International Journal of Control and Automation
Vol. 7, No. 11 (2014), pp. 289-300
http://dx.doi.org/10.14257/ijca.2014.7.11.29

Risk Degree of Ship-bridge Collision based on Theory of Ship Collision Avoidance

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Abstract

Bridges have played an integral role in the development of economy and progress of human society, which facilitate transportation and promote regional economic development. However, a large number of bridges for sea-crossing or river-crossing have impeded the water transportation to varying degrees, and then one part of bridges are confronted with higher risk of ship-bridge collision. There are many ship-bridge collision accidents in the world in recent decades, which caused huge casualties and property losses. This paper proposes the model of risk degree for ship-bridge collision based on the theory of ship collision avoidance, as one parts of the system of active warning of ship-bridge collision avoidance, which can show the index of dynamic risk degree for vessels passing through bridge area. The index of ship-bridge collision can make more efficiency for the system of active warning of ship-bridge collision avoidance, which can ensure safety for vessels and bridges. The verification results show the application possibility of the model in practice.

Keywords: *Risk Degree; Ship-Bridge Collision; Ship Collision Avoidance; Active Warning, Closest Point of Approach (CPA), Automatic Radar Plotting Aid (ARPA)*

1. Introduction

Following with bridges increase rapidly and the tendencies of ship large-scale in recent years, the environments of navigation near by bridges are more complicated, and some navigation safety problems of bridge had been on the table gradually, ship-bridge collision accidents often happens in the world, which usually mad amazing loss [1-2]. On May 12, 2013, the ship named "Xin Chuan 8" had collision with Nanjing Yangtze River Bridge at the 6th pier when the ship passed through the bridge, there has been 36 times of ship collision since 1968 [3]. On March 27, 2008, the deck of the under-construction JinTang Bridge in Ningbo, Zhejiang, China, was struck by the mast of a ship, resulting in one span of the box girder dropping into water, four sailors were killed in the accident [4]. On June 15, 2007, the highway 325 bridge over the Jiujiang River in Foshan, Guangdong, China, collapsed due to a ship collision, with the deck of the middle span dropping into the river, the accident led to eight fatalities and four vehicles plunging into the river [5]. The traditional methods for anti-collision for bridge only focused on itself, it just depend on its' strong structure to against ship collision in order to minimize the loss [6-7]. Because of the limitation of ages and economic development and design concepts of bridge for anti-collision, many of bridges rarely consider the risk of ship-bridge collision, and the non navigable spans of bridge are almost in the open state, so the risk of ship-bridge collision of non navigable span should be taken seriously [8-9]. The current measures cannot meet the security needs for bridges and ships [10]. This paper presents a model of the risk degree of ship-bridge collision based on the theory of ship collision avoidance, which calculate the key index of risk to direct the behaviors of anti-collision system [11]. The model had been test by the practice in the project of Shepan Bridge, which illustrates the feasibility of active warning system for ship-bridge collision avoidance.

ISSN: 2005-4297 IJCA

Figure 1. The JinTang Bridge in Ningbo Collapsed due to a Ship Collision

2. Theory of Ship Collision Avoidance

According to the definition, the ship collision avoidance is defined as prediction and avoidance. Prediction is to forecast the target ship when and where will stay the same point or have collision risk with own ship on the sea. Avoidance is that the action been taken by both ships, so that the two ship are not simultaneously occupy the same point or avoid to encounter the situation of risk of collision [12].

2.1. The Algorithm of Distance and the Relative Speed for Both Ships

As Figure 2 illustrations, the origin of the coordinate O shows the position of own ship ,T shows the position of target ship, set λ_1, φ_1 as longitude, latitude of position for own ship , λ_2 , φ_2 as longitude, latitude of position of target ship, D_λ and D_φ as difference of longitude and latitude between both ships.

