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Hydrodynamic Force Estimation for Hexapod Robot Walking in Tidal Current Environment

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ABSTRACT

This paper presents the horizontal drag force with different angle of attack over the robotic body for four degree of freedom hexapod robot model. In order to analyse the main hydrodynamic characteristics several estimations are made on the basis of fundamental hydrodynamic theories and fluid dynamics. The motion of the ocean water at its Ekman layer is described by the Navier-Stokes equation. For the complex body structure of the robot. In this study, through numerical calculation the Reynolds number is measured in order to understand the type of water flow over the structure. The relative velocity vectors, Reynolds number, drag and lift forces for each state of motion is obtained in both static water condition and in ocean current condition. Drag and lift forces are calculated differently for several relative velocities for the same and opposite direction of water flow and robot motion. A hydrodynamic analysis using Computational Fluid Mechanics software packages is conducted in order to verify the estimated parameters and confront the numerical solutions and characterize the hydrodynamic forces. This analysis and results further implemented to modern adaptive drag force model-based controller in horizontal flow disturbance control for underwater hexapod walking robot

***Keywords*—** Drag Force, Lift Force, Hydrodynamics Damping Effect, Hexapod Robot, Tidal Current.

I. Introduction

Autonomous underwater robots are one of the most useful tools for some under-ocean applications such as exploring the marine life and environment, rescue operation, sea-bed mining detection as well as survey, inspection, construction and repairing of underwater structures. The environment of seabed is very different than the environment of land, air or space whereby the hydrostatic and hydrodynamic forces acting on a submerged object cannot be ignored in its dynamic characteristics considering various type of external disturbances and uncertainties during an underwater operation [1]. The decision-making and sensing technique of underwater robot remains some problems. Regarding to consider about these problems, an underwater robot should be learning on self-organizing about relationship to own condition, surroundings and behaviors. Therefore, the underwater robot should be implemented an adaptive controller to the high tidal current of sea-bed environment.

It is essential to define the accurate hydrodynamic profile for the motion control of the underwater walking robot. The drag and lift forces relates the interaction between the robotic object and the fluid surrounding which is very robust and changes based on the system dynamics as well as the environmental situations [2, 3]. At present researchers are applying two approaches in estimating hydrodynamic terms-

1. Experiment based method such as Lagrange method based Morison equation [3], Kane's approach [4] to obtain the generalized active forces and the generalized inertia forces for underwater robot, DATCOM method to calculate four longitudinal hydrodynamic coefficients, The Roskam method to present detailed expressions for the estimation of the hydrodynamic coefficients, The University College London method for primary hydrodynamic design calculations, and estimating the consequences of small changes to a design[5], kinetic energy theorem based on fluid mechanics theory [6].
2. Computational Fluid Dynamics (CFD) methodology which uses numerous software packages such as ANSYS-CFX, FEATFLOW, FLUENT, OPENFLOW FIDAP,GERRIS etc to study underwater autonomous vehicles (AUVs) reaction to hydrodynamic forces and flow simulations[7-9].

In this paper in order to develop an adaptive impedance based control architecture we conducted hydrodynamic analyses using numerical calculations and then FLOWSQUARE, CAEDIUM etc CFD software packages to verify the main hydrodynamic parameters of the robot, which reflect its stable performance. Water resistance and pressure distribution are also taken into consideration when investigating interactions between a robotic body and ocean water. The drag coefficient is another important parameter when analyzing the force of water drag. In order to demonstrate the application of this approach, the drag profile of a common known shape, such as a rectangle shape for the robotic object is being considered. Several simulations are conducted for control the controller which is verified in 4 degree of freedom (DOF) of hexapod robot with tripod walking pattern at the Ekman layer (50-100m) sea-bed of South China Sea (SCS) where the ocean current speed is maximum 0.6-0.7 ms^{-1} [10].

II. TIDAL CURRENT MODEL AND ESTIMATION

In order to ensure the maximum effectiveness in the dynamics of the underwater autonomous system, it is possible to design the hydrodynamic profile using the available hydrodynamic theorems.

An underwater walking robot, submerged in the viscous water flow of seabed undergoes a force due to the relative velocity water and object. This force can be decomposed with an element along the direction of the velocity, called the drag force, and another perpendicular element, called lift forces[11], as shown in Fig. 1.

