Safety analysis of resting on the seafloor of an AUV with mooring system

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Received 16 November 2016; revised 02 March 2017

Safety analysis of resting on the seafloor of the AUV with mooring system mainly includes two parts, stability analysis and chain impact analysis. In order to analyze this problem, mathematical model of 6-DOF motion of the AUV is established. Stability analysis model is established and an example is presented to verify its correctness. Combined with the characteristics of this AUV, mathematic models of chain impact analysis are established. Based on this, simulation system of motion and chain impact under disturbance is established using MATLAB. Based on the simulation system, the motion and forces of chain of the AUV when resting on the seafloor under disturbance are analyzed and the safety of AUV is verified. Conclusions in this paper will provide theoretical basis to mooring system design and improvement of the AUV.

Keywords: Autonomous underwater vehicle, Resting on the seafloor, Mooring system, Safety analysis, Stability, Impact of chain

Introduction

In order to survey the environment of a specific sea area, it needs a long-term investigation. Marine exploration ship and ROV can meet such a requirement, but it is very costly. To solve this problem, the Naval Postgraduate School (NPS) proposed an AUV that can land and rest on the sea floor ¹.

This AUV can rest on the seafloor and survey the environment of ports and straits in a low-power state after a long-range and low-speed voyage. The NPS AUV ², designed by the US Naval Postgraduate School, can land and rest on the seafloor with the help of variable buoyancy system and vertical thrusters. Ocean Explorer II ³ can rest on the seafloor by using the support mechanisms of sensors and the shell of AUV as the supporting system. Discus Glider ⁴ can rest on the seafloor directly using its shell. Slocum Gliders ⁵ can land and rest on the seafloor using a variable buoyancy system. The AUV ⁶, ⁷ designed by University of Tokyo and the deep manned submersible “JIAOLONG” ⁸ of China can rest on the seafloor using a strut. The AUV-VBS ⁹, ¹⁰ designed by Tianjin University can rest on the seafloor using two slender-cylindrical ballast tanks equipped on both sides of the main body of the AUV.

The way of resting on the seafloor of the upper AUVs can accomplish tasks very well in a deep sea region which has a rocky seabed, but these AUVs will be buried when it works a long time in a port or coastal region which has a lot of sediment. In order to solve this problem, the Northwestern Polytechnical University of China presented two kinds of AUV ¹¹ that can rest on the seafloor, one has retractable hydraulic struts and the other has a mooring system. The one that has retractable hydraulic struts is suitable for working at deep sea region while the other one is suitable for ports and coastal areas.

Materials and Methods

Safety of the AUV with a mooring system, such as colliding with the seafloor or the chain broken, should be analyzed when it resting on the seafloor because of the disturbance of current. The AUV proposed in [11] (Figure 1) is taken as the study object and main parameters of it are shown in Table 1. In order to study the safety of AUV when resting on the seafloor, models of 6-DOF motion, resting stability and impact of chain are established.

Mathematical models of 6-DOF motion

In order to analyze the stability of resting on the seafloor and the impact of chain, mathematical models of three-dimensional motion, which includes kinematics and dynamics models¹²,¹³, should be established. Coordinate systems should be selected in order to establish these motion models.
Figure 2 illustrates coordinate systems adopted in this paper, which include the earth-fixed coordinate system \(\mathbf{E}\_x\_y\_z\), the body-fixed frame \(\mathbf{B}\_x\_y\_z\) and the velocity-fixed frame \(\mathbf{1}\_x\_y\_z\). Detail information of these coordinate systems and coordinate transformation matrix can refer to [14].

Kinematics model of the AUV can be expressed as:

\[
\dot{\eta} = \mathbf{C(\eta)\nu}
\]  

Viz.

\[
\begin{bmatrix}
\dot{r}_E \\
\dot{\Omega}
\end{bmatrix} =
\begin{bmatrix}
\mathbf{C}_E^B & \mathbf{0}_{3\times3} \\
\mathbf{0}_{3\times3} & \mathbf{R}_{wbwe}
\end{bmatrix}
\begin{bmatrix}
\dot{v}_B \\
\dot{\omega}
\end{bmatrix}
\]  