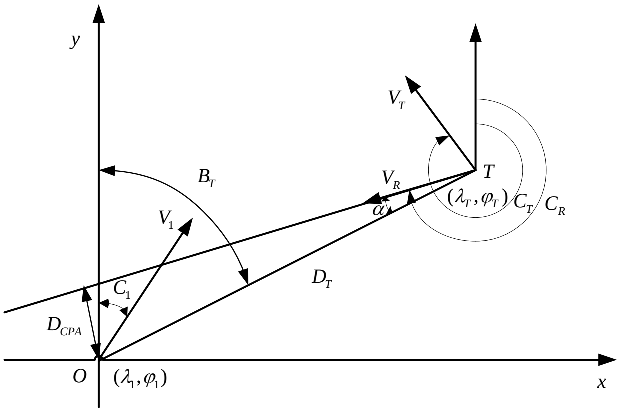

Figure 2. Diagram of Calculation Theory for DCPA and TCPA

It could be expressed as:

$$\begin{cases} D_\lambda = 60(\lambda_T - \lambda_1) \\ D_\varphi = 60(\varphi_T - \varphi_1) \end{cases} \tag{1}$$

And the true azimuth of target ship relative to own ship

$$B_T \quad (°) = \text{arctan} \quad (D_\lambda / D_M) + \tau \tag{2}$$

$$D_T = \begin{cases} |D_\varphi / \cos(B_T)| & D_\varphi \neq 0 \\ |D_\lambda| & D_\varphi = 0 \end{cases} \tag{3}$$

$$D_M = M(\varphi_T) - M(\varphi_1) \tag{4}$$

$$\tau = \begin{cases} 0 & D_\lambda \geq 0, \quad D_\varphi \geq 0 \\ 180 & D_\varphi < 0 \\ 360 & D_\lambda < 0, \quad D_\varphi \geq 0 \end{cases} \tag{5}$$

$$M(\varphi) = 7915.70447\lg\left[\tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)\right]\text{-}23\sin(\varphi) \tag{6}$$

where: D_M = Difference of meridian parts between target ship and own ship； $M(\varphi)$ = Meridian parts； τ =The parameters of circumferential azimuth adjustment（°）； D_T =Distance of target ship and own ship（n mile）。

$$\begin{cases} V_{1x} = V_1 \sin(C_1), & V_{Tx} = V_T \sin(C_T) \\ V_{1y} = V_1 \cos(C_1), & V_{Ty} = V_T \cos(C_T) \end{cases} \tag{7}$$

$$V_R = \sqrt{(V_{Ty} - V_{1y})^2 + (V_{Tx} - V_{1x})^2} \tag{8}$$

$$C_R = \arctan\left(\frac{V_{Tx} - V_{1x}}{V_{Ty} - V_{1y}}\right) + \beta \tag{9}$$

$$\beta = \begin{cases} 0 & V_{Tx} - V_{1x} \geq 0, \quad V_{Ty} - V_{1y} \geq 0 \\ 180 & V_{Tx} - V_{1x} < 0, \quad V_{Ty} - V_{1y} < 0 \\ 180 & V_{Tx} - V_{1x} \geq 0, \quad V_{Ty} - V_{1y} < 0 \\ 360 & V_{Tx} - V_{1x} < 0, \quad V_{Ty} - V_{1y} \geq 0 \end{cases} \tag{10}$$

where: V_1 =Speed of own ship（kn）、 C_1 =Course of own ship（°）, V_{1x} = Component On the x axis of own ship、 V_{1y} = Component On the y axis of own ship; V_T =Speed of target own ship（kn）、 C_T =Course of target ship（°）, V_{Tx} = Component On the x axis of target ship、 V_{Ty} = Component On the y axis of target ship; V_R =Relative speed between own ship with target ship（kn）； C_R =Relative course（°）； β = The parameters of circumferential azimuth adjustment（°）。

