Experiment of Ship Maneuvering Motion in Muddy Navigation Area

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Abstract. In order to make full use of natural resources and ensure the safety of the ship navigation, based on the self-designed ship trajectory tracking system, the self-propelled model test of ship maneuverability which include cycle test and zig-zag test under the combined effects of water and fluid mud was completed in the test pool. And then based on the results of the tests, the influences of under-keel clearance on ship resistance, heading stability and turning radius were analyzed, and the maneuverability of the ship's navigation in the fluid mud was comprehensively evaluated. The results show that as the under-keel clearance decreases, the linear stability of the ship increases, but its maneuverability deteriorates. In order to ensure safety, the depth of ship dragging into the fluid mud must be less than 10% of ship’s draft.

1. Introduction

Due to the characteristics of the muddy coast, the silt in these ports usually exists in the form of fluid mud, and the amount of sediment per unit volume is less, and the flow characteristics of upper silt are similar to water bodies. In order to make full use of this resource, reduce the comprehensive cost of the enterprise, since the 1930s, many countries have begun to study and apply fluid mud and navigable depth technology [1-5]. The so-called navigable depth technology is to use the fluid mud layer with a lower density as the navigable water depth while ensuring the safety of the ship's navigation.

In a large number of relevant tests carried out at home and abroad, the rheological characteristics [6-7] and ship resistance are usually taken as the conditions for judging the interface under the navigable depth [8-9]. However, there are few studies on how many navigable resources can be utilized while ensuring the safety of ships. According to the actual use of navigable depth of various ports in China, in order to ensure the navigation safety of ships, the navigable depth is mainly used as the rich water depth, and few ships really contact with the fluid mud layer, which makes the navigable resources may not be fully utilized. If these resources are used as much as possible to make the keel close to the mud surface as far as possible and even enter the mud surface for a certain distance, the application value of navigable depth will be higher, but in this case, since the bottom of the ship is covered with fluid slurry suspension, its properties and characteristics may also affect the maneuverability and navigation safety of the ship. Therefore, to ensure the safety of the ship, it is necessary to clearly understand the ship resistance, heading stability, turning half-diameter and other key issues when the ship is sailing in the fluid mud water area.

Based on the self-designed ship trajectory tracking system, the cycle test and zig-zag test of ship model are carried out in the test pool. The maneuverability of the ship sailing in the floating mud water
area is analyzed comprehensively, and the influence of the distance between the lower boundary of the keel and the fluid mud layer on the navigation safety is studied.

2. Test ship type
In this study, a 100,000 DWT container ship (scale: 1:200) is selected as the experimental research object to study the influence of fluid mud on its maneuverability. The ship type parameters of the ship at actual scale and model scale ratio are shown in Table 1. The shape and profile of the ship are shown in Figure 1.

|                      | Real Ship | Ship Model |
|----------------------|-----------|------------|
| **Length (m)**       | 351.96    | 1.76       |
| **Width (m)**        | 42.82     | 0.21       |
| **Draft (m)**        | 14.54     | 0.07       |
| **Square Coefficient** | 0.66     | 0.66       |
| **Arrival Speed**    | 6.65 kn   | 0.24 m/s   |
| **Froude Number**    | 0.06      | 0.06       |

3. Experimental design

3.1 Experimental setup and test conditions

3.1.1 Test site.
This experiment is carried out in a self-made test pool in a large-scale hydrodynamic experiment hall. The size of the pool is 15m×15m×0.8m.

This test is to study the maneuverability of the ship in fluid mud, which is different from the clean water test [10-11]. In the process of this test, the pool used in this test has undergone a certain transformation and adjustment. First of all, a small water storage container made of plexiglass is added to the side of the pool, which is separated from the test pool by a self-made gate. When the gate is opened, it is connected to the pool, the gate is closed, the water storage container as completely separate from the test pool. The size of the water storage container is 0.3m×0.3m×0.8m, a rule is attached to the outer wall of the container, which is convenient to observe the variation of the thickness and density of the fluid mud. In addition, a certain number of gas transmission pipelines are evenly arranged at the bottom of the pool, which are connected with the air pump. A certain number of exhaust holes are set on the pipeline, and the air is input into the pipeline and discharged into the pool through the exhaust holes to play the stirring effect, which is to make the distribution of floating mud more uniform. The conditions of the test site are shown in Figure 1.

3.1.2 Ship model design.
The ship model is made of FRP according to the prototype. The propulsion system of the ship model is mainly composed of power supply, control switch, indicator light, motor, main shaft, coupling, universal joint, propeller, etc. All parts are purchased or processed. The motor is a DC permanent magnet motor with a maximum speed of 7000 r/min, which uses 24 V battery packs and inverters to provide power for shipboard equipment.

