Numerical simulation and analysis of the sink-stability for the deep-sea walking & swimming robot

Wei Wei¹, Xinliang Wang¹, Kang Zhang¹ and Hong Chen¹

¹ Wuhan Second Ship Design & Research Institute, Wuhan 430205, China
E-mail: 15307141325@163.com

Abstract. A brief introduction to the design concept of deep-sea walking & swimming robot is provided in this paper. And based on the computational fluid dynamics (CFD) method, a hydrodynamic numerical simulation model for the robot body is established. Then the flow field under different body inclination conditions and different ocean currents is numerically simulated by ANSYS Fluent, and the curves of resistance, lift and pitching moment with inclination are obtained. At the same time, the stability analysis method for deep-sea walking & swimming robot is established by combining dynamic stability margin method (DSM), and the stability of the walking & swimming robot is analysed. The stability of the tilting activity threshold is obtained under different inflow environments.

1. Introduction

With the increasing demand for energy all over the world and the difficulties for finding resources in land and shallow water, the competition for marine resources has shifted from offshore to deep water. Deep-sea submersible is important Marine engineering equipment for the exploration and development of deep-sea resources. By carrying various electronic devices and mechanical equipment, it can quickly and accurately work in the complex environment of the deep sea for resource exploration, scientific research and special military use.

Autonomous underwater vehicles (AUVs) are typical deep-sea submersibles. They can independently accomplish various tasks such as detection or exploration with low risk, and play an important role in maritime activities. However, with the demand for vehicles with long-range, large-depth and multi-functional characters, Wuhan Second Ship Design & Research Institute proposed a concept of Deep-sea Walking & Swimming Robot that had the ability of both cruising in deep sea and crawling on the sea bed[1]. As shown in Fig. 1, it can realize a wide range of manoeuvres through the propeller very fast, and loading near the working area. Then, it can use multi-feet to accurately move to the working place on the complex seabed. So it can meet the needs of exploration, sampling, and mechanical operations in the deep sea floor. The robot combines the high-efficiency, wide-range characters of the unmanned autonomous vehicle (AUV) and the precise operating capability of the remotely operated vehicle (ROV). It has the characteristics of high stability, low energy consumption and strong environmental adaptability.

It’s important for the robot to keep steady in the current environment during the operation. So an analysis of the stability of the robot after it has landed on the seabed called “sink-stability” in this paper is made.
2. Numerical method

2.1. Simulation mode and grid generations
In this paper, in order to save computing resources, the simulation is conducted on a simplified model as shown in Fig. 2. The propeller and frame structure are both ignored, and the distance between bottom of the body and ground is 500mm. The length, width and height of the robot body are 2500mm, B=1500mm, D=1000mm. Six legs are simplified as cylinder, whose diameter is 140mm and the length of two sections is 400mm and 700mm, respectively.

As shown in Fig.3, the dimensions of the calculation domain are \(-10L<x<25L\), \(-10L<y<10L\), \(-1.2L<z<10L\) (L is the height of the robot body), respectively. The unstructured tetrahedral mesh is used for the calculation, and at the area around the interfaces, the grids are well refined. With the study of grid indifference, the final mesh number of the calculation domain is 2.5 million.

2.2. Governing equation
In this paper, the calculations are conducted based on Reynolds Averaged Navier-Stokes equations. The governing equations are as follows [2]:
\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = - \frac{1}{\rho} \frac{\partial p}{\partial x_j} + \frac{1}{\rho} \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho u_i u_j \right)
\]  

(2)

Where \( u_i, u_j, p \) are time-averaged variables; \( \frac{\partial}{\partial x_j} \left( -\rho u_i u_j \right) \) is Reynolds stress term; \( \rho \) and \( \mu \) respectively are density and hydrodynamic viscosity coefficient.

3. Force analysis in current environment

3.1. Analysis model

The coordinate system of the simulation model was established as shown in Fig. 2. The \( x_E-y_E-z_E \) is the reference coordinate system, and the \( x_G-y_G-z_G \) is the body coordinate system. In this paper, it is assumed that the centre of buoyancy coincides with the centre of gravity for simplification, and they both at the origin of body coordinate.

As shown in Fig. 4, the force acting on the robot includes: gravity \( W \), buoyancy \( B \), drag force \( F_D \), lift force \( F_L \), and \( M_h \) is defined as pitching moment. The angle between \( x_G \) and \( x_E \) is defined as pitch angle \( \theta \), and the clockwise sense as positive. The analysis assumes that the ocean current flows are uniform and constant, considering near-ground effects.

![Force diagram](image-url)
3.2. Simulation result

In this paper, the numerical simulations were performed for the force acting on the robot in current environment. The pitch angle of the robot varies from -30° to 30° and the current velocity varies from 0 to 1.5 m/s.

Fig. 5 shows the simulated flow around the body when the pitch angle is 30°. And as shown in Fig. 6 when the current velocity is 1 m/s, the drag force varies from 329 N to 598 N, and the lift force as well as the pitching moment has an approximate linear relationship with the pitch angle.