Where,

\[
\eta = \left[ r_E^T, \Omega^T \right]^T
\]  

is the generalized position vector at the buoyancy center of AUV with respect to the earth-fixed coordinate system, \(r_E = [x_e, y_e, z_e]^T\) is the position vector at the buoyancy center of AUV in the earth-fix coordinate system, and \(\Omega = [\psi, \theta, \phi]^T\) is the Euler angles;

\[
\nu = \left[ v_B^T, \omega^T \right]^T
\]  

is the generalized velocity vector at the buoyancy center of the AUV in the body-fixed frame; \(v_B = [v_x, v_y, v_z]^T\) is the translational velocity expressed in the body-fixed frame, and

\[
\omega = [\omega_x, \omega_y, \omega_z]^T
\]

is the rotational velocity expressed in the body-fixed frame;

\[
\mathbf{C}_E^B
\]

is the transformation matrix between the body-fixed coordinate system and the earth-fixed coordinate system.

Dynamics model of the three-dimensional motion of AUV can be expressed as:

\[
(A_m + A_\lambda) \dot{V} = -A_m (A_m V) + A_{FM}
\]

Where,

\[
A_m\text{ is the matrix of mass and inertia moment:}
\]

\[
A_m =
\begin{bmatrix}
0 & 0 & 0 & m z_e & -m y_e \\
0 & 0 & -m z_e & 0 & m x_e \\
0 & -m y_e & m y_e & -m x_e & 0 \\
m z_e & 0 & -m x_e & -J_{xx} & -J_{xy} & -J_{xz} \\
-m y_e & m x_e & 0 & -J_{yx} & -J_{yy} & -J_{yz} \\
-J_{x} & -J_{y} & -J_{z} & J_{zz}
\end{bmatrix}
\]

Where \(m\) is the mass of the AUV, \(x_e, y_e, z_e\) is the coordinate of the gravity center in the body-fixed frame, and \(J_{ij}\) is the moment of inertia.

\[
A_\lambda\text{ is the matrix of added mass, } V\text{ is the generalized velocity vector and } A_{FM}\text{ is the matrix of velocity } v\text{ and angular velocity } \omega:\n\]
The stability analysis of resting on the seafloor of the AUV is mainly analyzing the distance between the AUV and seafloor under the effect of current to prevent the AUV from colliding with the sea floor. When the current direction is perpendicular to the AUV axis, this AUV has a most probability to collide with seafloor because it has the biggest current forces in this condition, so this section will analyze the safety of this condition.

Figure 3 shows the forces on the AUV with mooring system when resting on the sea floor, which mainly include the lateral force of the current $F_{l}$, the current lift $F_{y}$, chain force $F_{c}$ and positive buoyancy $F_{BG}$.

When the AUV is in a steady state:

$$F_{c} \cos \gamma - F_{y} = 0$$  \hspace{1cm} (3)  

$$F_{c} \sin \gamma - F_{BG} - F_{y} = 0$$  \hspace{1cm} (4)  

The distance between the AUV and seafloor is expressed as $l_b$ and the length of chain is expressed as $l_c$. The relationship between $l_b$ and $l_c$ when resting on the sea floor is:

$$l_b = l_c \sin \gamma$$  \hspace{1cm} (5)

The stability analysis model can be established from (4), (5) and (6):

$$l_b = l_c \sin \left( a \tan \left( \frac{F_{BG} + F_{y}}{F_{c}} \right) \right)$$  \hspace{1cm} (6)

Stability of resting on the seafloor can be analyzed according to the above models using MATLAB.

Mathematical model of the impact of chain under disturbance

When the AUV is resting on the seafloor, the attitude of AUV and the impact of chain will be affected when there is a velocity disturbance. In order to ensure that the AUV does not collide with the seafloor and the chain of anchor does not break, motion and forces of the AUV under velocity disturbance should be studied.

Hydrodynamic forces and weight of the anchor chain are ignored because the chain is very short and slender.

The force model of anchor chain can be simplified as a spring model. According to Hooke's law, the force can be expressed as:

$$F_{c} = k_{c} dx$$  \hspace{1cm} (7)

Where, $F_{c}$ is the impact force, $dx$ is the elastic deformation of the chain, and $k_{c}$ is equivalent Hooke coefficient of the chain. The formula of $k_{c}$ is shown in (11).

$$k_{c} = \frac{ES}{L}$$  \hspace{1cm} (8)

Where, $E$ is the elastic modulus of the material of chain, $S$ is the cross-section area of the chain, and $L$ is the length of the chain.
Model of the impact force can be obtained according to (10) and (11):

\[ F_c = \frac{ES}{L} dx \]  

(9)

Formula (12) expresses the way of calculating the magnitude of the impact force, but it does not present directions. Vector model of impact force needs to be established in order to apply the force on this vehicle. The fore anchor chain is taken as an example to establish its vector model in this paper.

