covariant tracking MATLAB™ program to locate the coordinates of the white marker. Next, the time history of θ is determined from the x and y coordinates. Finally, apply the least square algorithm to calculate the added mass, linear damping and quadratic damping (m_a, K_L,K_Q).

The same procedures will be done in surge, heave and sway directions. In our particular case the model is symmetric so the surge and sway directions are the same.

For rotational damping coefficients the similar setup is used but the pendulum effect is done by a torsion spring with known torsion spring constant K_t. then the equation will be

$$\ddot{\theta} = \frac{\mathrm{K_t}}{(I+I_a)}\theta - \frac{K_L}{(I+I_a)}\dot{\theta} - \frac{K_L}{(I+I_a)}|\dot{\theta}|\dot{\theta} \qquad (8)$$

where I is the moment of inertia, I_a is the added moment of inertia

5. Covariance Tracking

A simple and elegant algorithm to track non-rigid objects using a covariance based object description and an update mechanism based on means on Riemannian manifolds [9]. An object window, Fig. 4, is represented as the covariance matrix of features; therefore we manage to capture the spatial and statistical properties as well as their correlation within the same representation. The covariance matrix enables efficient fusion of different types of features and modalities, and its dimensionality is small. We incorporated a model update algorithm using the elements of Riemannian geometry. The update mechanism effectively adapts to the undergoing object deformations and appearance changes. The covariance tracking method does not make any assumption on the measurement noise and the motion of the tracked objects, and provides the global optimal solution. We show that it is capable of accurately detecting the non-rigid, moving objects in non-stationary camera sequences while achieving a promising detection rate of 97.4 percent.

6. Results and Discussion

The captured swinging video was (30 frames per second), so the time interval between each frame is 1/30 second. The angle θ versus time is plotted in Fig. 5.

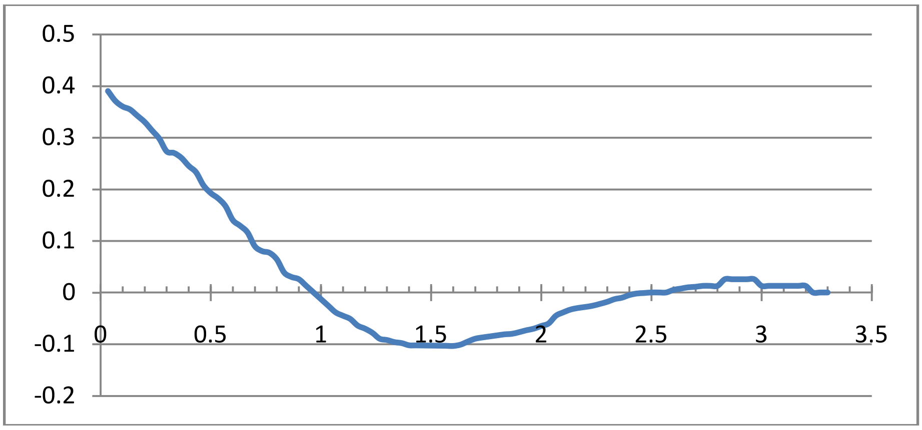

Fig. 5 Angle (θ) vs. time

Table (1) presents sample of values of (θ), ($\dot{\theta}$) and ($\ddot{\theta}$) versus time, these values are then used in equations (6, 8) to determine the values of (m_a, K_L and K_Q).

Table (2) (θ ,$\dot{\theta}$ and $\ddot{\theta}$) versus time

Time [s]	θ [rad]	$\dot{\theta}$ [rad/s]	$\ddot{\theta}$ [rad/s^2]
0.033333	0.389918	-0.23847	-1.14786
0.066667	0.370891	-0.27673	-1.03656
0.1	0.36	-0.31128	-0.9292
0.133333	0.354259	-0.34226	-0.82576
0.166667	0.342156	-0.36978	-0.72623
0.2	0.33	-0.39399	-0.63058
0.233333	0.313621	-0.41501	-0.53881
0.266667	0.297562	-0.43297	-0.45087
0.3	0.273009	-0.448	-0.36676
0.333333	0.27	-0.46022	-0.28644
0.366667	0.260602	-0.46977	-0.2099
0.4	0.244979	-0.47677	-0.13709
0.433333	0.232557	-0.48134	-0.06798
0.466667	0.207496	-0.4836	-0.00255
0.5	0.192396	-0.48369	0.059236
0.533333	0.182168	-0.48171	0.117421
0.566667	0.167254	-0.4778	0.172042
0.6	0.140102	-0.47207	0.223138

The analysis of the data collected in 3 trails from the motion in surge direction produced the following data, Table (3).

