Thesis for the doctor degree of engineering

Development of

Ship Typhoon-Avoidance Simulation System

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February 2005

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Abstract

태풍피항훈련 교육시스템 개발에 관한 연구

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요약문

해운산업의 급속한 발전과 더불어 선박의 대형화, 특수선 및 위험화물선이 증가함에 따라 해양안전사고 발생시의 자연환경 및 피해액이 막대하다. 여러 조사에 의하면, 이러한 해양안전사고의 86.5%가 기상학적 원인에 의해 발생하며 그 중 상당수의 사고는 태풍발생에 따른 기상악화에 의해 발생되고 있다고 한다.

현재, 최첨단 통신기술 및 조선기술의 발달로 인하여, 과거에 비해 튼튼한 선체구조를 가졌으며 해양에서 운항중인 선박이 취득할 수 있는 정보 또한 양적으로나 질적으로 상당히 좋아지긴 하였지만, 불행하게도 여전히 태풍에 의해 발생하는 해양안전사고는 줄어들지 않고 있으며 그로 인한 해양환경파괴 또한 작지 않은 실정이다. 항해중에 발생하는 태풍으로 인한 해양안전사고의 주요 원인으로는 태풍 피항에 관한 항해사의 지식부족을 들 수 있으며, 무엇보다 태풍 피항에 관한 항해사 대상의 교육훈련시스템이 없는 것 또한 중요한 원인으로 지적되고 있다.

태풍 피항을 위한 교육훈련시스템이 갖추어야 할 기본요소로서는, 실제 해상에서 발생하는 태풍의 발생 및 진로 패턴을 가지는 다양한 태풍정보 데이터베이스가 필요하며, 실제 해상에서 항해사가 접하는 태풍에 관한 정보와 유사한 정보가 피교육자인 항해사에게 제공되어야 한다. 또한, 태풍 및 조종선박에 관해 주어진 조건하에서 실제 항해사가 진로, 풍향/풍속 등 태풍의 정보를 보면서 선박을 조종할 수 있는 도구가 필요하며, 항해사의 태풍 피항 동작에 관한 평가 기능이 필요하다.

이 논문에서는, 태풍 피항 교육 훈련을 위한 시스템을 개발하기 위하여, 1945 년부터 2001 년까지 56 년간 북서태평양해역에서 발생한 태풍의 궤적 및 상태 정보를 수집하여 데이터베이스화하여 태풍의 진행 방향 및 태풍 예상 위치 등의 정보를 계산하는 태풍 이동에 관한 수학모델을 개발하였으며, 기압차 및 태풍의 속도를 이용하여 태풍 발생 주변 해역에서의 풍속, 풍향 및 파랑을 계산할 수 있는 수학모델을 개발하였다. 또한, 태풍에 관한 각종 정보를 이용하여 피항 동작을 취한 항해사의 행위가 적당 유효 및 안전인지 확인하기 위하여 선박의 항해안전 정도를 평가하기 위한 평가기능을 추가하였다. 이 논문에서 제안한 교육 훈련 시스템은 피교육자와 교육자를 위하여 Client/Server 형태의 구조와 TCP/IP 통신에 근거하여 설계되었으며, Server 시스템은 교육훈련 상황을 설정하고 Client 시스템에 전달하고, Client 시스템을 이용하여 이루어지는 피교육자의 피항 동작 행위를 감시하며 평가할 수 있는 기능을 갖추고 있다.

이 논문에서 제안한 수학모델의 유효성을 검증하기 위하여, 1997 년에 발생한 14 호 태풍의 각종 정보를 이용하여 태풍의 진행 방향 및 태풍 예상 위치 등의 정보를 계산하는 수학모델 및 태풍 발생 지역에서의 풍속, 풍향 및 파랑을 계산하기 위한 수학모델을 적용한 결과 및 그 유효성을 검토하였으며, 이러한 모델이 태풍 피항 훈련을 하기 위한 교육시스템 제작에 유효하게 사용될 수 있으며, 항해사 및 학생의 교육 훈련에 적합함을 알 수 있었다.

Chapter 1
Introduction

1-1 Background and purpose

Tropical cyclones develop over tropical or subtropical waters. Tropical depressions, tropical storms and typhoons/hurricanes are all forms of tropical cyclones, which are differentiated only by the intensity of the winds associated with them. The most severe tropical cyclones are thus typhoons/hurricanes. The name of typhoon or hurricane depends on where they are formed. The names stand for the same phenomenon. They are called typhoons when they are formed in the Western North Pacific, and hurricanes when they are formed in the North Atlantic or Eastern North Pacific. In this study, these systems are called typhoons for convenience. Typhoon always causes a very great threat to vessels navigating around it, and tends to make a lot of life losses and damages to property owing to its strong winds and huge waves.

With the rapid development of the shipping industry in the world, the marine disasters relatively increase too. Typhoons/hurricanes have been the main cause of many marine disasters caused by bad weather, and unfortunately, there is no single rule that can be used by mariners to ensure safe avoidance from typhoon at sea. Although, in recent decades, modern technologies make communications more convenient and rapid, vessels stronger, meteorological information more complete and accurate, vessels are still stricken by typhoons frequently and suffered a lot of losses and damages. We are aware that the main cause of such disasters is that mariners are lack of not only necessary knowledge for avoiding typhoon at sea, but also relevant training.

With the swift developing of the computer technology and information technology, these new technologies are widely applied in all industries. Particularly, in maritime field, all kinds

of simulators had been developed based on these, such as RADAR simulator, shiphandling simulator, GMDSS simulator and so on. But, a simulator for avoiding typhoon at sea has never been developed in maritime field by investigating, and such kind of simulator is deadly important for mariners, so, an idea comes into my mind, that is to develop a simulation system on this purpose.

Maritime Education and Training (MET) is a vital part of the marine affairs. The emphasis on hand-on experience cannot be better justified in any vocation than the maritime field, and training on board ship is a natural necessity. Over the years, however, with the strides in technology, the development of simulation tools has made it possible to reproduce real life situations at sea in the school. It means that some 'sea experience' is obtainable on land, and some uncommon experiences are also easily 'experienced'. Several other advantages do exist especially where the simulator-training tool is properly utilized.

In this research, in order to offer a scenario close to the actual situation to train students and mariners so that they can take suitable actions to evade typhoon's strike promptly and sufficiently while facing a threat from typhoon at sea, a simulation system is purposely developed.

1-2 Research methodology

In view of that there is only the past typhoon's track data information available for us to utilize, and in order to be close to the corresponding actual condition, I have to develop a forecast mathematical model of typhoon's track. For this purpose, firstly, we build a database of all tropical cyclone tracks, and then, based on this database and on similarity theory, the typhoon's track forecast model is developed according to three similarity criteria. In this model, the present central position, the lowest pressure, the maximum wind speed and the estimated movement direction with the positions after 24 and/or 48 hours of 6-hour interval can be shown to trainees just like actual condition.

In the next stage, we propose wind-field and wave-field models of typhoon by analyzing and comparing existing models in view of our limited conditions. In these models, wind and wave information at any location in typhoon region can be calculated and shown to trainees, and then they can take appropriate actions for evading the typhoon based on their knowledge and experience.

Then, an evaluation on the effectiveness of avoiding actions is carried out based on seakeeping performance, to see if the actions are appropriate or not, and the ship is in safe or becomes dangerous.

Finally, the whole simulation system is realized by programming based on client/server model using Microsoft Visual Basic 6.0.

1-3 Outline of the thesis

This thesis consists of six chapters.

Chapter 1 expounds the background and purpose of the study and briefly introduces the research methodology and outline of the thesis.

Chapter 2 firstly makes a database of the past typhoon's track data, then proposes three similarity criteria used to judge whether a track is the similar track or not, finally develops a mathematical model for forecasting typhoon's track and shows the forecasted information to trainees in graphic.

Chapter3 proposes a wind-field model and a wave-field model of typhoon based on the precedent researches made by other scholars and, shows the wind and wave information at any location within typhoon region to trainees.

Chapter 4 evaluates the degree of navigation safety based on the seakeeping performance, and then confirms the effectiveness of avoiding actions taken by trainees, and judges whether the actions are appropriate and effective in order to advance their experience.

Chapter 5 designs the simulation system that can provide multi-user training simultaneously based on the Client/Server mode, and describes its corresponding operations in detail.

Chapter 6 is the conclusion of the thesis and, depicts the further research in this field in future.

Chapter 2
Forecast model of typhoon's track

Normally when a typhoon happens, mariners take actions under the consideration of information about the typhoon such as present position, the lowest pressure, maximum wind speed and the estimated movement direction with the positions after 24 and/or 48 hours from meteorological center. Therefore, in this kind of simulation system, in order to be closer to the actual condition, the forecast information of existing typhoon's movement should be supplied to the trainees so that they can take right actions to evade the existing typhoon. However, since we have no further information about historical typhoons except the track data, it is very difficult to get such kind of information even if we want to make a simulation system with the past typhoons' data (Hope, 1969; Hope, 1970; Goerss, 2004).