The position of buoyancy center can be expressed as \( O_{UUV_e} \) and the anchored position of fore chain on the sea bottom can be express as \( O_{qme} \) in the earth-fixed frame. The positon of fore anchor chain hanging on the AUV can be express as \( O_{qmb/UUV_b} \) in the body-fixed frame. Vectors of fore anchor chain are shown in Figure 4.

In Figure 4, the position of fore anchor chain hanging on the AUV can be express as (13) in the earth-fixed frame according to the coordinate transformation matrix between the body-fixed frame and the earth-fixed frame.

\[ O_{qmb/UUV_e} = O_{UUV_e} + C^b_E O_{qmb/UUV_b} \]  

(10)

Direction vector of the force of fore chain can be expressed as:

\[ \Delta O_{qme} = O_{qme} - O_{qmb/UUV_e} \]  

(11)

The force of fore chain in the earth-fixed frame can be obtained according to (12) and (14).

\[ F_{qme} = F_c \frac{\Delta O_{qme}}{O_{qmb/UUV_e}} \]  

(12)

The force of fore chain in the body-fixed frame can be established according to the coordinate transformation matrix between the body-fixed frame and the earth-fixed frame.

\[ F_{qmb} = C^b_E F_{qme} \]  

(13)

The moment of fore anchor chain on the AUV in the body-fixed frame can be expressed as:

\[ M_{qmb} = O_{qmb/UUV_b} \times F_{qmb} \]  

(14)

When force and moment generated by the anchor chain are applied to the 6-DOF-motion models of the vehicle, impact force of anchor chain and the motion of AUV can be analyzed when the AUV has a velocity disturbance.

**Establishment of simulation model**

Simulation model of AUV motion is established based on mathematical model of 6-DOF motion and the impact model of the chain under disturbance using S-fun of MATLAB. The motion of the AUV and impact of the chain when resting on the seafloor under disturbance can be analyzed by entering different values into the simulation model. Hydrodynamic parameters of the AUV when resting on the seafloor adopt the results calculated in 15 using the method of CFD. Added mass and damping coefficients are calculated using theories and empirical formulas in 16.

**Results and Discussion**

**Example of Stability analysis**

2kn is often taken as the limit of current velocity when the safety is analyzed. In this paper, hydrodynamic parameters of the AUV when resting on the seafloor adopt the results calculated in 15 using the method of CFD in different working conditions. The lift (\( F_y \)) and drag (\( F_z \)) of the AUV changing with the distance between the AUV and seafloor (\( l_b \)) can be obtained by the method of least-square fitting.

\[ F_y = 35.596 \times l_b^2 - 165.09 \times l_b + 0.8081 \quad N \]  

(15)

\[ F_z = 227.07 \times l_b^2 - 779.47 \times l_b + 1696.5 \quad N \]  

(16)

The relationship of \( l_b \) and \( l_c, F_{BC} \) can be obtained from (7), (8), (9). Figure 5 presents the curve of \( l_b \).
changing with \( l_c \) when \( F_{BG} = 30\text{kg} \). Figure 6 presents the curve of \( l_b \) changing with \( F_{BG} \) when \( l_c = 2\text{m} \).

As can be seen in Figure 5, \( l_b \) increases nearly in direct proportion to \( l_c \). When \( l_c > 1.606\text{m} \), it meets the requirement that the AUV would not collide with the seafloor which is \( l_b \geq 0.2672\text{m} \).

As can be seen in Figure 6, \( l_b \) increases nearly in direct proportion to \( F_{BG} \). When \( F_{BG} > 24.77\text{kg} \), it meets the requirement that the AUV would not collide with the seafloor which is \( l_b \geq 0.2672\text{m} \).

It can be obtained through the above analysis that the AUV will not collide with seafloor when parameters of the AUV adopt \( F_{BG} = 30\text{kg} \) and \( l_c = 1.606\text{m} \).