Table (3) Results of three tests in surge direction

Test	Added mass [kg]	Linear damping coeff. [N/(m/s)]	Quadric damping coeff. [N/(m/s)^2]
1	22.55	16.88	48.15
2	18.65	13.96	39.83
3	20.29	15.19	43.33
Average	20.50	15.34	43.77

The results from the CFX model Fig. (6) where the ROV model was subjected to variable speeds from 0.1 to 1 m/s, and the force then been calculated.

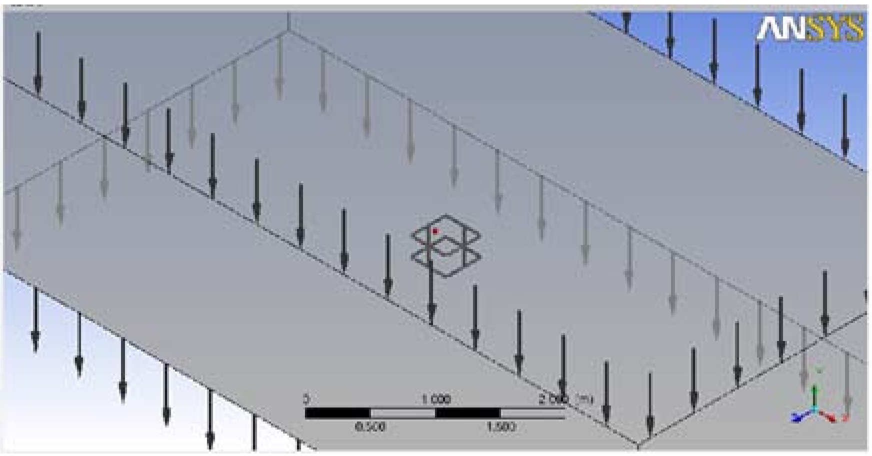

Fig. 6 CFX Model

The model was made upon a constant fluid velocity, so the coefficients calculated was linear and quadric damping coefficients only, while the added mass could not be calculated since there is no acceleration. The values of force versus velocity are shown in Table (4).

Table (4) Force vs. velocity in CFX model

Velocity [m/s]	Force [N]
0.1	1.933905
0.2	4.698164
0.3	8.462566
0.4	12.97699
0.5	18.34189
0.6	24.55196
0.7	32.13808
0.8	40.31375
0.9	48.93912
1	57.84638

Depending on the previous values, the linear and quadric damping coefficients are determined, Table (5)

Table (5) Coefficients calculated from CFX model

Linear damping coefficient	13.5	N/(m/s)
Quadric damping coefficient	38.5	$N/(m/s)^2$

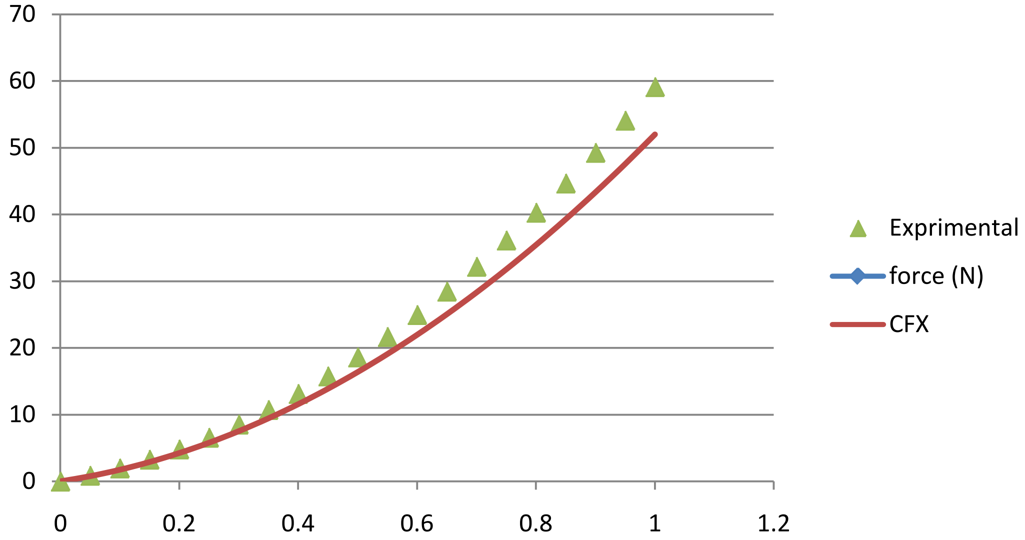

Fig. 7 Force vs velocity for experimental and CFX model

6. Conclusion

The use of free decay pendulum motion is a useful and low cost method to determine the hydrodynamic coefficients. In this model the values of coefficients varied between the experimental and the CFX model due to effect of friction in the ball bearing, and the inaccuracy of weight and dimensions measurements, Fig. 7.

The experiment can be done again in sway and heave directions, also the torsion damping coefficient and added inertia could similarly be calculated.

The use of covariant tracking can represent an accurate method to determine the swinging angle.

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