2.2. DCPA and TCPA

DCPA（n mile）and TCPA (min) can get from：

$$D_{CPA} = D_T \sin(\alpha) \tag{11}$$

$$T_{CPA} = \frac{D_T \cos(\alpha)}{\mathrm{V_R}} \tag{12}$$

$$\alpha = |C_R - B_T + 180| \tag{13}$$

$$\alpha = \begin{cases} \alpha - 360 & \alpha \geq 360 \\ 360 - \alpha & 360 > \alpha \geq 180 \\ \alpha & 180 > \alpha \geq 0 \end{cases} \tag{14}$$

where： α =The angle between the relative movement line and target ship bear line（°）.

i) Target ship pass through the bow of own ship: DCPA>0,
ii) Target ship pass through the stern of own ship: DCPA<0;
iii) Both ships are close to each other: TCPA≥0,
iv) Both ships has been passed the closest point of approach: TCPA<0。

DCPA is always positive, which only shows the minimum distance between the pier and the target ship in this paper. TCPA illustrates that whether target ship passed the closest point of approach or not, use “(14)”for setting the value of α.

3. Algorithm of Risk Degree of Ship-bridge Collision

DCPA and TCPA are the two parameters used to determine the degree of risk of ship collision at sea. DCPA can directly reflect the minimum distance at most dangerous moment for both ships. TCPA directly reflects the extent of urgency both ships. In the present, automatic radar plotting aids (ARPA) can calculate the tracked object's course, speed and closest point of approach (CPA), thereby knowing if there is a danger of collision with the other ship or landmass through the two parameters. Thus DCPA and TPCA have been recognized as very important parameter for research of ship collision in marine industry.

This paper adopts the normalization of DCPA and TCPA and weighted synthesis to determine the degree of model of ship-bridge collision risk, k as value to descript the degree of risk of collision, bigger, more dangerous. ρ is the index of the degree of collision risk.

$$\rho = (\mathrm{a}DCPA)^2 + \left(b\frac{TCPA}{\mathrm{m}}\right)^2 \tag{15}$$

$$k = \sigma\frac{1}{\rho} \quad (\text{if } k \geq 1, \quad k = 1) \tag{16}$$

where: a and b are weighted value, if target ship pass through the pier of bridge from right side: $a = 5$, $b = 0.5$; from left side: $a = 5$, $b = 1$; m =1.4, as constant is to eliminate the influence of different dimensions of TCPA and DCPA. σ =revision coefficient, which value depend on actual practice. According to the target ship motion parameters from sensors, it will get the dynamic curve of risk degree of ship-bridge collision by calculating the circulation finally.

4. Application Examples

4.1. Prepare of Simulation

In this research, simulation experiments are carried out using the full-mission simulators of Shanghai Maritime University, which have been widely practiced and made good results in port and waterway engineering [13]. The fields of study from assessment of navigation safety and methods of ship maneuvering, had been extended to safe under-keel clearance(UKC),ship stopping Distance, turn region, the track width, the width of channel, ship navigation subsidence, settings of the navigation aids, and ship traffic management, emergency evacuation [14]. Its application has benefited in social and economy. This paper has made the model of risk degree of ship-bridge collision for Shepan Bridge using the Visual Basic 6 programming language, which includes three main modules: monitoring information, results display and data analysis. Software interface as shown in Figure 3.