The control system mainly performs real-time steering control according to actual needs, so as to complete various maneuvering movements of ships. The system is mainly composed of tiller, rudder fan, rudder stock, steering gear and some auxiliary devices. The steering gear is powered by a battery pack.
3.2 Data collection and analysis
In order to ensure the accuracy of the results, the author used image processing technology to design a set of automatic ship model movement track monitoring system. This system is mainly divided into two parts. First, the whole process of the test is collected by the camera. After the test is completed, the post-processing software based on MATLAB is used to image the test video, and the binary image is obtained by comparing the test image with the background image, and then the position changes before and after the ship model is obtained, and the target tracking is carried out sequentially.

4. Test method and content

4.1 Test method
Before the test, a certain amount of mud water mixed samples are prepared and injected into the test pool. After the mixture is fully stirred and evenly mixed, the test is carried out. The density required for the test is 1250 kg/m³. In this test, the initial velocity of the ship model is set to 0.24m/s, and the Froude number is 0.06. In order to determine the sailing speed of the ship model, a self-propelled test was carried out in the test pool in advance to determine the relationship between the ship speed and the propeller speed. Before the test, adjust the propeller speed, and then carry out relevant tests.

In the cycle test, the ship model sailed straight on the initial course at a constant speed. After issuing the steering command, steer at the fastest speed to a rudder angle of 30° and maintain this rudder angle until the heading changes by 540° to end the test.

In the zig-zag test, the rudder is steered at 10°/10° according to the change of bow heading angle, and the time histories of pitch and roll of ship model in zig-zag motion are recorded.

During the whole test process, the movement of the ship is recorded through the camera, and the image is post-processed with the automatic tracking system of the ship model. The data of the ship's movement trajectory, heading angle and rudder angle are obtained for the analysis of ship maneuverability.

4.2 Test content
According to the difference of the distance between the lower interface of the ship's keel and the fluid mud layer, this test has formulated 5 different under-keel clearance test plans. Figure 3 and Table 2 describe all the working conditions of this test, where D is the ship's draft, \( H_{\text{water}} \) is the distance from the water surface to the fluid mud surface, \( H_{\text{mud}} \) is the thickness of the fluid mud, and \( H_{\text{clear}} \) is the
under-keel clearance.

![Diagram](image)

Figure 3. Working conditions of the test

### Table 2. Summary of model test conditions

| Research object | Scale | Density of fluid mud | Speed | Draft | $H_{\text{mud}}$ | $H_{\text{clear}}$ |
|-----------------|-------|----------------------|-------|-------|------------------|-------------------|
| Container Ship  | 1:200 | 1250 kg/m$^3$        | 0.24 m/s | D     | 0.3 D            | -0.2 D            |
|                 |       |                      |       |       |                  | -0.1 D            |
|                 |       |                      |       |       |                  | 0 D               |
|                 |       |                      |       |       |                  | 0.1 D             |
|                 |       |                      |       |       |                  | 0.2 D             |

5. Test results and discussion

5.1 Analysis of the cycle test

Through the simulation of each group of working conditions, the author has made statistics on the motion trajectory of the ship model under different test conditions. As shown in Figure 4, for the case where the under-keel clearance is -0.1 and -0.2 times the draft, the complete turning circle of the ship is beyond the scope of the test pool, so only part of the trajectory is shown in the figure. Table 3 shows the rotation diameter corresponding to each working condition.

From the test results, under the condition where the under-keel clearance is 0.2 times the draft (which can be considered as a clear water condition), the turning diameter is about 4.83 times the length of the ship; for the condition where the under-keel clearance is 0.1 times the draft, the turning diameter is 53% larger than the diameter in the clear water; when the under-keel clearance is 0, the bottom of the hull just touches the fluid mud, and the turning diameter of the ship is about 1.7 times the diameter in the clear water; for the case that the under keel clearance depth is -0.1 times of draft, the depth of mud intake is 0.1 times of draft, and the turning diameter is 1.9 times of the middle diameter in clear water; and for the working condition where the under keel clearance depth is -0.2 times the draft, the turning diameter of the ship reached 2.73 times of clear water, which is a large increase. Through the test, although various maneuvering commands can be completed, the turning radius and time are both significantly increased.

### Table 3. Comparison of turning diameters under different test conditions

| Thickness of mud | Under-keel clearance | Turning diameter/Length | Comparison with the results of clean water |
|------------------|-----------------------|-------------------------|------------------------------------------|
| 0.3 D            | 0.2 D                 | 4.83                    | –                                        |
|                  | 0.1 D                 | 7.38                    | 53%                                      |
|                  | 0                     | 8.18                    | 69%                                      |
|                  | -0.1 D                | 9.18                    | 90%                                      |
|                  | -0.2 D                | 13.20                   | 173%                                     |
5.2 Analysis of the influence of zig-zag test

