Quantitative Analysis of the Effect of Pier Turbulence on Ship Yaw Moment

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Abstract. In order to quantitatively analyze the action mechanism of the pier flow field on the adjacent bow, Fluent was used to simulate the flow field variation characteristics of a single cylinder pier without ship passing. Secondly, the DES model and the dynamic grid technology are used to simulate the turbulence and the change of the ship's bow moment when the ship passes through a single cylinder pier under different transverse distance parameters. The numerical simulation results under multiple working conditions show that when the ship approaches the pier, the bow moment is significantly affected by the flow field of the pier. With the increase of the distance between the pier and the ship, the influence of the pier flow field on the ship's bow moment is gradually strengthened to gradually weakened.

Keywords: Ship maneuverability; Moving grid; Flow field; Yaw moment; Safe distance

1. Introduction

With the rapid development of the Yangtze River economic belt, more and more cross-river bridges stand on the surface of the Yangtze River. These cross-river bridges communicate the economy and culture between different regions on both sides of the Yangtze River. However, due to the early construction of some bridges, the navigable scale of some bridges is small, or the location is improper, which limits the ships with normal navigation in the waterway waters. Moreover, due to the completion of the bridge, the navigation environment of the nearby waters has been greatly changed, resulting in frequent ship-bridge collision accidents.

At present, there are many researches on these two aspects by relevant scholars at home and abroad. Among them, Pan Jin [1] modified the AASHTO basic model based on the AIS data and the characteristics of the flow in the bridge area, and calculated the collision probability between ships and bridges under different flow conditions according to the modified model.

Zhu man [2] based on the motion model of ship out of control, combined with Monte Carlo method, a ship-bridge collision model based on ship out of control is established, and the risk of ship out of control hitting bridge under different wind and current conditions is calculated.

Gan Langxiong [3] simulated the flow field changes of ships sailing in the field of bridge piers by computational fluid dynamics software Fluent. The test results show that the hydrodynamic change between the pier and the sailing ship is closely related to the distance between the ship and the bridge. Within a certain range of distance from the pier, the pier has obvious interference to the hydrodynamic characteristics of the ship. Ye Yukang [4] takes the series double cylindrical piers as the research object, and simulates the change of the flow field around the piers by Fluent software. The test results show that the pier spacing of tandem double cylindrical piers will significantly affect the trailing vortex of bridge piers, and the safe distance of tandem double cylindrical piers is determined.
according to the turbulence width. Md. Mahbub Alam studies the vibration response of tandem double cylindrical piers under subcritical conditions by Fluent software. The results show that the resistance coefficient and lift coefficient of downstream piers are very sensitive to the distance between tandem double cylinders [5].

From the above research, it can be seen that most of the current studies on the interaction mechanism between pier turbulence and ship motion are based on the separate study of pier flow field turbulence or ship motion, and their effects on ship navigation safety are studied separately. It is rare to analyze the coupling of the two. Therefore, this paper intends to combine the ship and the bridge pier organically by the method of numerical simulation to study the reaction of the ship motion to the turbulent flow of the bridge pier and analyze the interaction mechanism between them.

2. Establishment of Mathematical Model

2.1. Turbulence Modeling

Spalart proposed the DES model in 1997. The turbulence model is suitable for two-dimensional, three-dimensional and unsteady numerical models, also known as coupled LES/RANS model, which is an improvement of the standard Spalart-Allmaras (S-A) one-equation model. It has the advantages of less calculation of Reynolds time-averaged turbulence model and high accuracy of large eddy simulation, and can be used to solve unsteady, two-dimensional and three-dimensional turbulent flows [6].

\[ \frac{\partial}{\partial t} \left( \rho k \right) + \frac{\partial}{\partial x_i} \left( \rho k u_i \right) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k \]  \hspace{1cm} (1)

\[ \frac{\partial}{\partial t} \left( \rho \omega \right) + \frac{\partial}{\partial x_i} \left( \rho \omega u_i \right) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega \]  \hspace{1cm} (2)

Where \( G_k \) is the generation term of \( k \), and \( G_\omega \) represents the turbulent kinetic energy generation term caused by the average velocity gradient, \( \Gamma_k, \Gamma_\omega \) represents the effective diffusion term of \( k \) and \( \omega \), \( D_\omega \) represents the orthogonal divergence term, \( S_k \) and \( S_\omega \) is a custom parameter [7].

Effective diffusion equation:

\[ \Gamma_k = \mu + \frac{\mu_t}{\sigma_k} \]  \hspace{1cm} (3)

\[ \Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega} \]  \hspace{1cm} (4)

Where \( \sigma_k \) and \( \sigma_\omega \) represents the turbulent Prandtl number of \( k \) and \( \omega \), \( \mu_t \) is the turbulent viscosity coefficient [8].