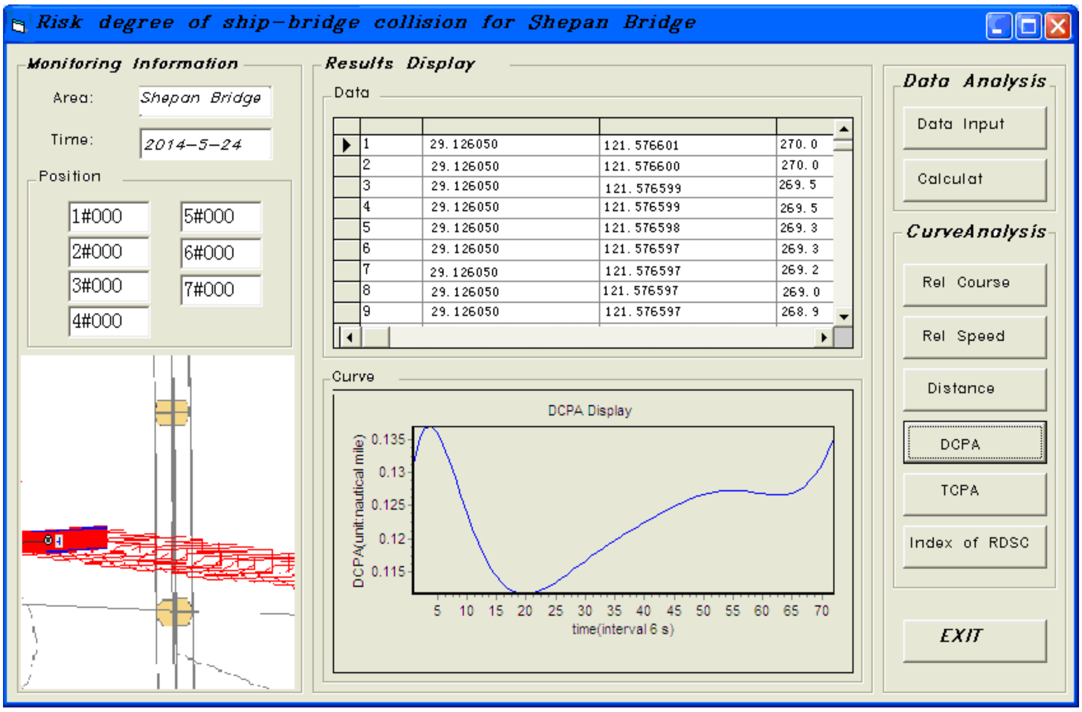

Figure 3. Interface of Collision Risk Analysis Program

4.2. Requirements of Experiment

In order to get the traffic information of vessels passing through bridge after being built, this paper gets the data from simulating according to the nature condition and representative ship types based on full mission ship handle simulator in SMU, and then checks the model of risk degree of ship-bridge collision by using the simulation data as inputs.

The contents of the ship experiment include two operations: under control and non control, under control just simulate ship pass through bridge area normally, Non-control has three conditions: Engine Failure, Rudder Failure and Engine and Rudder both Failures.

Under the actual situation, setting the states and types of ship, nature conditions *ect*. It got the tracks of ship based on full mission ship handle simulator, and then verify the rationality of the model of risk degree of ship-bridge collision on the basis of data of simulation. It gave references for active warning system for ship-bridge collision avoidance [15].

4.3. Simulation Implementation

The Shepan Bridge is located in Sanmen Bay of Zhejiang province of China, it is between the mainland coastal beach and Shepan Island. The water area of bridge-crossing is very broad, 2380m in width, water depth greater than 5m deep groove span is 1640m, maximum water depth is 10m. After the completion of the bridge, the width of navigation waters has been reduced to 220m. Because of sharp narrowing of the navigable waters and the change of custom route, the risk of ship-bridge collision of non navigable span is very higher than others when ship passing through the bridge. So the Shepan Bridge was selected as project for simulation on basis of above-mentioned factors.

According to the contents and requirements of simulation, combined with the natural conditions of the Shepan Bridge, we carried out the simulation experiment of routine operation and ship out of control, and then got the track information and test data, finally verified the model of risk degree of ship-bridge collision by using simulation data, in order to provide reliable index of risk degree of ship-bridge collision [16].

Simulation include the establishment of electronic chart of bridge area, the selection of prototype ship, the building of mathematical model of ship based on prototype ship ,the persons put the simulation scheme into practice. The application of simulation data is to verify the model of risk degree of ship-bridge collision at the end.