Therefore, in this chapter, we propose a mathematical model for making the forecast information of typhoon's movement such as the estimated movement direction and positions after 24 and/or 48 hours. The proposed model calculates such kind of information of a typhoon by several past typhoons' track data that are selected according to three similarity criteria that are proposed in the next sectors. In this simulation system, an instructor sets initial simulation environment parameters such as typhoon's position, date/month and so on. Then, the mathematical model calculates the forecast information of existing typhoon's movement with initial set parameters and shows such information to trainees in two-dimensional graphics.

2-1 Overview of typhoon's track

A typhoon track is the result jointly caused by various physical factors, which influence typhoon's movement, such as its forming area, air pressure field surrounding area, upper air flow, season, forward speed and direction, and so on. A typhoon track can be commonly forecasted in consideration of similar tracks in history; in this study, similar tracks mean the

past tracks that are of similar movement and weather situation to these of existing typhoon.

The proposed model calculates the future movement of a typhoon using the information of similar tracks selected by similarity criteria among 1,662 tropical cyclone tracks in the Western North Pacific basin for 56 years from 1945 to 2001 (Source: The Joint Typhoon Warning Center Best Track Data of U.S.A.). All 1,662 tropical cyclone tracks and twelve past typhoons' tracks among them are shown in Fig.2-1 and Fig.2-2.

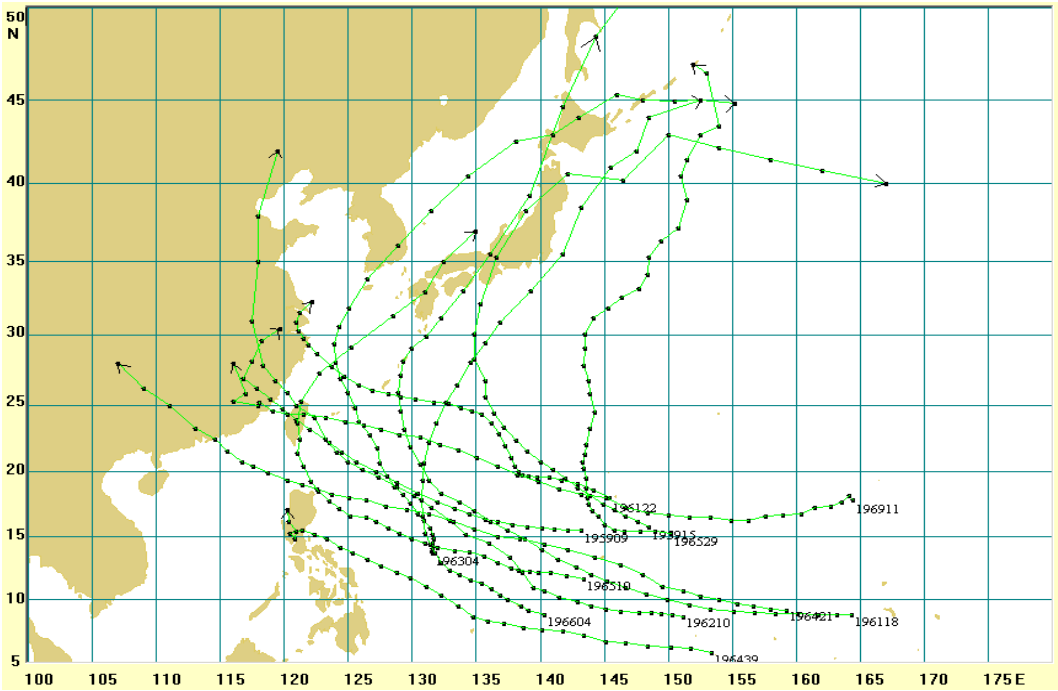


Fig.2-1 Examples of past typhoon track

In Fig.2-1, the time interval between two next points on a track is 6 hours, and the trend of typhoon's movement is palpable. In Fig.2-2, the tracks cover almost all waters of western North Pacific, and its density is high enough. The high dense tracks mean that it is easy to find similar track for a specific typhoon.

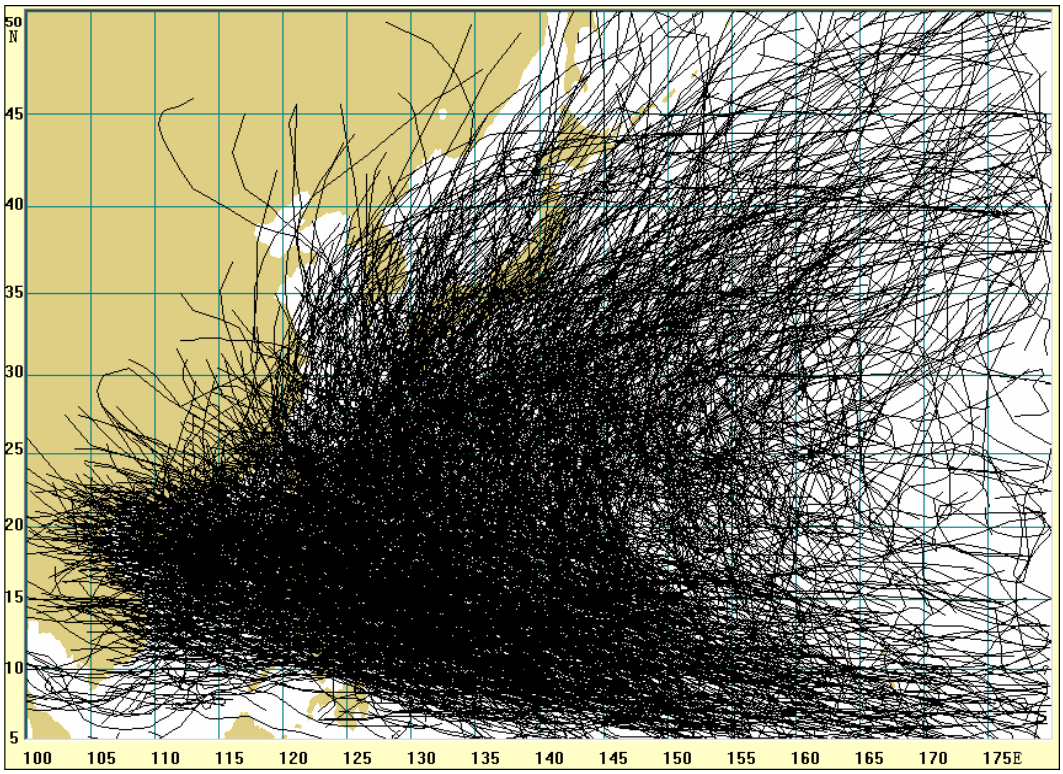


Fig.2-2 All tropical cyclone tracks from 1945 to 2001

2-2 Database of past track data

Since the forecast model of typhoon track will be developed based on the past typhoon's track data, and in order to utilize those data efficiently and swiftly, it is necessary to build a database of the data. An example of the original past track data is shown in Table 2-1:

Table 2-1 An example of the past typhoon track data

Date: 5-23 AUG 1997 Super Typhoon #14						
ADV	**LAT**(N)	**LON**(E)	**TIME**	**WIND**(kn)	**PR**(hPa)	**STAT**
1	5.6	168.0	08/05/00Z	15	1006	TROPICAL DEPRESSION
2	5.7	167.7	08/05/06Z	15	1006	TROPICAL DEPRESSION
3	5.8	167.4	08/05/12Z	15	1006	TROPICAL DEPRESSION
4	5.9	167.1	08/05/18Z	15	1006	TROPICAL DEPRESSION