2.2. Numerical Simulation Scheme

According to the actual situation of ship motion and combined with the existing experimental conditions, this paper combines the two-dimensional flow model around the pier with the dynamic grid technology to simulate the ship-bridge intersection phenomenon in the two-dimensional dimension. The specific plans are as follows:

1) The flow model of a single pier around a cylinder is established to study the flow length of a single cylindrical pier when there is no ship passing through.
(2) A ship-bridge encounter model is established to study the change of the flow field around the pier when the ship passes through a single pier normally, and the influence of the ship-bridge transverse distance on the ship-bridge interaction mechanism is considered.

2.3. Calculation Model and Boundary Conditions
The inlet of the model adopts the condition of velocity inlet, the outlet is set as the pressure outlet, the walls on both sides are set as symmetrical boundaries, and the piers and hulls are set as non-slip wall boundaries. The calculation domain and boundary condition settings are shown in figure 1.

![Figure 1. Calculation of domain scale and boundary conditions by single pier model.](image)

In this paper, the diameter of the pier is 5m. At present, the tonnage of the barge passing through the Yangtze River is mostly concentrated in the range of 800m to 4500 tonnage. From the related research, it can be known that the smaller the ratio of the ship length to the pier diameter, the greater the influence of the turbulence caused by the pier on the passing ship. Therefore, the ship in this paper is selected as the 800m ordinary barge, whose scale is 56m × 11m and the flow speed is 2m/s. Because of the large scale and large amount of calculation of the model in this paper, in order to reduce the amount of calculation of the model, the model is scaled by the similarity theory, and the parameters of the model after scaling are shown in table 1.

### Table 1. Test model parameter table.

| Name   | Pier diameter (m) | Flow velocity (m/s) | Ship length (m) | Ship width (m) |
|--------|-------------------|---------------------|-----------------|---------------|
| numerical | 0.1               | 0.283               | 1.12            | 0.22          |

3. The Law of Interaction between Bridge Pier Water Flow Field and Ship

3.1. Analysis of Ship's Bowing Moment Change
In order to further analyze the mechanism of the ship-bridge interaction, this paper uses the built-in "Compute_Force_And_Moment" macro of Fluent to obtain the force of the ship when it passes through the pier, as shown in the figure 2, and the specific analysis is as follows [9]:
Figure 2. The change of the ship's bowing moment.

(1) From the graph of the ship's bowing moment change, it can be seen that when the ship passes the bridge pier at a speed slightly greater than the current flow rate, the ship's bowing moment changes periodically. There are three peaks of the ship's bowing moment, two of which are One is a positive peak and one is a negative peak.

(2) As the lateral distance between the ship and the bridge increases, the positive and negative peak attenuation amplitudes of the ship's bowing moment gradually attenuate; and with the increase of the ship's lateral distance, the second positive and negative peaks of the bowing moment The timing of occurrence has been advanced, while the timing of the first positive peak remains basically unchanged.

Table 2. The change of the peak value of the ship's bowing moment under different ship-bridge distances.

| Ship bridge spacing | First positive peak | Change range | Negative peak | Change range | Second positive peak | Change range |
|---------------------|---------------------|--------------|---------------|--------------|----------------------|--------------|
| 0.5D                | 0.593N.M            |              | -0.57N.M      |              | 0.43N.M             |              |
| 1.0D                | 0.559N.M            | 6.1%         | -0.49N.M      | 16.3%        | 0.401N.M            | 7.2%         |
| 1.5D                | 0.533N.M            | 4.8%         | -0.442N.M     | 10.8%        | 0.382N.M            | 4.9%         |

(3) It can be seen from table 2 that with the increase of the ship-bridge distance, the two positive peak attenuation amplitudes of the ship's bowing moment are approximately the same, while the negative peak attenuation amplitude is larger; at the same time, compare the ship-bridge distance The change of the ship's bowing torque from 0.5D to 1.0D and the ship-bridge distance from 1.0D to 1.5D shows that as the ship-bridge distance increases, the attenuation speed of the peak bowing torque decreases to a certain extent. Which means that when the ship-bridge distance reaches a certain value, the hydrodynamic effect between the ship and the bridge pier begins to weaken, and the ship can safely pass through the waters of the bridge area.

(4) It can be seen that the bow approaching the bridge piers causes the water flow to be squeezed by the ship, and the pressure difference between the water flow on both sides of the hull is the cause of the ship’s first forward bowing moment; the hull passes the bridge pier. When the ship and the bridge pier are squeezed, the water flow velocity between the ship and the bridge increases. The negative pressure zone formed between the ship and the bridge is the cause of the negative bowing moment of the ship; when the ship leaves the pier, the water flow The violent influx into the wake area of the bridge pier causes the flow velocity in the downstream area of the bridge pier to increase, and the increase in the negative pressure area is the cause of the second positive peak of the hull.
3.2. The Influence of Ship-bridge Lateral Distance on Water Flow Field

Because the ship-bridge lateral distance has a greater impact on the changes in the flow field, and the impact of the ship-bridge lateral distance on the flow field around the bridge piers can be used as an important reference for the ship-bridge safety distance. According to previous studies, the smaller the ship-bridge distance, the greater the impact of ship motion on the turbulence around the bridge piers. To this end, this paper selects the ship-bridge lateral spacing to be 0.5D, 1.0D, 1.5D, etc., to study the changes in the flow field around the pier when the ship passes by the pier.