4.3.1. Ship Type: According to the study of risk control of ship-bridge collision for Shepan Bridge, the ship model was adopted to have simulation described in the Table 1.

Table 1. Parameters of Simulated Ship

Ship type	Parameters (m)			Remarks
	Loa	B	Draft	
3000t	108	16.0	6.0	Simulation ship

4.3.2. Simulation Scheme: According to the hydrological conditions of cross area of Shepan Bridge, simulation were carried out by normal condition and under non-control two states, the later not only indicated the simulation of routine conditions, but also displayed limited condition, Simulation scheme is shown in Table 2.

Table 2. Simulation Scheme Table

NO.	Ship type	wind		current	
		Direction	Velocity(Level)	Direction	Speed (Kn)
1	3000t	135°	3/5/7	350 °~ 010 °	2.3
2	3000t	135°	3/5/7	180 °~ 200 °	2.5
3	3000t	180°	3/5/7	350 °~ 010 °	2.3
4	3000t	180°	3/5/7	180 °~ 200 °	2.5
5	3000t	293°	3/5/7	350 °~ 010 °	2.3
6	3000t	293°	3/5/7	180 °~ 200 °	2.5
7	3000t	315°	3/5/7	180 °~ 200 °	2.3
8	3000t	315°	3/5/7	350 °~ 010 °	2.5
9	3000t	338°	3/5/7	180 °~ 200 °	2.3
10	3000t	338°	3/5/7	350 °~ 010 °	2.5

4.3.3. Summary of Simulation:

1）Trajectory of Simulation

The ship track of simulation and probability distribution are shown in Figure 4 and Figure 5.