Further studies on the stability of AUV with mooring system when resting on the seafloor can be made by adopting different values of \( l_c \) and \( F_{BG} \). The results in this section will provide theoretical basis for the design of length of chain and positive buoyance of main body of the AUV.

Example of the analysis of chain impact under disturbance

Values of parameters adopted in this example are as follows: disturbance velocity adopts \( \Delta v = 2\text{kn} \), positive buoyancy of the AUV adopts 30kg, length of anchor chain adopts 2m, diameter adopts 12mm, elastic modulus of chain material adopts \( E = 210\text{GPa} \).

According to the analysis of established simulation model, under the action of velocity disturbance, trajectory of buoyancy center of the vehicle is presented in Figure 7. Curves of velocities changing with time are presented in Figure 8. Curves of attitude angles changing with time are presented in Figure 9 and impact forces of the fore and aft anchor chain are presented in Figures 10 and 11.
As seen in Figure 7, this vehicle moves toward lower-and-lateral side at first and it reaches the lowest position at the time of 7.5s and at this time the distance between the vehicle and the seafloor is 0.27m so that this vehicle does not collide with the seafloor. Then this vehicle moves towards the equilibrium position and has a fluctuating motion around the equilibrium position.

As seen in Figure 10, the maximum impact of the fore anchor chain reaches 38.3KN at 18.8s. The main reason why the maximum impact does not occur at 7.5s when the vehicle reaches the lowest position is that the anchor chain is often in extended state during downward movement so that it can affect the motion of the vehicle by applying forces on it constantly which can be seen by the values of impact forces of fore and aft chain from 0 to 7.5s in Figures 10 and 11.

As seen in Figure 11, the maximum impact of the aft anchor chain reaches 52.3KN at 13.8s and it is larger than the value of the fore chain. The generation of impact is due to a sudden extension of the anchor chain when this vehicle moves toward the equilibrium position rapidly. The reason why the maximum impact of the aft anchor chain is larger than the fore one is: the fore anchor chain unbends firstly and the velocity of the bow of AUV slow down rapidly while the velocity of stern increases so that the impact is larger when the aft anchor chain unbends.

As seen in Figure 11, the maximum stress of the fore anchor chain is $\sigma_{max}=338\text{MPa}$ at 18.8s. In Figure 11, the maximum stress of the aft anchor chain is
\( \sigma_{\text{max}} = 462 \text{MPa} \) at 13.8s. The material of chain is 45 steel and its tensile strength is 600 MPa, so the maximum stress of chain is less than the tensile strength. This anchor chain is verified safe under the velocity disturbance of 2kn from the above analysis.

Conclusion

In order to analyze the safety of resting on the seafloor of the AUV with mooring system, which mainly includes the stability of resting on the seafloor and the impact of the anchor chain, 6-DOF-motion model is established based on the momentum theorem and the momentum moment theorem after a brief introduction of the concept and research background of the AUV that can rest on the seafloor.

The stability model of resting on the seafloor of the vehicle is established to analyze the stability. Curves of the distance between AUV and the seafloor changing with parameters are obtained. An example is presented and the results show that: (1) the distance between AUV and the seafloor \((l_b)\) increases nearly in direct proportion to the length of chain \((l_c)\); (2) \(l_b\) increases nearly in direct proportion to the positive buoyancy of the main body of the AUV \((F_{BG})\); (3) the initial parameters of this vehicle adopted in this paper, which are \(F_{BG} = 30 \text{kg} \) and \(l_c = 1.606 \text{m}\), can meet the stability requirements.

Mathematical model of chain impact is established based on the theory of elasticity in order to analyze the impact of chain under velocity disturbance. After that, simulation system of 6-DOF motion and chain impact is established using MATLAB. Based on the simulation system, the motion and chain impact of the AUV when resting on the seafloor under disturbance are analyzed. An example is presented and the curves of trace of buoyancy center, velocity, attitude angle, and impact force of chain changing with time are obtained. The results show that the AUV can rest on the seafloor safely and stably under 2kn velocity disturbance.

Acknowledgments

This research was supported by the National Natural Science Foundation of China under grant no. 51309125 and the Doctoral Scientific Research Foundation of Jiangsu University of Science and Technology under grant no. 1012931605.

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