![Diagram](image)

(a) The ship-bridge distance is 0.5D.

(b) The ship-bridge distance is 1.0D.

(c) The ship-bridge distance is 1.5D.

**Figure 3.** The turbulence diagram of the bridge pier when the ship passes the bridge pier at close range.

(1) Figure 3(a) shows that when the ship passes the bridge pier at a distance of 0.5D, the flow velocity in the ship-bridge channel increases, resulting in the velocity on the left side of the bridge pier being significantly greater than the velocity on the right side, resulting in the approach to the side near the hull. The wake vortices fall off in advance, causing the wake vortices on both sides of the bridge piers to no
longer be distributed symmetrically, and the influence range of the pier wake vortices is significantly enlarged by the hull;

(2) Figure 3(b) shows that when the ship passes through the pier at a distance of 1.0D, the wake vortex generated by the pier is partially attached to the hull due to the action of the current, but the vortex street structure is different from the vortex street structure when no ship passes by. Not large, the shedding vortex remains symmetrically distributed.

(3) Figure 3(c) shows that when the lateral distance between the ship and the bridge is maintained at 1.5D, when the ship passes the pier, the vortex street structure generated by the bridge pier is basically the same as the vortex street structure generated by the bridge pier when no ship passes by. It shows that when the ship-bridge distance is 1.5D, the ship has basically no effect on the wake vortex generated by the bridge piers, that is, when the ship-bridge lateral distance is maintained at 1.5D and above, the turbulence of the bridge piers basically has no obvious effect on the ship, so the ship-bridge. When the lateral distance is 1.5D, it can be used as the safety distance of the ship bridge.

4. Conclusion

The main results are as follows:

When the ship passes the pier, the peak value of yaw moment appears alternately from positive peak to negative peak to positive peak, and the reason of the peak value is closely related to the change of flow field between ship and bridge.

Among them, the water flow caused by the bow close to the bridge pier is squeezed by the ship, and the pressure difference between the two sides of the hull is the reason why the ship produces the first positive yaw moment; when the hull passes through the bridge pier, the flow velocity between the ship and the bridge increases due to the extrusion between the ship and the pier, and the negative pressure zone between the ship and the bridge is the reason for the negative yaw moment.

When the stern leaves the pier, the water flows violently into the wake area of the pier, resulting in an increase in the velocity in the downstream area of the pier, and the enlargement of the negative pressure area is the reason for the second positive peak value of the hull.

References

[1] Pan J, Wang Y, Huang Y F and Xu M C 2019 Research on evaluation method of ship-Bridge collision probability based on AIS data Journal of Huazhong University of Science and Technology (Natural Science Edition) 47(11): 109-114.

[2] Zhu M, Gan L X, Wen Y Q, et al. 2013 A method for defining the water area of the bridge area when the ship is out of control Chinese Journal of Safety Science (07): 85-91.

[3] Gan L X, Zou Z J and Xu H X 2014 Hydrodynamic calculation and Analysis of navigating ships in Bridge area Ship Mechanics 18(06): 613-622.

[4] Ye Y K, Liu X P and Li A B 2019 Study on the characteristics of flow field around tandem double cylindrical piers People's Pearl River 40(10): 73-79.

[5] Alam M M, Moriya M, Takai K, et al. 2001 Fluctuating fluid forces acting on two circular cylinders in a tandem arrangement at a subcritical Reynolds number Journal of Wind Engineering & Industrial Aerodynamics 91(1-2): 139-154.

[6] Hua X G, Deng W P, Chen Zh Q and Tang Y 2021 Measurement and numerical simulation of dynamic response of concrete beam bridge with double cylindrical piers under the action of water flow Engineering Mechanics 38(01): 40-51.

[7] Xu G P 2016 Study on Unsteady Flow around Bridge Piers Beijing Jiaotong University.

[8] Gotfredsen E, Kunoy J D, Mayer S and Meyer K E 2020 Experimental validation of RANS and DES modelling of pipe flow mixing Heat and Mass Transfer: Wärme- und Stoffübertragung 56(11).

[9] Ai W Zh, Liu H and Ding T M 2013 Numerical study on turbulent range of circular piers Journal of Wuhan University of Technology (Traffic Science and Engineering Edition) 737(05): 1003-1006.