5	6.1	166.7	08/06/00Z	20	1004	TROPICAL DEPRESSION
6	6.3	166.2	08/06/06Z	20	1004	TROPICAL DEPRESSION
7	6.5	165.4	08/06/12Z	20	1004	TROPICAL DEPRESSION
8	6.8	164.4	08/06/18Z	20	1004	TROPICAL DEPRESSION
9	7.2	163.0	08/07/00Z	20	1004	TROPICAL DEPRESSION
10	7.8	161.7	08/07/06Z	20	1004	TROPICAL DEPRESSION
11	8.7	160.6	08/07/12Z	20	1004	TROPICAL DEPRESSION
12	9.5	159.7	08/07/18Z	20	1004	TROPICAL DEPRESSION
13	10.3	158.8	08/08/00Z	25	1002	TROPICAL DEPRESSION
14	11.3	158.1	08/08/06Z	25	1002	TROPICAL DEPRESSION
15	12.2	157.3	08/08/12Z	30	999	TROPICAL DEPRESSION
16	13.0	156.5	08/08/18Z	30	999	TROPICAL DEPRESSION
17	13.7	155.8	08/09/00Z	30	999	TROPICAL DEPRESSION
18	14.4	155.2	08/09/06Z	35	996	TROPICAL STORM
19	14.8	154.6	08/09/12Z	45	990	TROPICAL STORM
20	15.1	154.1	08/09/18Z	55	983	TROPICAL STORM
21	15.4	153.6	08/10/00Z	65	976	TYPHOON-1
22	15.8	152.8	08/10/06Z	75	968	TYPHOON-1
23	16.0	151.8	08/10/12Z	85	959	TYPHOON-2
24	16.1	150.8	08/10/18Z	95	950	TYPHOON-2
25	16.2	150.1	08/11/00Z	100	945	TYPHOON-3
26	16.4	149.4	08/11/06Z	105	940	TYPHOON-3
27	16.6	148.7	08/11/12Z	115	929	TYPHOON-4
28	16.8	148.0	08/11/18Z	125	917	TYPHOON-4
29	17.2	147.1	08/12/00Z	140	899	TYPHOON-5
30	17.6	146.0	08/12/06Z	140	899	TYPHOON-5
31	18.0	144.9	08/12/12Z	140	899	TYPHOON-5
32	18.4	143.9	08/12/18Z	140	899	TYPHOON-5
33	18.9	143.1	08/13/00Z	140	899	TYPHOON-5
34	19.5	142.2	08/13/06Z	135	905	TYPHOON-4
35	20.1	141.3	08/13/12Z	135	905	TYPHOON-4
36	20.5	140.3	08/13/18Z	130	911	TYPHOON-4
37	21.0	139.5	08/14/00Z	115	929	TYPHOON-4
38	21.5	138.7	08/14/06Z	115	929	TYPHOON-4
39	22.0	137.7	08/14/12Z	110	934	TYPHOON-3
40	22.5	136.7	08/14/18Z	105	940	TYPHOON-3
41	22.8	135.7	08/15/00Z	105	940	TYPHOON-3
42	23.0	134.8	08/15/06Z	95	950	TYPHOON-2
43	23.3	134.0	08/15/12Z	90	955	TYPHOON-2
44	23.6	133.1	08/15/18Z	90	955	TYPHOON-2
45	23.8	132.1	08/16/00Z	85	959	TYPHOON-2

46	24.0	131.1	08/16/06Z	85	959	TYPHOON-2
47	24.1	130.2	08/16/12Z	80	964	TYPHOON-1
48	24.3	129.2	08/16/18Z	80	964	TYPHOON-1
49	24.7	128.2	08/17/00Z	75	968	TYPHOON-1
50	25.1	127.0	08/17/06Z	75	968	TYPHOON-1
51	25.4	126.0	08/17/12Z	75	968	TYPHOON-1
52	25.9	124.9	08/17/18Z	75	968	TYPHOON-1
53	26.6	124.0	08/18/00Z	75	968	TYPHOON-1
54	27.4	122.7	08/18/06Z	75	968	TYPHOON-1
55	28.2	121.4	08/18/12Z	75	968	TYPHOON-1
56	29.1	120.2	08/18/18Z	65	976	TYPHOON-1
57	30.1	119.0	08/19/00Z	55	983	TROPICAL STORM
58	31.2	118.3	08/19/06Z	45	990	TROPICAL STORM
59	32.1	117.8	08/19/12Z	35	996	TROPICAL STORM
60	33.7	117.8	08/19/18Z	30	999	TROPICAL DEPRESSION
61	35.4	117.8	08/20/00Z	30	999	TROPICAL DEPRESSION
62	37.0	118.4	08/20/06Z	30	999	TROPICAL DEPRESSION
63	38.4	119.4	08/20/12Z	30	999	TROPICAL DEPRESSION
64	39.5	120.9	08/20/18Z	30	999	TROPICAL DEPRESSION
65	40.7	122.5	08/21/00Z	30	999	TROPICAL DEPRESSION
66	41.8	124.6	08/21/06Z	30	999	TROPICAL DEPRESSION
67	42.9	126.7	08/21/12Z	30	999	TROPICAL DEPRESSION
68	44.1	128.8	08/21/18Z	30	999	TROPICAL DEPRESSION
69	45.1	130.7	08/22/00Z	25	1002	TROPICAL DEPRESSION
70	45.7	131.8	08/22/06Z	25	1002	TROPICAL DEPRESSION
71	46.2	133.1	08/22/12Z	25	1002	TROPICAL DEPRESSION
72	46.7	134.3	08/22/18Z	25	1002	TROPICAL DEPRESSION
73	47.2	135.5	08/23/00Z	20	1004	TROPICAL DEPRESSION

Table 2-1 shows the track data of No.14 typhoon dated from Aug. 5 to Aug. 23 in 1997. The table includes some fields of the advance number (ADV), the central position in latitude (LAT) and longitude (LON), the time (TIME) in MM/DD/HHz, the maximum sustained winds (WIND) in knots, the central pressure (PR) in *hPa* and the category (STAT) based on Saffir-Simpson scale as shown in Table 2-2.

Table 2-2 The category of tropical cyclone

State	Pressure(hPa)	Wind(kn)
Tropical Depression	-----	< 34
Tropical Storm	-----	34-63
Typhoon-1	> 980	64-82
Typhoon-2	965-980	83-95
Typhoon-3	945-965	96-112
Typhoon-4	920-945	113-135
Typhoon-5	< 920	>135

The original track data totally include 1662 files in text format and, each track data file includes dozens of records. In order to use these data fast and efficiently, it is necessary to build a database using the tools of Microsoft Access which provides an inexpensive yet powerful database solution for small projects. In this database, there are only two tables: one is "Summary" with 9 fields (YearNo, Name, FromMonth, FromDate, ToMonth, ToDate, MaxWind, MinPressure, and Category), and the other is "TrackData" with 9 fields (No, ADV, LAT, LON, TIME, WIND, PR, STAT and YearNo). The relation of these two tables is indicated by the field "YearNo" owned in common. The structure of the database and the contents of two tables are shown in Fig. 2-3 and Fig. 2-4.

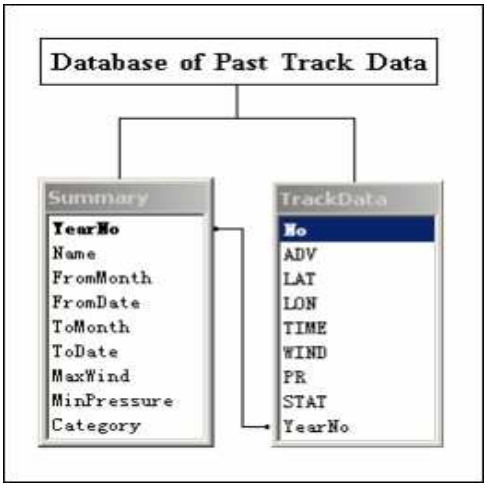


Fig.2-3 Structure of the database

Summary : Table

YearNo	Name	FromMonth	FromDate	ToMonth	ToDate	MaxWind	MinPressure	Category
199714	Super Typhoon	8	5	8	23	140	899	5
199715	Typhoon	8	9	8	27	65	976	1
199716	Subtropical Stoı	8	13	8	19	30	999	-1
199717	Typhoon	8	19	8	23	75	968	1
199718	Typhoon	8	19	8	30	110	934	3
199719	Super Typhoon	8	24	9	6	135	905	4
199720	Tropical Storm	8	26	8	31	45	990	0
199721	Typhoon	9	9	9	22	95	950	2

Record: 1530 of 1662

TrackData : Table

No	ADV	LAT	LON	TIME	WIND	PR	STAT	YearNo
43874	1	5.6	168	08/05/00Z	15	1006	TROPICAL DEPRESSION	199714
43875	2	5.7	167.7	08/05/06Z	15	1006	TROPICAL DEPRESSION	199714
43876	3	5.8	167.4	08/05/12Z	15	1006	TROPICAL DEPRESSION	199714
43877	4	5.9	167.1	08/05/18Z	15	1006	TROPICAL DEPRESSION	199714
43878	5	6.1	166.7	08/06/00Z	20	1004	TROPICAL DEPRESSION	199714
43879	6	6.3	166.2	08/06/06Z	20	1004	TROPICAL DEPRESSION	199714
43880	7	6.5	165.4	08/06/12Z	20	1004	TROPICAL DEPRESSION	199714
43881	8	6.8	164.4	08/06/18Z	20	1004	TROPICAL DEPRESSION	199714

Record: 13 of 48033

Fig.2-4 Tables of the database

2-3 Similarity criteria

The forecasting of a typhoon's track by using similar course and similar weather situation in the past is a common method based on experience. A typhoon's track is a result jointly caused by various kinds of physical factors that influence typhoon's movement. Similar tracks show that the comprehensive effect of those factors is equivalent. This is the foundation of similarity method. Hence, the future movement of existing typhoon can be forecasted by information of similar tracks selected from the database of all past typhoons' tracks according to similarity criteria.