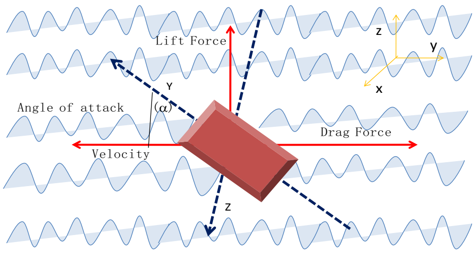


Fig. 1. Hydrodynamic Force in a reference frame alog Y-Z axis

When the immersed object walks through the water of seabed, a state of rapid velocity change occurs adjacent to the surface. The velocity gradient results in a shear stress on the surface; the force generated from combining the shear stresses throughout the body, called the skin friction. Additionally, in the viscous water, pressure at the rear of the body becomes lower than that at the front[12]. The pressure difference gives rise to a pressure and form drag as well as lift forces on the body which can be expressed as follows:

$$F_d = \frac{1}{2} d_w C_d A_{cs} v_r |v_r| \tag{1}$$

$$F_l = \frac{1}{2} d_w C_l A_{cs} v_r |v_r| \tag{2}$$

Where, F_d is the drag force, F_l is the lift force, according to International Association for the Properties of Water and Steam (IAPWS) at 20 ^{o}C temperature ocean water density d_w=1024.8103 kg/m^3, A_{cs} is the cross sectional area perpendicular to the direction of the flow, V_r is relative velocity of the object relative to the water, C_d and C_l are respectively denoted as the drag and lift coefficients.

The drag coefficient is a function of different parameters such as structure of the robotic body, Reynolds number for the flow, Roughness of the Surface. The Reynolds Number for non-dimensional flow can be expressed as follows:

$$R_e = \frac{d_w V L}{\mu_w} \tag{3}$$

Where, V is the velocity of flow, L is the characteristic length, and dynamic viscosity for ocean water, $\mu_{w\,=}$ 0.001077 Pa.s [13].

If the angle of attack (AoA) is α in a reference (y-z) frame as in Fig 1., the drag and lift force components in (1) and (2) can be transformed as,

$$F_y = Y = F_l \sin\alpha - F_d \cos\alpha \tag{4}$$

$$F_z = Z = -F_l \cos\alpha - F_d \sin\alpha \tag{5}$$

D' Alembert's paradox stated that there is no drag force for a submerged moving object with constant velocity relative to the water. At the tidal current in higher velocities corresponding with higher Reynolds numbers, zero drag force is in direct opposition to the study of substantial drag on bodies moving relative to water flow[14]. The continuity equation for unsteady motion of a viscous compressible fluid having variable physical properties can be expressed by as follows:

$$\frac{\partial d_w}{\partial t} + (u.\nabla) d_w = -d_w \nabla . u \tag{6}$$

Where, the velocity field $u(r, t)$ is a function of the kinetic pressure p and the density d_w. When viscosity coefficients η and the change of velocity is Ψ, the equation for the conservation of momentum can be defined as follows:

$$d_w \left[\frac{\partial u}{\partial t} + (u.\nabla) u \right] = -\nabla p + \eta \nabla^2 u + \left(\psi + \frac{\eta}{3} \right) \nabla (\nabla . u) \tag{7}$$

The density of fluid (sea water) is considered as constant, so for the incompressible fluid (5) and (6) can be simplified as non-linear Navier-Stokes (NS) equation as follows:

$$\frac{\partial u}{\partial t} + (u.\nabla) u = -\left(\frac{\nabla d_w}{d_w} \right) + \mu \nabla^2 u \tag{8}$$

On the velocity scale U and length scale L, in order to define dimensionless independent variables the NS equation can be expressed in terms of Reynolds Numbers[15], named Reynolds-averaged Navier–Stokes (RANs) equations which is time-averaged equations of motion for fluid flow can be defined as follows:

$$\frac{\partial u'}{\partial t'} + (u'.\nabla') u' = -\nabla' d'_w + R_e^{-1} \nabla'^2 u' \tag{9}$$

Where, $\nabla = \nabla' / L$; $t = t'(L/U)$; $u = u'U$ and $d_w = d'_w U^2 d_w$. Turbulence is the consequences of these non-linear dynamics of water flows.