![Figure 5. Flow around the robot in current (θ=30°).](image)

![Figure 6. Hydrodynamic force and moment in current(v=1 m/s).](image)

4. Stability analysis in current environment

4.1. Stability judgment method

The sink-stability analysis of the deep-sea robot can be conducted based on the research achievements of land multi-foot robots which have been well studied in recent years. The stability of multi-foot robot usually includes static stability and dynamic stability. The study of static stability started earlier and developed more. As early as 1968, R B Mcghee et al. [3] proposed the centre of gravity shadow method, and other static stability methods developed afterwards were all based on it, such as static stability margin method [4], energy stability margin method, [5], normalized energy stability margin method [6] and so on. With the rise of walking robots, especially the rise of bipedal walking robots, the requirements for dynamic stability of robots are getting higher and higher, and the research on dynamic stability is mostly concentrated in this field. For the dynamic stability problem, LIN and SONG [7] proposed the concept of Dynamic Stability Margin (DSM). In this paper, based on the characteristics of the Deep-sea Walking & Swimming robots, the DSM method is used to analyze the stability characteristics of the robot in ocean current disturbance environment.
The Dynamic Stability Margin (DSM) is defined as the minimum moments of each rotating axis in the support polygon. The normalized mathematical expression is as follows.

\[ S_{\text{DSM}} = \min_i \left( \frac{M_i}{mg} \right) = \min_i \left( \frac{e_i \cdot (F_E \times P + M_E)}{mg} \right) \]  

(3)

Where \( P_i \) is the position vector from the centre of gravity to the \( i \)-th support foot, \( e_i \) is a unit vector that revolves around the support polygon in the clockwise sense, \( F_E \) and \( M_E \) are the resultant force and moment of robot/ground interaction.

When all the moments are positive which means \( S_{\text{DSM}} > 0 \), the system is stable.

As for the deep-sea robot in this paper, if we assume that the heading of robot is aligned with the current direction, the stability margin of deep-sea walking robot in current can be written as follows, and the notations follow the definition above.

\[ S_{\text{DSM}} = \left( \frac{M}{mg} \right) = \left( \frac{(F_D + F_E + W + B) \times R + M_a}{mg} \right) \]  

(4)

4.2. Stability in current environment

In this paper, the velocity of the ocean current varies from 0 to 1.5 m/s, and the pitch angle of the body varies from -30°~30°. The difference between gravity and buoyancy is 500N. It can be seen from the previous analysis that when the stability margin parameter \( S_{\text{DSM}} \) is positive, the corresponding working condition is stable, and vice versa. And when \( S_{\text{DSM}} = 0 \), the corresponding angle will be the critical safety pitch angle.

Fig. 7 shows the variation of the stability margin parameter \( S_{\text{DSM}} \) with the body pitch angle at different inflow speeds when the lateral distance of the tumble axis is 1m. It can be seen from the figure that when the incoming flow velocity is 0 m/s, it is mainly determined by the difference between the weight and the buoyancy. As the inflow velocity increases, the amplitude changes sharply with the angle. When the flow velocity is 1 m/s, the body begins to tip over when \( \theta = -5° \). In addition, it can be known from the curve that when the flow velocity \( v \leq 0.5 \text{ m/s} \), the body is stable in the range of -30°~30°. When \( \theta \geq 6° \), the body can remain stable within the flow velocity varies from 0 to 1.5 m/s.

Fig. 8 shows the stability margin as a function of the pitch angle of the body when the position of the rear foot (or the tumble axis) is different (the value of x is different). It can be seen from the analysis that as the value of x is larger, the corresponding critical safety pitch angle is larger. When x=1m, the corresponding critical overturning angle is -5°, and when x=1.5m, the critical overturning angle is -17°.
It can be seen that, within the allowable range, the more backward the hind foot is, the higher the stability of the body in the ocean current disturbance.

5. Conclusion
In this paper, the force and stability of the Deep-sea Walking and Swimming robot in the ocean current environment are analysed, and the following conclusions are obtained:
(1) When the current velocity is 1 m/s, the resistance value varies from 329 N to 598 N, and the lift force as well as the pitching moment has an approximate linear relationship with the pitch angle.
(2) When the lateral distance between the tumble axis and the centre of gravity is 1 m, and the flow velocity $v \leq 0.5$ m/s, the body is stable with the pitch angle of the body ranging from $-30^\circ$ to $30^\circ$. When the pitch angle $\theta \geq 6^\circ$, the body can remain stable within the flow velocity varies from 0 to 1.5 m/s.
(3) Within the allowable range, the more backward the rear foot is, the body is more stable in the ocean current disturbance. Therefore, in order to ensure the stability of the robot in the ocean current environment, the distance between the rear foot and the centre of gravity can be increased as much as possible.

6. References
[1] Chen H, Wang X L, Wei W, Liu Z, Ma Z, Zheng C and Tang P P 2018 Concept and Key Technology Analysis of Deep-sea Robots Chinese Ship Research 6 p19-26
[2] Jing S R and Zhang M Y 2001 Fluid Mechanics (China: Xi'an Jiaotong University Press) p68-72
[3] McGhee R B and Frank A A 1968 On the stability properties of quadruped creeping gaits Mathematical Bioscience 3 p331-351
[4] McGhee R B and Iswardhi G I 1979 Adaptive Locomotion for a Multilegged Robot over Rough Terrain IEEE Transl. on Systems, Man, and Cybernetics 4 p176–182
[5] Messuri D A and Klein C A 1985 Automatic body regulation for maintaining stability of a legged vehicle during rough-terrain locomotion IEEE Journal of Robotics and Automation RA-1(3) p132-141
[6] Hirose S, Tsukagoshi H and Yoneda K 1998 Normalized energy stability margin generalized stability criterion for walking vehicles Proc. of Int. Conf. Climbing and Walking Robots 11 p71-76
[7] Lin B S and Song S M 1998 Dynamic modeling stability and energy efficiency of a quadrupedal walking machine Journal of Robotic System 1(4) p657-670

Acknowledgments
The work was supported by the National Key Research and Development Program of China (2016YFC0301700).