Three similarity criteria, detailed as follows, are defined for selecting a similar track in this study. If a track meets these criteria at the same time, it is a similar track.

2-3-1 Occurrence time similarity criterion

Since the climate characteristic of atmosphere circulation varies with time through the year and influences the typhoon's movement, the occurrence time of typhoon is greatly important factor when we determine its similar tracks.

According to the time when the future positions of the existing typhoon will be forecasted, this criterion checks the occurrence time of all past typhoons and defines as a occurrence time similar track which existed within a period of 30 days, 15 days before and after the existing typhoon's occurrence time respectively (Wang, 1987). In the season with a rare occurrence of typhoon, this period may be longer in order to increase the amount of samples.

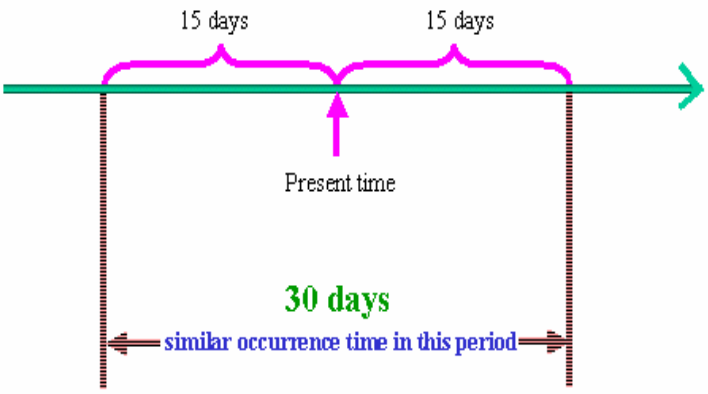


Fig.2-5 Occurrence time similarity of typhoon

2-3-2 Geographical region similarity criterion

If a typhoon occurs in a different region, factors effecting the typhoon's movement are also different even if it meets occurrence time similarity criterion. So, it is necessary to provide that similar tracks meet geographical region similarity criterion

According to the present position of the existing typhoon, this criterion calculates the

distance from this position to a past typhoon's track and is defined as a geographical region similar track if this distance is less than or equal to 150 n miles (Wang, 1987). Fig.2-6 shows that, for the existing typhoon 0, the past typhoon tracks 1, 2, 3, and 4 meet the geographical region similarity criteria, but the track 5 is not.

$$D \leq 150 \text{ n miles} \tag{2-1}$$

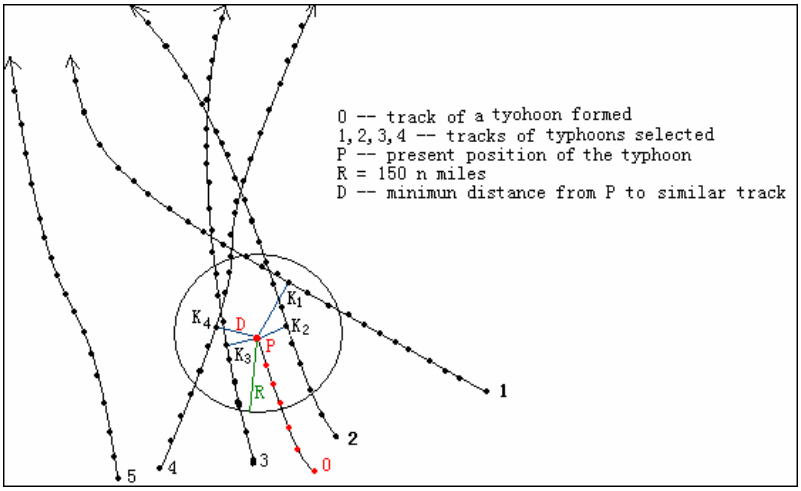


Fig.2-6 Geographical region similarity of typhoon

2-3-3 Direction and speed similarity criterion

Similar moving directions and speeds of typhoon indirectly reflect the similar comprehensive interactive effect of basic atmosphere circulation and the typhoon's internal force. Moving direction and speed are very sensitive to forecast result even it may lead to forecast failure. In order to dispel the influence of the little fluctuation, we provide that moving direction and speed take the mean values of them within 12 hours. This criterion calculates the differences of moving direction and speed between the existing typhoon and the tracks of all past typhoons' tracks, and defines as a direction and speed similar track which meets the following conditions (Wang, 1987):

direction difference $\Delta\theta = |\theta - \theta_0| \leq 22.5°$ (2-2)

speed difference $\Delta v = |v - v_0| \leq v_0/2$ (2-3)

where, θ_0 and v_0 are the mean values of moving direction and speed of the existing typhoon at 12- hour interval, and θ and v are the mean values of moving direction and speed of the selected past typhoon at 12-hour interval, respectively.

In a word, if a past typhoon track meets three criteria abovementioned at the same time, the track is a similar track of the typhoon formed.

2-4 Track Forecast Model

The proposed model calculates the estimated forecast position of a typhoon formed by two factors, which are the inertial factor of the typhoon's movement and the average position's difference of similar tracks selected by three similarity criteria abovementioned from the database of all past track data.

In this model, the inertial factor means an effect of initial typhoon's characteristics. Since the inertial factor is considered only within 36 hours and reduced with time at the rate of 1/6 every 6 hours during the simulation, it is no longer considered after 36 hours, and then the forecast result is completely determined by the every 6-hour average position of similar tracks selected. The Fig. 2-7 shows this process simply.

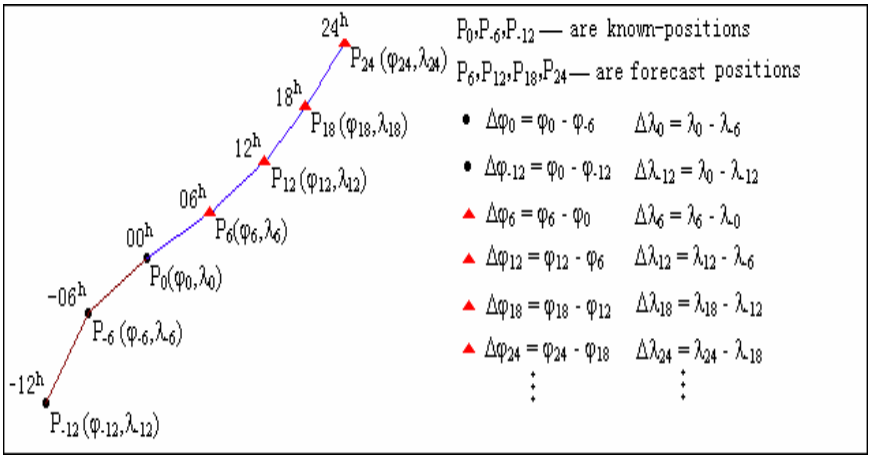


Fig.2-7 Sketch of forecast process

In Fig. 2-6, the *P* indicates the position of a typhoon No.0 and the K_j (j =1, 2, 3, 4) are the positions on each similar track with minimum distance to P. This model calculates the average values of every 6-hour latitude difference ($\Delta\varphi_{ij}$) and longitude difference ($\Delta\lambda_{ij}$) of selected similar tracks from the positions K_j as follows (Chen, 1979):

$$\begin{cases} \overline{\Delta\lambda_i} = \dfrac{1}{N}\sum\limits_{j=1}^{N}\Delta\lambda_{ij} & \text{(2-4a)} \\ \overline{\Delta\varphi_i} = \dfrac{1}{N}\sum\limits_{j=1}^{N}\Delta\varphi_{ij} & \text{(2-4b)} \end{cases}$$

where, N is the total number of selected similar tracks

i(=6,12, ⋯,72) is the forecast time

j(=1, ⋯, N) is the sequential number of similar tracks

Then, taking into consideration of the weight of inertial effect reduces with time within 36 hours (Chen, 1980). The model seeks the every 6-hour latitude difference ($\Delta\varphi_{ij}$) and longitude difference ($\Delta\lambda_{ij}$) of a typhoon formed as follows:

$$\left.\begin{cases} \Delta\lambda_i = \dfrac{36-i}{36}\Delta\lambda_0 + \dfrac{i}{36}\overline{\Delta\lambda_i} \\ \Delta\varphi_i = \dfrac{36-i}{36}\Delta\varphi_0 + \dfrac{i}{36}\overline{\Delta\varphi_i} \end{cases} \quad i < 36 \\ \begin{cases} \Delta\lambda_i = \overline{\Delta\lambda_i} \\ \Delta\varphi_i = \overline{\Delta\varphi_i} \end{cases} \quad i \geq 36 \right\} \qquad (2\text{-}5)$$

where, $\Delta\varphi_0$ and $\Delta\lambda_0$ are the average values of latitude difference and longitude difference within 12 hours, 6 hours before and after the initial position of the typhoon formed, respectively.