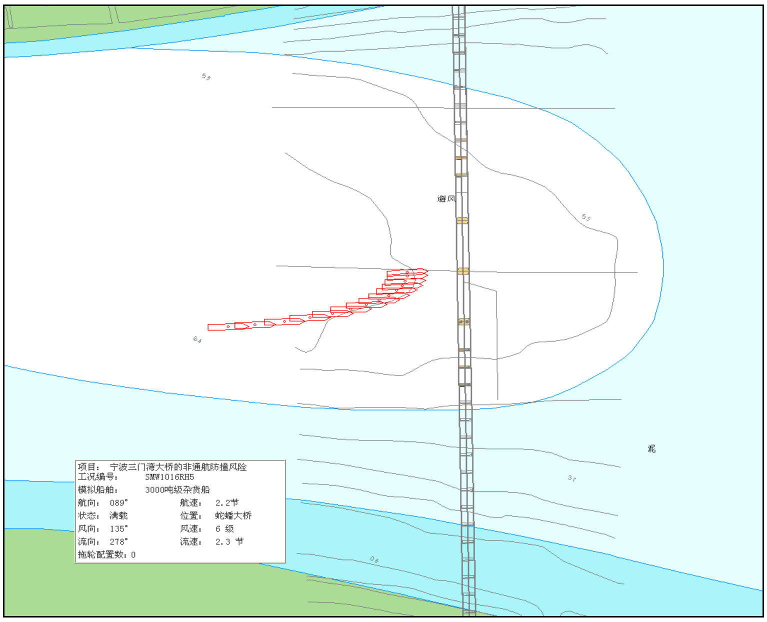

Figure 4. The Track of Ship Simulation

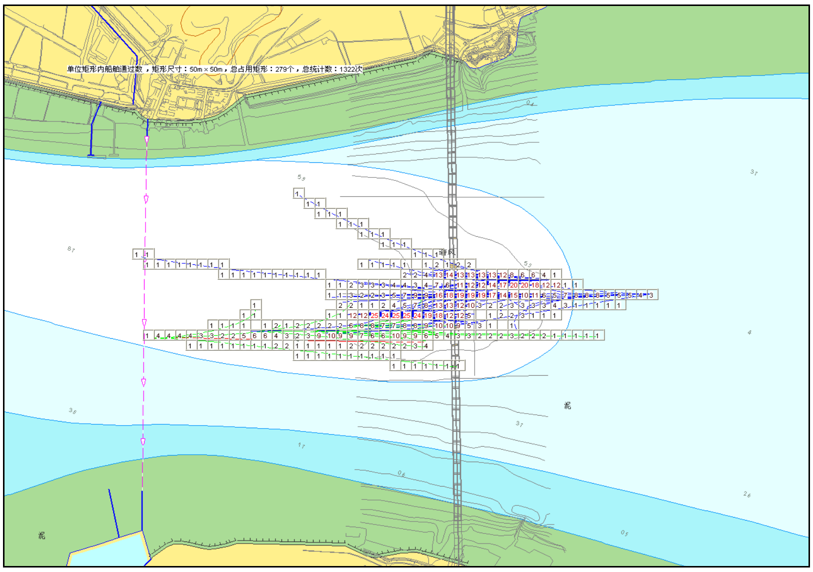

Figure 5. The Probability Distribution of Ship Passing through Shepan Bridge

i) Analysis of simulation data of normal condition

Table 3. The Analysis of Not Under Control Ship Collision with Bridge

NO.	Ship type	Distance from bridge	Speed of collision	Time of arrive the bridge
		(m)	(kn)	(min)
1	3000t	754	2.6	8.2
2	3000t	770	3.3	10.0
3	3000t	740	3.4	7.1
4	3000t	701	3.1	9.7

5	3000t	748	3.2	9.9
6	3000t	710	2.8	8.1
7	3000t	688	2.9	7.9
8	3000t	580	2.9	6.9
9	3000t	883	3.5	7.3
10	3000t	856	3.5	8.3
11	3000t	740	4.0	9.0
12	3000t	737	3.5	10.0
13	3000t	856	3.1	6.8
14	3000t	706	3.6	9.0
15	3000t	685	4.1	9.6
16	3000t	774	3.9	7.1
17	3000t	630	4.0	10.0
18	3000t	708	2.6	7.4
19	3000t	572	3.6	9.1
20	3000t	670	2.5	8.6
21	3000t	801	4.1	8.3
22	3000t	700	3.2	8.6
23	3000t	715	3.9	7.3
24	3000t	812	2.8	7.3
25	3000t	777	4.0	6.3
26	3000t	712	2.6	7.6
27	3000t	833	3.8	8.8
28	3000t	679	2.9	6.5
29	3000t	758	2.7	9.3
30	3000t	598	4.0	8.1