Figure 5 shows the results of the ship model in zig-zag test, and Table 4 shows the K-T index analysis results under each group of working conditions. The results show that under different working conditions, the ship can control its heading through the rudder, but the bowing and heading stability will change as the under-keel clearance changes. When the clearance is 0.2 times of the draft, the overshoot angle is the largest, and the time required to complete the zig-zag test is the shortest. As the under-keel clearance decreases, the ship’s overshoot angle gradually decreases and it takes longer to stabilize on the new heading. The time required for the zig-zag test is gradually increasing. When the bottom of the ship is in contact with the mud, the time required to complete the test is about 2.3 times of the clear water. When the thickness of fluid mud in contact with the ship is more than 0.1 times of draft, the time to complete the test is more than 3 times of under the condition of clean water.
Table 4. K-T indexes under different test conditions

| H\textsubscript{clear} | K   | T   |
|------------------------|-----|-----|
| 0.2 D                  | 1.01| 0.122|
| 0.1 D                  | 0.48| 0.028|
| 0                      | 0.37| 0.009|
| -0.1 D                 | 0.28| -0.002|
| -0.2 D                 | 0.28| -0.009|

5.3 Analysis of the influence of fluid mud on ship maneuverability

From the above maneuvering test results, it is shown that when the under-keel clearance is low or negative, the ship's controllability and maneuverability have changed significantly.

- In order to overcome the resistance caused by fluid mud, a higher propeller load is required to maintain the corresponding ship speed. When the power provided by the propeller remains unchanged, the ship speed will decrease to a certain extent. Therefore, the time required to complete the corresponding maneuverability test is significantly increased.

- In various tests, with the decrease of the under-keel clearance, the linear stability increased significantly, and the yaw rate caused by the rudder decreased significantly. Therefore, in the turning test, the ship needs a larger turning radius to complete the corresponding operation, and in the zig-zag test, the drift angle of the ship was reduced.

- Under each selected fluid mud condition, the ship can control its heading through the rudder, but it takes longer time and more space to complete. As the under-keel clearance decreases, the maneuverability of the ship is significantly worse. From a safety perspective, the use of navigable depth technology is basically feasible when the thickness of fluid mud contact with the ship's keel does not exceed 10% of its draft.

6. Conclusion

In this paper, the 100,000 DWT container ship is taken as the research object, and the self-propelled model test is carried out in the improved pool. The maneuverability of the ship in the fluid mud water area is analyzed comprehensively:

- The turning diameter of the ship increases with the decrease of the under-keel clearance. When the thickness of mud contact with the keel is greater than 10% of the draft, although the ship can still complete the various maneuvering instructions, the space and time have increased significantly.

- The bowing and heading stability of the ship will change with the difference of the under-keel clearance. As the clearance decreases, the ship’s overtaking angle gradually decreases and it takes longer to stabilize on the new heading. When the thickness of fluid mud in contact with the keel is more than 0.1 times of draft, the time to complete the test is more than 3 times of under the condition of clean water.

- As the under-keel clearance decreases, the linear stability increases, but its heading performance becomes worse. From a safety point of view, when using navigable depth, it should be ensured that the depth of fluid mud contacted with the ship's keel does not exceed 10% of its draft.

Reference

[1] Bochve, G. van, Nederloe, L., Manoeuvringbehaviour of ships in muddy canals and harbours, The Dock and Harbour Authority, 1981.

[2] Ashish J. Mehta, Rajesh Srinivas. Fluid mud movement on an inclined bed Nearshore and estuarine cohesive sediment transport. American geophysical Union. 1993: 281-294.

[3] William H.M, Carl Friedrihs, Gongles Hamiltou. Management of fluid mud in Estuaries, bays, and lakes[J]. 2007, 133, (1):1-9.
[4] Mehta AJ, Samsami F, Khare YP, et al. Fluid mud properties in nautical depth estimation. Journal of Waterway, 296 Port, Coastal and Ocean Engineering. 2014; 140 (2):210-222.
[5] Pang Qixiu, Yanghua. Research and Application of Technique of Nautical Depth in China[A], PIANC MMX Congress, 2010.5.
[6] Chou, Hsien-ter. Rheological response of cohesive sediments to water waves[D]. PhD. Dissertation of university of Valifornia, 1989.
[7] Zhenhua Huang, Huhe Aode. Laboratory Study of rheological properties of mudflows in Hangzhou Bay, China. International Journal of Sediment Reseach.
[8] Jin L, Yu Z Y, He Q. Improvement of method for determining nautical density in muddy harbor[J]. Port&Waterway Engineering, 2013(2): 91-106.
[9] Wen C P, Pang Q X, Zhang R B. Research on nautical depth and field measurement in main channel of Lianyungang[J]. Journal of Waterway and Harbor, 2015, 36(6):528-532.
[10] Fan S M, Zhou X B, Yu Z H. Model test of Ship Maneuvering in Waves[J]. Ship Engineering, 2000(5): 18-21.
[11] Liu X J, Xia Z D, Nie J. Correlation Analysis of Maneuverability Based on Model Tests and Sea Trials of a Ship[J]. Journal of Ship Mechanics, 2017(z1): 270-277.