Finally, we can obtain the forecast positions of a typhoon formed at every 6-hour interval as follows:

$$\left\{ \begin{cases} \varphi_6 = \varphi_0 + \Delta\varphi_6 \\ \lambda_6 = \lambda_0 + \Delta\lambda_6 \end{cases} \begin{cases} \varphi_{12} = \varphi_6 + \Delta\varphi_{12} \\ \lambda_{12} = \lambda_6 + \Delta\lambda_{12} \end{cases} \cdots \begin{cases} \varphi_{72} = \varphi_{66} + \Delta\varphi_{72} \\ \lambda_{72} = \lambda_{66} + \Delta\lambda_{72} \end{cases} \right\} \qquad (2\text{-}6)$$

If there are no similar tracks of a typhoon formed, the model calculates its forecast positions by an extrapolation method using quadratic polynomial with the latest past three positions.

But, sometimes this model cannot find any similar track sample in the past track database. In this case, we have to do it by extrapolation method using quadratic polynomial. The result is detailed as follows:

$$\begin{cases} \Delta\varphi_{06} = 3\Delta\varphi_0 - \Delta\varphi_{-12} \\ \Delta\lambda_{06} = 3\Delta\lambda_0 - \Delta\lambda_{-12} \end{cases} \begin{cases} \Delta\varphi_{12} = 5\Delta\varphi_0 - 2\Delta\varphi_{-12} \\ \Delta\lambda_{12} = 5\Delta\lambda_0 - 2\Delta\lambda_{-12} \end{cases} \begin{cases} \Delta\varphi_{18} = 7\Delta\varphi_0 - 3\Delta\varphi_{-12} \\ \Delta\lambda_{18} = 7\Delta\lambda_0 - 3\Delta\lambda_{-12} \end{cases} \begin{cases} \Delta\varphi_{24} = 9\Delta\varphi_0 - 4\Delta\varphi_{-12} \\ \Delta\lambda_{24} = 9\Delta\lambda_0 - 4\Delta\lambda_{-12} \end{cases}$$

where, $\Delta\varphi_i$ $\Delta\lambda_i$ (i=06, 12, 18, 24) are the same meaning with the foresaid.

Then, we can get forecast positions at every 6-hours interval according to equation (2-6). Because the accuracy of this method is not low, we make this kind forecast within 24-hours.

2-5 Realization of the mathematical model

2-5-1 Flow chart of the model

This forecast procedure is realized on PC by programming using Visual Basic 6.0 and the flow chart is shown in the following figure:

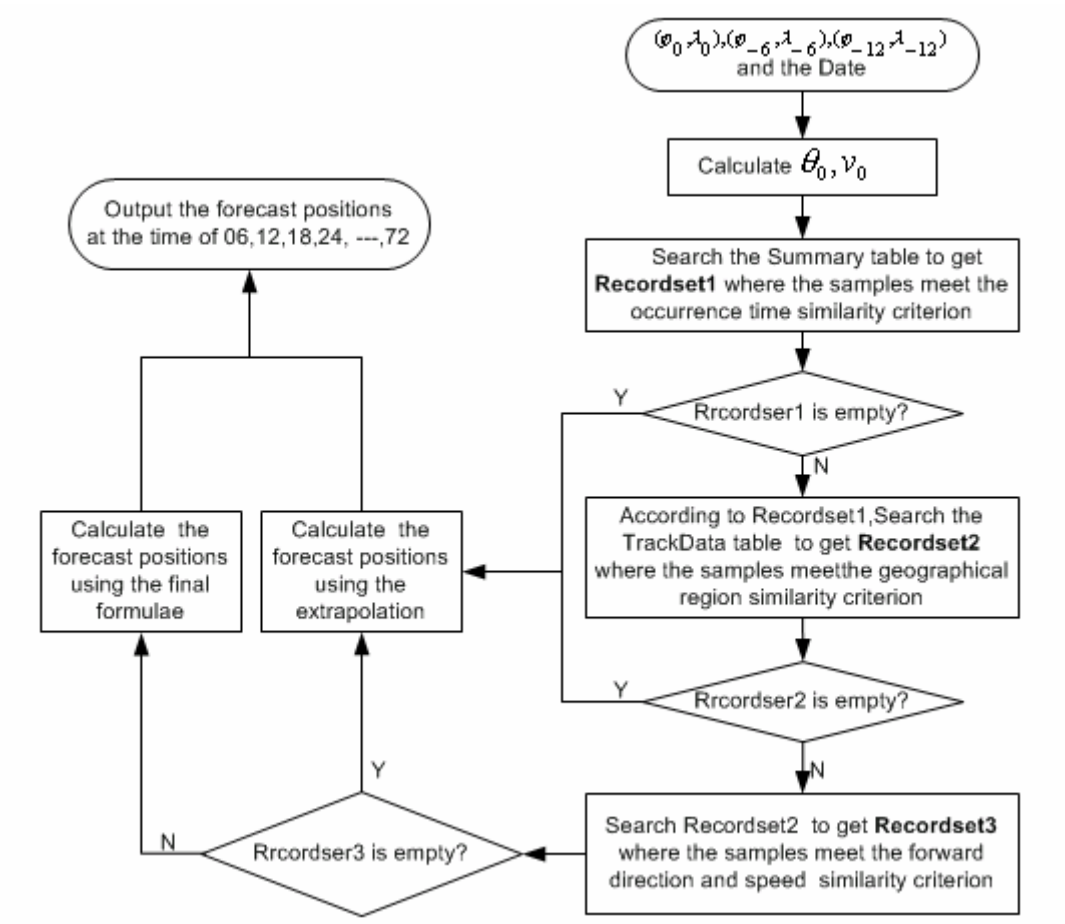


Fig.2-8 Flow chart of the Model

The Fig.2-8 is the flow chart of the forecast model. ①The initial input data are the present position (φ_0 , λ_0), the position (φ_{-6} , λ_{-6}) at the time 6 hours before, the position (φ_{-12} , λ_{-12}) at the time 12 hours before and the present date and the month; ②calculate the initial forward direction angle θ_0 and speed v_0; ③ search the "Summary" table of the database to get the recordset1 that meets the occurrence time similarity criterion. If the recordset1 is empty, calculate the forecast positions by extrapolation, otherwise; ④ according to the recordset1, search the "TrackData" table of the database to get the recordset2 that meets the geographical region similarity criterion. If the recordset2 is empty, calculate the forecast positions by extrapolation, otherwise; ⑤ search the recordset2 to get the recordset3 that meets the forward direction and speed similarity criterion. If the recordset3 is empty, calculate the forecast positions by extrapolation, otherwise, calculate the forecast positions according to the final mathematical formulae Eq.(2-5)~(2-6). This procedure repeats once every 6 hours and outputs the latest forecast positions.

2-5-2 Error radius of 24-hour and 48-hour forecast positions

Mariners receive the typhoon's information through the weather facsimile at sea such as the present typhoon's location, lowest pressure, maximum wind speed, its forecast positions with circles and so on. In order to make the simulation more actual, the present and forecast positions of a typhoon should be shown to trainees with its error circles.

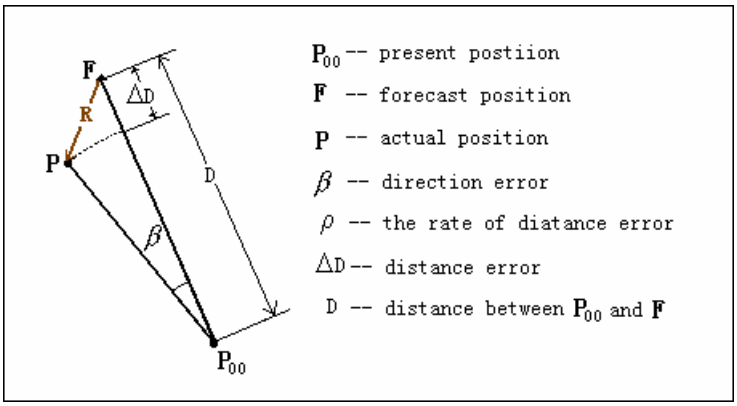


Fig.2-9 Radius of forecast error

As shown in Fig.2-9, we may consider that the forecast error circle is caused by direction forecast error and distance forecast error, so that it could be calculated from these two errors by Eq.(2-7):

$$R_i = \sqrt{\left(\frac{\beta \cdot \pi}{180} D_i\right)^2 + (\rho \cdot D_i)^2} = D_i \sqrt{\left(\frac{\beta \cdot \pi}{180}\right)^2 + (\rho)^2} \qquad (2\text{-}7)$$

where, as shown in Fig.2-8, i is the forecast time (24 or 48 hours) and, β and ρ are the forecast direction error and the ratio of forecast distance error respectively. Here, β is the angle between $\overrightarrow{P_0F}$ and $\overrightarrow{P_0P}$, and ρ is the rate of ΔD (the length difference between $\overrightarrow{P_0F}$ and $\overrightarrow{P_0P}$) to D (the distance between the present position and forecast position). We found the statistical values of those errors through simulation forecasting 141 typhoons' tracks as shown in the following Table 2-3.