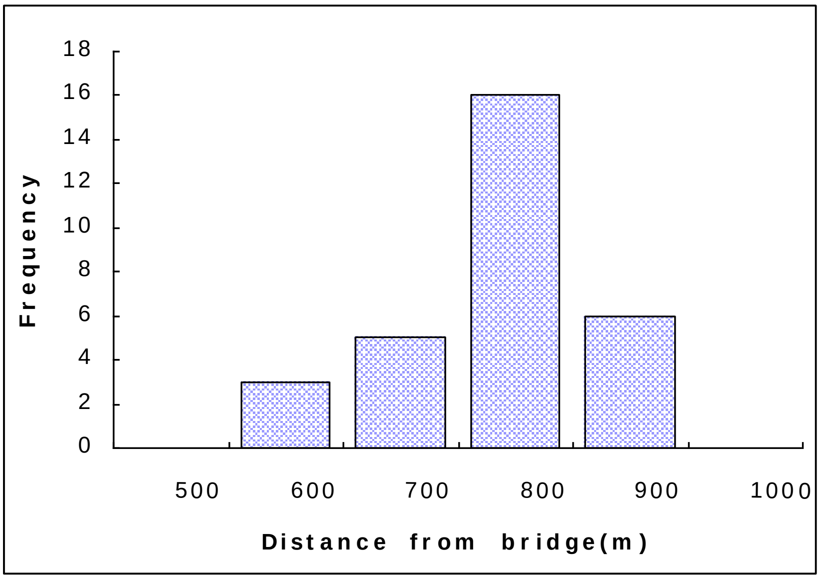

Figure 6. The Histogram of Distance of Ship-bridge Collision

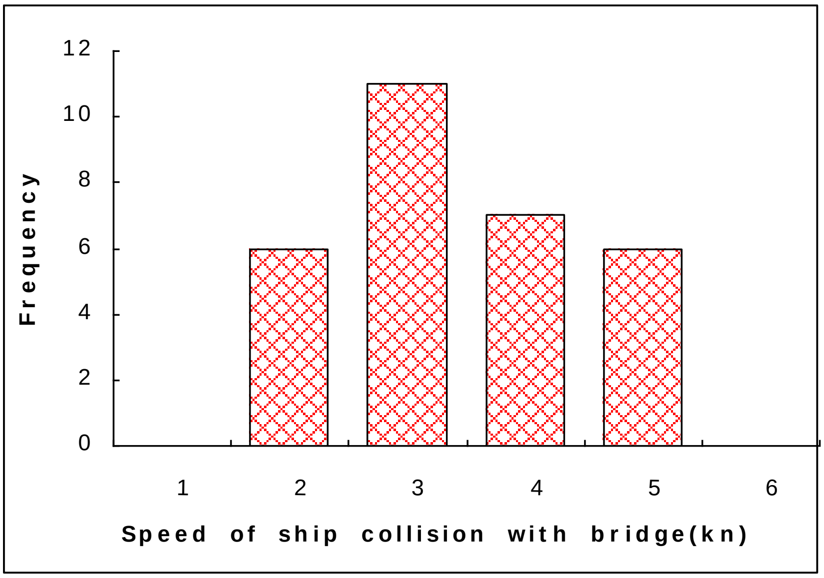

Figure 7. The Histogram of Speed of Ship-bridge Collision

As a result, the probability distance of ship-bridge collision is 600m to 900m, the speed of ship-bridge collision distributes between 2.0kn and 5.0kn, the shortest time of ship-bridge collision from start position is 6.5 minutes, the average time is 8.3 minutes.

ii) Analysis of Simulation Data of Limited Condition Frequency

Table 4. The Analysis of Not Under Control Ship Collision with Bridge Under Limited Condition

NO.	Ship type	Distance from bridge	Speed of collision	Time of arrive the bridge
		(m)	(kn)	(min)
1	3000t	754	4.4	5.8
2	3000t	770	3.7	6.4
3	3000t	740	4.0	5.0
4	3000t	701	3.9	6.6
5	3000t	748	5.1	5.7
6	3000t	710	5.1	5.6
7	3000t	688	4.7	6.0
8	3000t	580	3.5	7.8
9	3000t	883	2.2	6.3
10	3000t	856	3.3	5.6
11	3000t	740	4.2	5.8
12	3000t	737	2.5	9.3
13	3000t	856	5.0	5.8
14	3000t	706	3.6	4.4
15	3000t	685	5.2	6.2
16	3000t	774	3.9	6.1

17	3000t	630	4.3	5.6
18	3000t	708	4.1	7.7
19	3000t	572	3.4	8.0
20	3000t	670	3.0	6.9
21	3000t	801	2.6	6.6
22	3000t	700	4.1	5.7
23	3000t	715	4.9	4.4
24	3000t	812	3.7	7.2
25	3000t	777	5.4	6.2
26	3000t	712	2.9	4.9
27	3000t	833	4.7	5.5
28	3000t	679	3.6	5.7
29	3000t	758	3.2	6.4
30	3000t	598	5.7	7.4

