Simulation and Optimization of Protection Method for Large Surface Vessels

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Abstract. In order to determine the main protection parts of the protective structure of large surface vessels, a model of acoustic wake homing underwater vehicle entering the position and course of wake based on probability distribution is established. Also, a simulation system of acoustic wake homing underwater vehicle based on simulation method is designed on the basis of wake acoustic simulation model, underwater vehicle acoustic homing detection model and trajectory model. On this basis, the hit area of acoustic wake homing underwater vehicle is simulated, and the protection method of large surface vessels is optimized. This method can be used to realize the lightweight design of vessels and improve its protection ability.

1. Introduction

At present, the biggest threat to surface vessels is all kinds of underwater vehicle weapons. The wake homing underwater vehicle is recognized as one of the most effective anti-ship means with its unique guidance mode. If the main hit area of the wake homing underwater vehicle to the surface vessels is determined, and the structure protection in the key area can be arranged to the point. It can realize the lightweight design of the vessels and improve its survival probability [1, 2]. Based on the establishment of relevant simulation models, the simulation system of acoustic wake homing underwater vehicle based on the operational effectiveness of underwater vehicle is designed. On this basis, the hit area of acoustic wake homing underwater vehicle is simulated, and the protection method of large surface vessels is optimized.

2. Simulation model

2.1. Wake detection model

From the angle of attack simulation of wake homing underwater vehicle, if the underwater vehicle is in or under the wake area, the wake signal can be considered as successfully detected. Therefore, the wake characteristics in the simulation mainly refer to the geometry and geometric size of wake length and width, which are usually determined by actual measurement and statistics.

(1) Wake length model

The length of wake refers to the life of wake, which is related to the change of vessels speed and sea state, as well as the property of wake and the detection ability of wake homing device of
underwater vehicle. At present, the effective length \( L \) of bubble wake (active acoustic wake) used in underwater vehicle guidance is usually expressed by the following empirical formula:

\[
L = CA \cdot V_w
\]  

(1)

Where, \( V_w \) is the speed of target ship (m/s); \( CA \) is the constant, which is related to the sea state and the ability of wake homing detection. Three values are considered in the simulation, i.e., \( CA = 300s \), \( CA = 180s \) and \( CA = 120s \).

(2) Wake width model

According to the actual measurement and statistics of the wake, the width of the bubble wake is generally similar to a sharpened pencil shaped cone. A large number of investigations and studies find that the wake is only about half the width of vessels at the stern. With the extension of wake, the width of the wake diverges linearly, and the divergence angle is about \( 40^\circ - 60^\circ \). When the distance is larger than a certain distance, the wake width will only expand at about \( 1^\circ \) divergence angle. At medium distances, the wake width increases to about 2.5 times of the ship width (see Figure 1).

![Figure 1. The wake of vessels](image)

Based on this, the mathematical model of the variation of half wake width with wake length can be solved [3].

![Figure 2. Half wake width solution](image)

As shown in Fig. 2, a rectangular coordinate system XOY is established with the horizontal center of the ship as the origin and the heading line as the X-axis. Let the ship length \( A = 2b \) and width \( b = 2a \), the line segment \( MN \) can be expressed according to the linear expression of analytic geometry:

\[
y = kx + c_0
\]  

(2)

Where, \( k = \tan(\pi - \theta) \) and \( c_0 \) are constant.
Substitute the coordinates of N point \((-a, 0.5b)\) into the above formula, then,

\[ 0.5b = k \cdot (-a) + c_0 \Rightarrow c_0 = 0.5b + ka \]  \hspace{1cm} (3)

According to the above formula, the abscissa of point M is as follows:

\[ 2.5b = k \cdot x_M + c_0 \Rightarrow x_M = 2b / k - a \]  \hspace{1cm} (4)

Then the half wake width can be expressed as:

\[
\begin{cases}
 b, & \text{if } -a \leq x < a \\
 k(x + a) + 0.5b, & \text{if } x_M \leq x < -a \\
 2.5b, & \text{if } x < x_M
\end{cases}
\]  \hspace{1cm} (5)

2.2. Solution of position and course of underwater vehicle entering wake

Taking the ship center point \(O(0,0)\) when the underwater vehicle enters the ship wake as the origin, and the geographic reference frame \(YOX\) is established. Assuming that the time coordinate of the underwater vehicle is \(I(r_x, r_y)\) and the course is \(C_T\), shown in Fig. 3.

\[ \theta = 2\pi - R_q \]  \hspace{1cm} (6)

\[ C_r = \pi + C_w - \theta \quad C_r \in [-2\pi, 2\pi] \]  \hspace{1cm} (7)
2.3. Solution of hit position of underwater vehicle

Taking the vessels center point \( O(0,0) \) when the underwater vehicle enters the wake as the origin, the geographical reference system \( YOX \) is established, and the coordinate when the underwater vehicle hits the ship is set as \( H(r_x, r_y) \). In order to solve the coordinate relative to the vessels center point, the relative geographic reference system \( Y'OX' \) and the stable ship reference system \( Y_nO'X_n \) are established respectively based on the ship center point \( O'(x_o, y_o) \) as the origin at the time of hitting, shown as Fig. 4. The axis direction of relative geo-reference system \( Y'OX' \) is the same as that of geo-reference system \( YoX \). The stable ship reference system \( O'(x_o, y_o) \) takes the course line of the ship as the \( y \)-axis, and the \( x \)-axis points to the starboard side of the ship. If let the course of vessels as \( C_w \), there is \( \theta = C_w - \pi / 2 \). It can be considered that the stable ship reference frame \( Y_nO'X_n \) is obtained by rotating the relative geographical reference frame \( Y'O'X' \) counterclockwise by \( \theta \).