Table 2-3 The average values of forecast error

	24 hours	**48 hours**
β	14.3°	17.5°
ρ	0.236	0.273

2-5-3 Experiment of the model

We applied No.14 typhoon in 1997 to this forecast model, and evaluated its performance by comparing eight forecast positions with the corresponding actual ones from the time of 1200 on 14th August. Fig. 2-9 shows both the forecast and actual positions for two days, and those data at 6-hour interval are shown in Table 2-4. Fig.2-11 is an example screen frame which is shown to trainees and it includes the present and forecast positions of the typhoon with the forecast error circle.

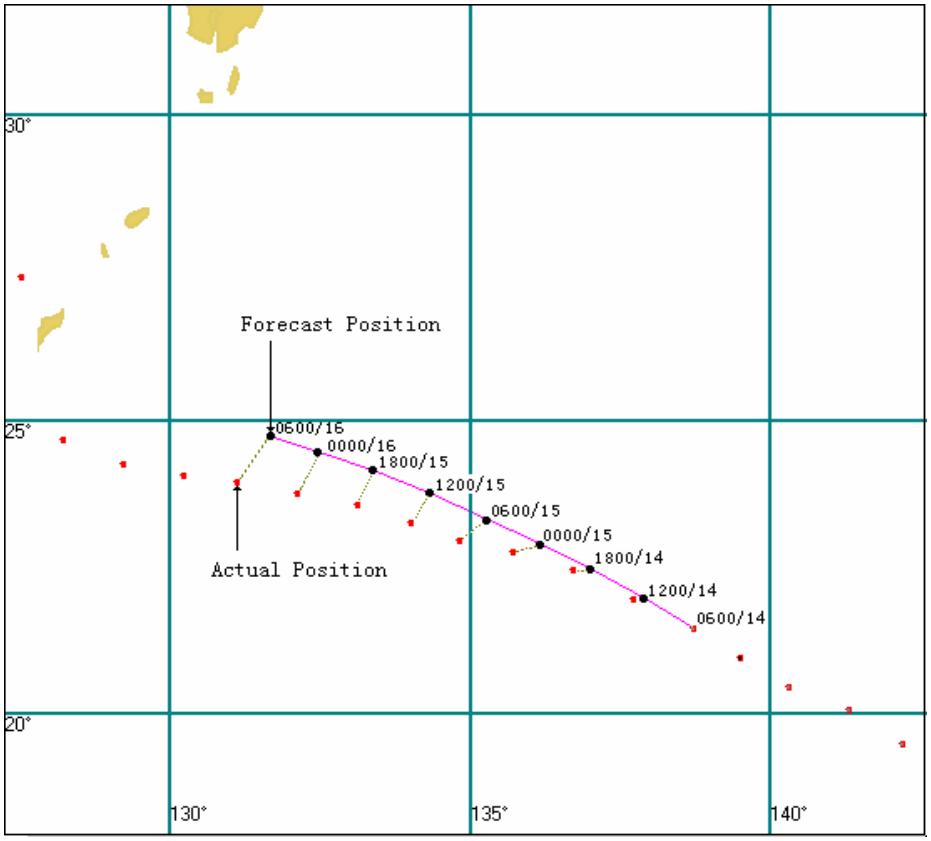


Fig.2-10 Result of simulated forecast on No.14 typhoon in 1997

Table 2-4 Comparison between forecast and actual values

Interval	**Time**	**Actual Values**		**Forecast Values**		**Radius of Forecast Error**
00	**0600/14**	**φ**	**λ**	**φ**	**λ**	**R_i(n miles)**
06	1200/14	22.00	137.70	22.00	137.89	22.26
12	1800/14	22.50	136.70	22.49	137.02	45.46
18	0000/15	22.80	135.70	22.95	136.14	68.25
24	**0600/15**	**23.00**	**134.80**	**23.36**	**135.25**	**90.65**
30	1200/15	23.30	134.00	23.78	134.31	114.30
36	1800/15	23.60	133.10	24.18	133.36	137.81
42	0000/16	23.80	132.10	24.48	132.46	158.94
48	**0600/16**	**24.00**	**131.10**	**24.75**	**131.64**	**178.44**

Obviously, the accuracy of this kind forecast result is depended on the quantity and the quality of track samples selected. Since there are many past tracks to be selected in low latitude area and in midsummer season, the performance of this forecast model is fair and acceptable. Conversely, in transitional season and higher latitude area, and in other area with many samples but large degree of track dispersion, the result is poor. Moreover, for typhoons with low-probability movement (such as stagnating, spinning and twisting) and with a sudden change of moving speed, this model is lack of capability to forecast them. And certainly, this model also cannot forecast an appearance of typhoon.

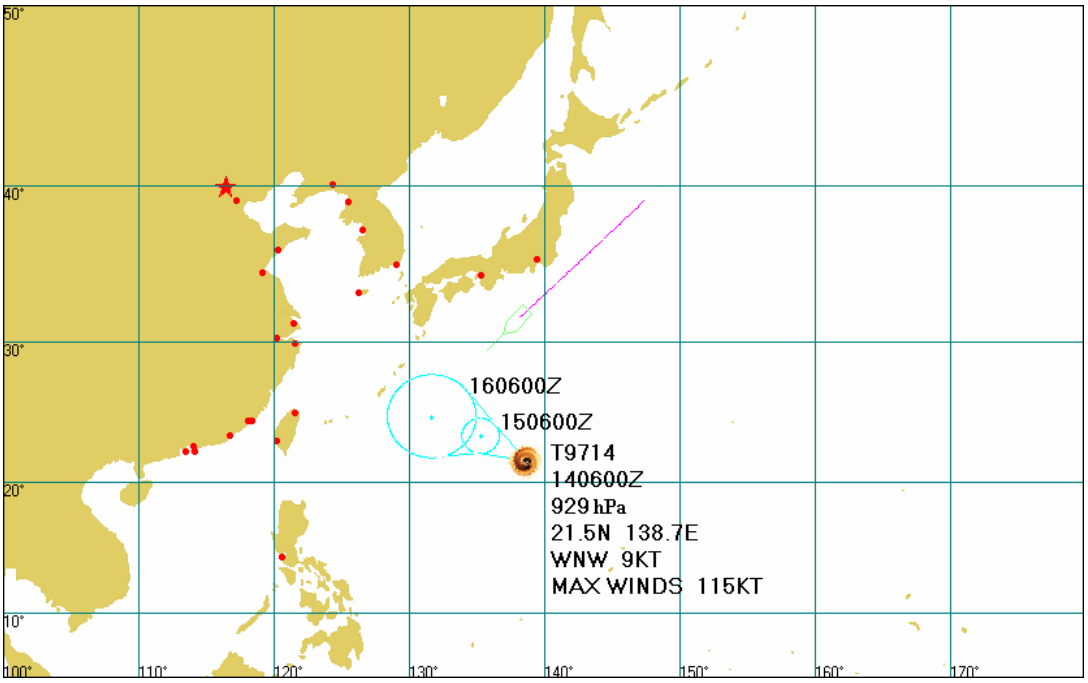


Fig.2-11 A frame of simulating forecast

In this chapter, built a database of past typhoon tracks, defined three criteria for determining similar tracks, and then proposed a mathematical model for forecasting a typhoon's movement with the forecast error circle. Carried out a simulation forecast on No.14 typhoon in 1997, and found that the result of the proposed model was reasonable and acceptable. In the next chapter, we try to develop models for calculating meteorological

information such as wind force and direction, wave height and period at any site around the center of typhoon, so that they can take appropriate actions to evade the typhoon while facing a typhoon at sea.

Chapter 3

Wind-field and Wave-Field Models of Typhoon

3-1 Overview of typhoon's structure

Typhoons are warm core, non-frontal low-pressure systems of synoptic scale that have a definite organized surface circulation. At the Northern Hemisphere they follow an anti-clockwise pattern and on the Southern Hemisphere a clockwise pattern. Their track speeds range from 0 to 15 m/s and they measure 320 to 480 kilometers across and may bring winds up to 290 kilometers an hour.