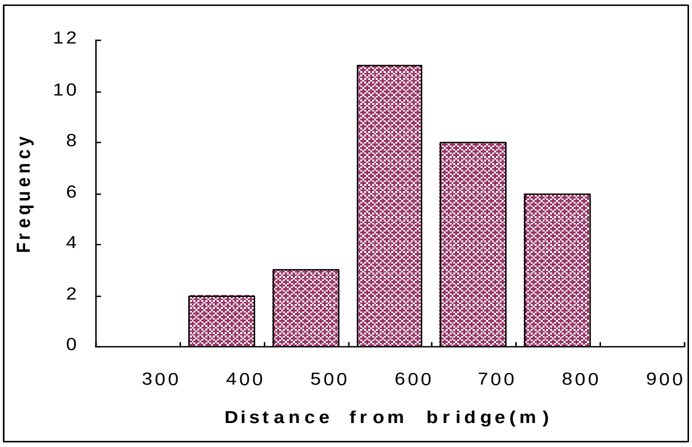

Figure 8. The Histogram of Distance of Ship-bridge Collision Under Limited Condition

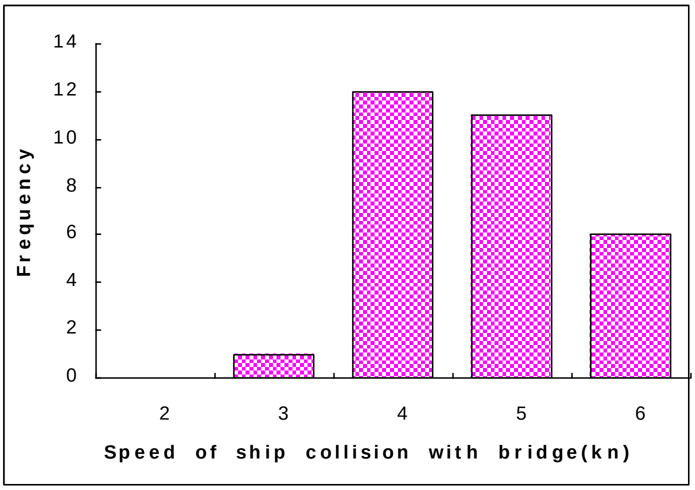

Figure 9. The Histogram of Speed of Ship-bridge Collision Under Limited Condition

Under limited condition, the probability distance of ship-bridge collision also is 300m to 800m, the speed of ship-bridge collision distributes increase to between 4.0kn and 6.0kn, the shortest time of ship-bridge collision from start position is 4.4 minutes, the average time is 9.3 minutes.

4.4. Verification

In the verification, which has been checked through using 180 simulations, including 30 simulations under normal condition, the same number under engine failure, 15 simulations under rudder failure, 105 simulations others. The 180 simulations data is as the input resource to run the software of risk degree of ship-bridge collision ,and the model of risk degree of ship-bridge collision had accurately distinguished 154 times, lost 5 times, mistake 21 times, especially in the 26 mistake times always make the safe as dangerous.

Table 5. The Verification Data of the Model of Risk Degree of Ship-bridge Collision

	Correctly recognition	Error recognition
dangerous	41	5
safe	103	21
total	154	26

The accuracy of the model of risk degree of ship-bridge collision is above 85%, indicating the majority condition, which shows us that the really ship-bridge collision is existing. The accuracy of model is satisfied with the demands of anti-collision function for active warning system of ship-bridge collision avoidance. But it is just checked by simulation data. So the test must be carried out to make sure that the model of risk degree really works in practice, and has good accuracy and can eventually meet the requirements for system of ship-bridge collision avoidance.

5. Conclusion

The model of risk degree of ship-bridge collision can provide the dynamic risk index for the anti-collision system; it has a good application prospect based on the test of simulation data. The next work should focus on precision and reliability of the model. And then should combine with the demonstration project to promote the value in practice through the closed loop circulation pattern.

Acknowledgement

The paper is supported by Shipping Simulation Technology Engineering Research Center of Ministry of Education and the National Natural Science Foundation of China (No.20120372).

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