Suppose that the coordinate of point \( H \) in relative geo-reference system \( Y'O'X' \) is \( H(r_x, r_y) \), according to the coordinate transformation formula of reference system translation, there are:

\[
\begin{align*}
  r_x &= r_x - x_o, \\
  r_y &= r_y - y_o.
\end{align*}
\]  

Then, the coordinate \( H(r_{xm}, r_{ym}) \) of point \( H \) in the stable ship reference frame \( Y_nO'X_n \) can be obtained according to the coordinate transformation method between the common origin reference systems:

\[
\begin{align*}
  r_{xm} &= r_x \cos \theta + r_y \sin \theta, \\
  r_{ym} &= -r_x \sin \theta + r_y \cos \theta.
\end{align*}
\]  

![Figure 4. Hit position solution of underwater vehicle](image-url)
3. Design of simulation system

3.1. System requirement analysis
The simulation system needs to complete the following main functions:
1) Target parameters and wake characteristics setting, including target type, speed, heading, maneuvering mode and the minimum size of wake rectangle block; 2) The parameter setting of underwater vehicle, including the overall parameters, homing system parameters and guidance method parameters; 3) Simulation environment settings, including hydrological conditions, simulation times and storage path of simulation results; 4) The attack process of an underwater vehicle guided by an acoustic wake, including the whole attack process from the calculation of launch parameters to the target or the end of the course exhaustion; 5) Output relevant simulation results in the form of chart, and save the simulation result data.

3.2. Overall scheme design
The whole system adopts modular design, and data interface is used to realize data exchange between each module. Fig. 5 describes the overall structure of the simulation system. The name of the sub-module is indicated in the box, and the line between the boxes indicates the calling relationship of the sub module [5].

The simulation system should include five simulation contents:
Launch parameter solution: according to the calculation principle of fire control system, the launch parameters should be calculated for the set tactical situation; Motion simulation of underwater vehicle: according to the trajectory control parameters of underwater vehicle, the trajectory of it is calculated according to the simulation step size. Target motion simulation: according to the target motion law, the target trajectory is calculated according to the simulation step size; Wake generation simulation: according to the set wake characteristics, the corresponding wake sequence is generated [6]. Simulation of homing detection process: According to the homing detection model of underwater vehicle, the detection process of it is simulated.

The simulation system is designed according to the following ideas: Firstly, the tactical situation is set by the parameter setting module, and the target motion model and wake generation model are determined. After the simulation starts, the launch parameters of the underwater vehicle are calculated based on the overall parameters and homing system parameters of the underwater vehicle. And then the rectangular coordinate system is established with the entry point of the underwater vehicle as the origin to determine the initial position and heading of the underwater vehicle and the target. Meanwhile, the initial wake is generated at the same time. In the subsequent simulation, according to the set step size for simulation, the homing detection module detects the wake signal in each simulation cycle to judge the status of the underwater vehicle in and out of the wake. The motion
simulation module of underwater vehicle simulates the underwater vehicle movement through the set guidance method according to the detection results. In the simulation process, the target operates independently according to the set motion mode, including the completion of maneuver process. The simulation process is repeated until the underwater vehicle hits the target or runs out of range.

4. Results analysis

![Simulation Results](image)

Figure 6. The simulation results
According to the set simulation conditions, based on two kinds of probability distribution of the location of underwater vehicle entering the wake, the area of the underwater vehicle hitting the ship is simulated. One is to take the effective wake center as the center, and half of the effective wake length as the maximum dispersion for model according to the normal distribution. The other is to model according to the uniform distribution in the effective wake length. The simulation results are shown in Fig. 6. Among them, the different color dots correspond to the life points of different surface ship speeds. The closer the hit points are, the higher the probability of being hit by the wake homing underwater vehicle.

According to the above simulation results, the hit area of the two kinds of underwater vehicles has the same characteristics under the probability distribution of wake position, that is, the hit area is basically concentrated in the middle and rear of the surface vessels. With the increase of target speed, the hit area is more concentrated on the left and right sides of the vessels tail. However, for the rear of the vessels, the probability of being hit is not significant compared with the side of the ship.

Therefore, for the attack of wake homing underwater vehicle, large surface vessels do not need to lay protective structures at all parts. The emphasis of protection should be on the left and right sides of the middle and rear of the vessels, especially the side passing through the stern. Meanwhile, when the vessels are attacked by the wake homing underwater vehicle, it should quickly increase the speed to maneuver, and cooperate with other defense means to improve its survival probability.

In addition, with regard to the uncertainty of measurement, relevant data are being collected to improve the wake trajectory model. In the simulation, it is found that for the wake model with additional errors of different levels, if the error is small, there is no obvious change in the distribution of hit location. But if the additional error is too large, the distribution change is very obvious, which is not consistent with the current wake model.

5. Conclusion
Wake homing underwater vehicle is the main threat to large surface ships. Based on the probability distribution model of the position and course of the acoustic wake homing underwater vehicle entering the wake, the hit area of the underwater vehicle is simulated and analyzed by using the simulation system of the acoustic wake homing underwater vehicle. It provides the simulation for optimizing the surface vessels protection method and realizing the lightweight design of the ship basis. However, in the actual combat, the surface vessels need to face not only the wake homing underwater vehicle, but also other threats such as mine or acoustic homing underwater vehicle, and the corresponding surface vessels protection method needs to be further studied.

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