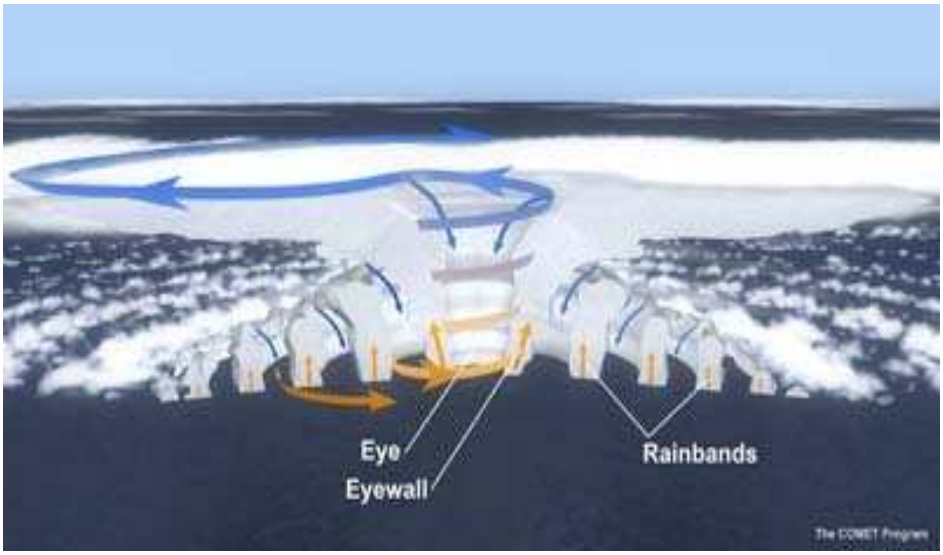


Fig.3-1 Vertical section of typhoon's Structure

As shown in Fig.3-1, the main parts of a typhoon are the rainbands on its outer edges, the eye, and the eyewall. At the North Hemisphere, air spirals are inward the center in a counter-clockwise pattern, and out of the top in the opposite direction. In the very center of the storm, air sinks, forming the cloud-free eye.

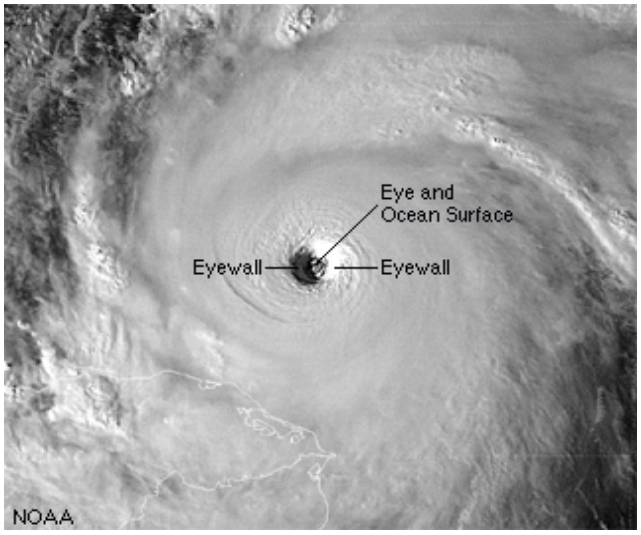


Fig.3-2 Details of the typhoon eye's structure

The eye, typhoon's center, is a relatively calm, clear area usually 20-40 miles across.

Fig.3-3 The wall of clouds surrounding the clear eye

As shown in Fig.3-3, the dense wall of thunderstorms surrounding the eye has the strongest winds within the storm. Changes in the structure of the eye and eyewall can cause changes in the wind speed, which is an indicator of the storm's intensity. The eye can grow or shrink in size, and double (concentric) eyewalls can form.

The Spiral Rainbands, the storm's outer rainbands (often with typhoon or tropical storm-force winds), can extend a few hundred miles from the center.

Typhoon Size typically is about 300 miles wide although they can vary considerably. Size is not necessarily an indication of typhoon intensity.

Do not focus on the location and track of the center, because the typhoon 's destructive winds and waves cover a wide swath. Typhoon -force winds can extend outward to about 25 miles from the storm center of a small typhoon and to more than 150 miles for a large one. The area over which tropical storm-force winds occur is even greater, ranging as far out as almost 300 miles from the eye of a large typhoon.

Contrary to how many weather maps appear, a typhoon is more than a point on a weather map, and its path is more than a line. It is a large system that can affect a wide area, requiring that precautions be taken far from where the eye is predicted.

In order to prevent striking from typhoon or to reduce the losses and damages caused by typhoon, many researchers have been engaging in studying typhoon, but they still cannot make completely clear of its structure, including its wind-field distribution and wave field distribution. Typhoon is a very complicated system, and it is difficult to find out an accurate mathematical model to depict it. Anyway, researchers have been trying to model typhoon in various approaches for their own purposes. All these models can be generally classified into three categories: analytical models, numerical models and parametric models. Analytical models have closed form solutions to the momentum equation in a simplified fashion (e.g., Tryggvason et al. 1976 and Batts et al. 1980), and their accuracy may be reduced by some simplifications. Numerical models solve the equation of motion by numerical methods (e.g., Chow 1971, Shapiro 1983 and Vickery et al. 1995), and these models generally have good accuracy but require significant computational efforts. Parametric models were introduced to approximate numerical solutions by functional forms, which define some functions of the

hurricanes' characteristics (e.g., Cooper 1988 and Daneshvaran et al. 1997), and these models have better numerical accuracy than the analytical models and greater computational efficiency than the numerical models.

Our purpose is to develop simulation software for training students and seafarers to avoid typhoon's strike at sea, and there is only past typhoon's track data information available for us to utilize, so we plan to try to find out simple parametric models for our purpose. This model is for calculating the pressure, wind speed & direction, wave height & direction & period at any location around the center of typhoon.

However, pressure field of typhoon is considered first of all, because it is the foundation that we develop typhoon wind and wave models.

3-2 Pressure Field of Typhoon

Because the motive power of causing wind is the pressure gradient force, we shall find out pressure field of typhoon before we study wind and wave field models of typhoon. A lot of researchers engaged in the study of surface pressure field of typhoon, and these models can be summarily classified into three representative categories: the first is theoretical pressure model, in early days, e.g. V. Bjerknes Equation (1921), Takahashi Equation (1939), Fujida Equation (1952), Myers Equation (1957) and Jelesnianski Equation (1965), and so on, those are of circular symmetric models. Then, based on this, Chinese scholars proposed several improved models, e.g. elliptic symmetric model by Chen Kongmo (1981), non-similar structure model by Zhang Jiabin (1986). The second is empirical model, e.g. Holland Equation (1980). The third is semi-theoretical and semi-empirical model, e.g. the model by Sheng Lifang (1993). All of these models are of advantages and disadvantages respectively. Theoretical model is convenient for describing and computing, but it cannot reflect surface pressure field objectively; empirical model is subject to time and region, and it is difficult to determine its empirical parameters; Semi-theoretical and semi-empirical model integrates the advantages of

two formers, it still be essential to improve further. In view of our limited past typhoon's track data, we decide to adopt theoretical model for simplicity.

Fujida Equation is as follows (Fujida 1987):

$$P(r) = P_\infty - (P_\infty - P_0) / \sqrt{1 + (r / R_{\max})^2} = P_\infty - \Delta P / \sqrt{1 + (r / R_{\max})^2} \qquad (3\text{-}8)$$

where:

$P(r)$ = surface pressure,

r = radial distance from the center,

P_∞ = unperturbed pressure,

P_0 = central pressure,

$R_{\max}$ = radius at which the wind attains its maximum speed,

ΔP = pressure difference between central and local position.

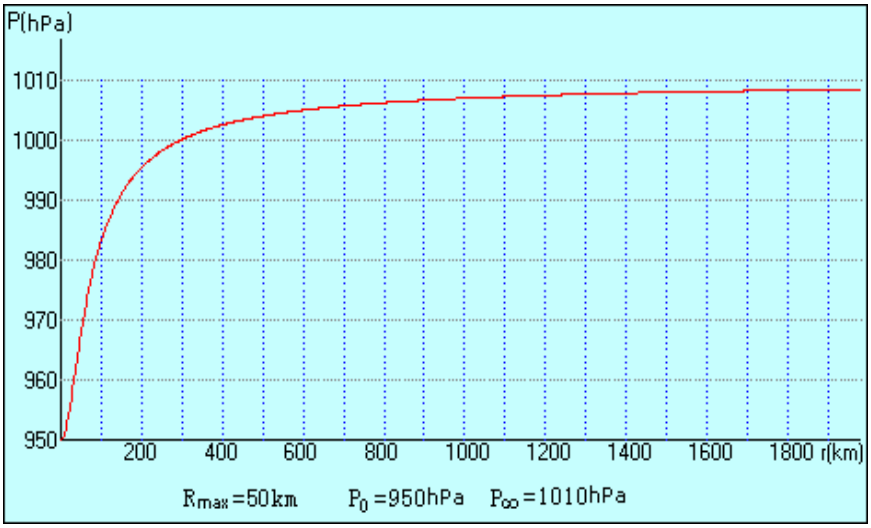


Fig.3-4 Radial pressure field of typhoon

Fig.3-4 shows an example of the radial distribution of surface pressure field of typhoon while R_{max}=50*km*, P_0=950*hPa* and P_∞=1010*hPa*, it is an ideal and circular-symmetric model.