A. Admittance control considering hydrodynamic Damping Effect

The dynamic equation for an underwater multi-legged robot with n-DOF can be expressed as [8]:

$$M(v)\ddot{v} + C(v,\dot{v}) + D(v,\dot{v}) + G(v) = \tau \qquad (10)$$

Where, $M \in R^{n \times n}$ is the inertia matrix together with added mass, $c \in R^n$ is the Coriolis and centrifugal term, $D \in R^n$ is the hydrodynamic drag and lift forces, $G \in R^n$ is defined as buoyancy and gravity, and the $\tau \in R^n$ is the joint torque vector. The specifications along with link range for the 4 DOF robotic system is as shown in Table 1.

TABLE I
SPECIFICATION OF THE ROBOTIC SYSTEM

Item	**Value (Unit)**	**Range**
Length	2.80 m	
Width	3.30 m	
Height	2.50 m	
Walking speed	0.30 m/s	
Shoulder (Link 1)	0.00 m	-120° << θ1<<60° (For leg 1-3) -60° << θ1<<120° (For leg 4-6)
Thigh (link 2)	1.13 m	53<<θ2<<131
Shank (link 3)	0.77 m	35<<θ3<<144
Foot (link 4)	0.39 m	-56<<θ4<<108
Body Mass	300 Kg	

For locomotion cases, total force on each leg need to be considered whereby the force on each leg can be calculated with reference to Fig.2 as follows;

$$F_{f_n} = -F_{e_n} = M_{e_n}\ddot{z}(t) + D_{e_n}\dot{z}(t) + K_{e_n}z(t) \qquad (11)$$

where n is denoted as the number of leg for a robot, D_{e_n} is damper coefficient and k_{e_n} is the stiffness coefficient of the tidal current and D_{e_n} is determined based on the vibration theory for spring-mass dampers by rearranging equation (11) using Newton's law, as follows:

$$\ddot{z} + \left(\frac{D_{e_n}}{M_{e_n}}\right)\dot{z} + \left(\frac{K_{e_n}}{M_{e_n}}\right)z = 0$$

The natural frequency ω_0 and damping ratio ξ for the impedance model can be expressed as follows:

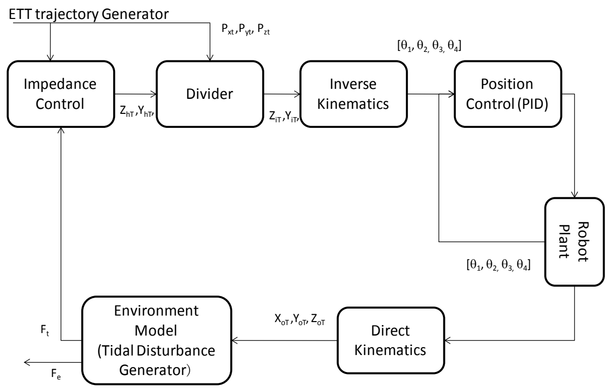
$$\omega_0 = \sqrt{\frac{K_{e_n}}{M_{e_n}}}$$
$$\zeta = \frac{D_{e_n}}{2\sqrt{M_{e_n}K_{e_n}}}$$

In order to control the oscillation in the input, critical damping (free vibration with damping) is chosen, where $\xi = 1$. Thus, D_{e_n} can be expressed as follows:

$$D_{e_n} = 2\sqrt{K_{e_n}} \qquad (12)$$

where weight for the environment (M_{e_n}) is assumed to be unknown. Moreover Z_{ht} *and* Y_{ht} are respectively the changes of vertical and horizontal axis motion of the leg in real-time.

The proposed controller considering the vertical buoyancy factor and center of mass (CoM) as well as horizontal tidal current force disturbance based on environment trailed trajectory (ETT) [16, 17] is shown in fig. 2.



Adaptive impedence based control architecture for underwater hexapod walking robot

III. SIMULATION AND RESULTS

Typical simulations are conducted based on initial and final required values and hydrodynamic coefficients to illustrate the ocean flow model over the underwater walking robot at tidal current. Through numerical calculation of Navier stroke equations the effect on ocean current, sea steady flows and unsteady flows are measured for both dispersive wave and non-dispersive waves. From the study result, the contribution of the dynamics can be analyzed in sort. Simulations has been done by considering the lift coefficient, Cl = 0.35 and drag coefficient, Cd = 0.82 on the structure to obtain the resultant drag and lift forces acting on the immersed body with attack of angle {-90°≤α≤90°} as in Fig.3. To determine this hydrodynamic forces the flow direction of ocean water is considered to and fro of the robot walking direction in order to measure the relative speed.

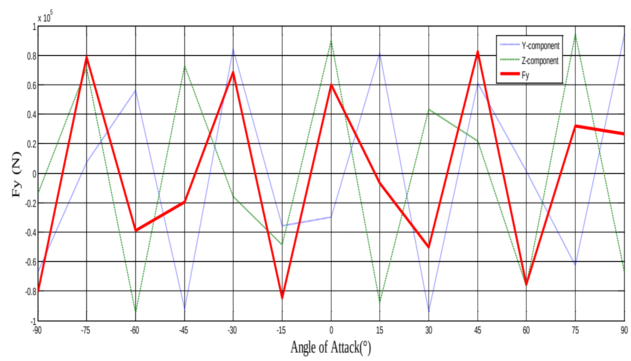


Fig. 2. Drag based tidal current disturbance

Reynolds number is obtained from the value of mean ocean water velocity as depicted on Fig.4. which indicates that the flow is turbulent as the Re >>4000 for the mean wave speed value. Since the flow of ocean wave at the

Ekman layer is circular the average horizontal and vertical motion and other hydrodynamic estimated values are also simulated by CFD tools.

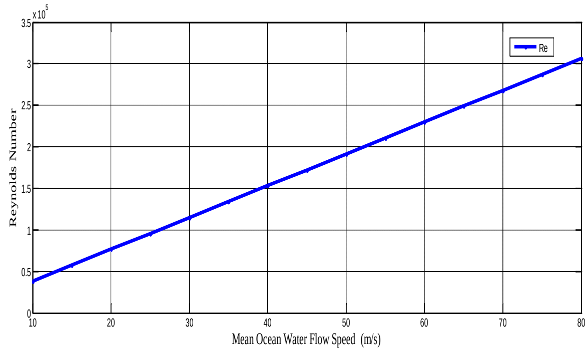


Fig. 3. Reynolds Number with mean water velocity

Simulation has been done by running the tripod side walking from left to right. The analysis is done on the foot point motion considering both horizontal drag force and vertical restoring force position as in fig.5.

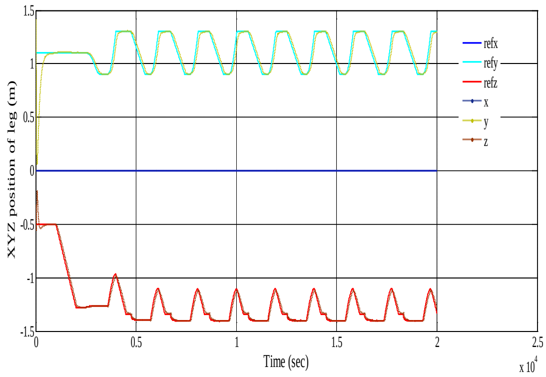


Fig. 4. Sample foot Position (Example leg 2)

The simulation is also extended by measuring the Y position in relation with Z position in y-z reference frame as in fig. 6.

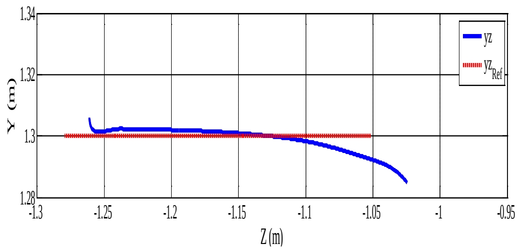


Fig. 5. YZ position for legs (Example leg 2)

IV. Conclusions

Horizontal drag based hydrodynamic simulation study for adaptive force based controller is presented on a multi-legged legged type of underwater robot . The force resistances on the robot at different angles of attack were calculated considering the hydrodynamic profile at 50-100 m depth of ocean. The Reynolds number provide an insight about the type of flow over the robotic system. All the calculations were validated from the numerical simulation and CFD analysis. These results provide an important reference to the force-estimation, control architecture design and analysis for the hexapod underwater walking robot which will be implemented in our future work to make the control architecture more stable and efficient.

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