3-3 Wind-field model in typhoon

Wind-field in typhoon is rarely, if ever, symmetric. Asymmetries arise from a range of processes, including cyclone movement, location and structure of the cloudy and clear regions around the typhoon, external influences from surrounding weather systems, and occasional high-intensity transients such as mesovortices.

The only asymmetrical processes routinely included in current parametric wind-field models are those of that arising from typhoon's movement. Therefore, for simulating the asymmetric characteristic of wind-field in typhoon, we tend to consider that wind-field in typhoon is a vector resultant of a circular symmetric wind-field of a stationary typhoon and a wind-field due to the movement of typhoon. Circular symmetric wind-field is caused by pressure gradient of typhoon, and moving wind-field is caused by weather system surrounding typhoon.

3-3-1 Wind-field of a stationary typhoon

Wind and wave fields in typhoon are generally calculated or forecasted from gradient wind or model-typhoon wind-field. While providing that surface pressure field has circular symmetric distribution, the gradient wind of typhoon can be calculated from the equation of gradient wind as follows (Chen, 1994):

$$V_g(r) = -\frac{1}{2} fr + \sqrt{\left(\frac{fr}{2}\right)^2 + \frac{r}{\rho}\frac{dP}{dr}} \tag{3-9}$$

where, $V_g(r)$ is gradient wind of stationary typhoon,

$\frac{dP}{dr}$ is pressure gradient, and can be calculated according to (Zhu, 2002),

r is radial distance from the center,

ρ is the air density,

f is the Coriolis parameter ($f = 2\Omega\sin\varphi$, Ω is the rotation rate of the Earth and φ is

the latitude of central position).

Obviously, the calculation of gradient wind is somewhat complicated, and the wind-fields of model-typhoons are relatively simple and easy to be applied. In general, these wind-fields are functions of the following typhoon characteristics and the relative location of site: central pressure difference ΔP, maximum winds $V_{\max}$, forward speed V_S, radius to maximum winds $R_{\max}$, site-to-eye distance r, site-to-eye angle α and Coriolis factor f. This kind of parametric wind-field model usually consists of two terms: a maximum magnitude term related to $V_{\max}$ and a decaying term related to $R_{\max}$.

In our database of past typhoon track data, most of records have the values of $V_{\max}$. If $V_{\max}$ is not available, it can be calculated from the following equation (Hsu, 2003):

$$V_{\max} = 6.3(1013 - P_0)^{0.5} \tag{3-10}$$

where,

$V_{\max}$ is the value of maximum wind speed (*m/s*) at 10m height (In the next, unless otherwise stated, $V_{\max}$ has the same meaning.),

P_0 is the minimum sea level pressure (*hPa*).

$R_{\max}$ is not available in our database, but it is a significant parameter. $R_{\max}$ is relating to many factors such as the intensity, the basin, the center position and so on. It is not a fixed value, but a variable changing from typhoon to typhoon, time to time and basin to basin. However, several research studies were done to formulate $R_{\max}$. Empirically determined equation for R_{max} as a function of maximum wind and central position latitude is as follows (H.E. Willoughby, 2003):

$$R_{\max} = 46.29\exp(-0.0153V_{\max} + 0.0166\varphi) \tag{3-11}$$

where,

$R_{\max}$ is the value of radius to maximum wind (*km*),

φ is the latitude of typhoon central position (°),

$V_{\max}$ is the value of maximum wind speed (*m/s*) at 10m height.

A variety of equations have been suggested to such kind of wind-field model. Indeed in modern times, there appear to as many models as there are researchers working in the field. We shall describe only three for comparison.

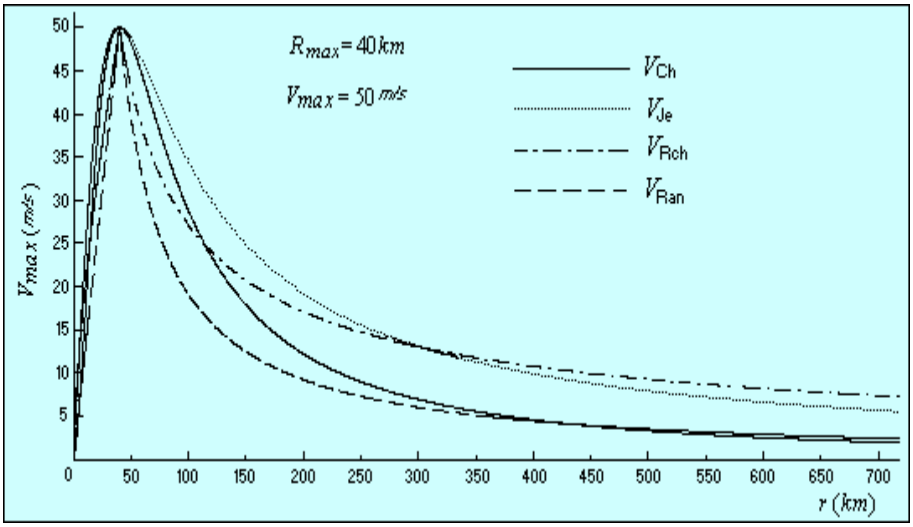


Fig.3-5 Profiles of some wind-field distributions

The first is a straightforward description of wind-field, which has its roots in the writings of Leonardo da Vinci, and was first applied to tropical cyclones by Depperman (1947). This is so called, Rankine-combined, or modified potential vortex (Greg Holland 1997):

$$\begin{cases} V_{Ran} = V_{\max}\left(\dfrac{r}{R_{\max}}\right) & if \quad r \le R_{\max} \qquad (3\text{-}12a) \\ V_{Ran} = V_{\max}\left(\dfrac{R_{\max}}{r}\right)^{x} & if \quad r > R_{\max} \qquad (3\text{-}12b) \end{cases}$$

where, r is a radial distance from typhoon center

x is a shape parameter of the wind-field outside R, for physical reasons, $0 < x < 1$, typically $x = 0.5$ and a reasonable range of values is $0.3 < x < 0.8$.

As shown in Fig.3-5, wind speed calculated from Rankine model tends to be lower than others, especially near the area of maximum wind radius, the reason is right that the wind speed decay rate is too large.

In order to overcome the shortage of Rankine model, Jelesnianski proposed the following wind-field model:

$$V_{Je} = 2V_{\max} \frac{R_{\max} / r}{(R_{\max} / r)^2 + 1} \tag{3-13}$$

This wind-field model is better than the first one (Rankine Model), but in the far area, the wind speeds tend to be higher because wind speed decay rate is slow (as shown in Fig.3-5).

Therefore, ChenKongmo proposed an improved wind-field model as follows (Chen,1994):

$$\begin{cases} V_{Rch} = V_{\max} (r / R_{\max})^{2/3} & r \le R_{\max} \quad \text{(3-14a)} \\ V_{Rch} = V_{\max} (R_{\max} / r)^{2/3} & r > R_{\max} \quad \text{(3-14b)} \end{cases}$$

This wind-field model is more actual and reasonable, but in the area far away from typhoon center wind speeds still tends to be higher than measured wind speed data (as shown in Fig.3-5).

Based on the abovementioned analysis, a more realistic wind-field model is further proposed as follows:

$$\begin{cases} V_{Ch} = V_{\max} \dfrac{r}{R_{\max}} \cdot \dfrac{3}{(R_{\max} / r)^{1/2} + r / R_{\max} + (r / R_{\max})^{5/2}} & r \le R_{\max} \quad \text{(3-15a)} \end{cases}$$

$$V_{Ch} = V_{\max} \frac{R_{\max}}{r} \cdot \frac{3}{(r/R_{\max})^{1/2} + R_{\max}/r + (R_{\max}/r)^{5/2}} \qquad r > R_{\max} \qquad (3\text{-}15b)$$

Expression (7a) and (7b) can be integrated into one equation as follows:

$$V_{Ch} = V_{\max} \frac{3(R_{\max} r)^{3/2}}{R_{\max}^3 + r^3 + (R_{\max} r)^{3/2}} \qquad (3\text{-}16)$$

As shown in Fig.3-5, the profile of this model wind speeds locates between these of Rankine and Jelesnianski model wind speeds, and decays far away at a reasonable rate.

Hence, referring to Fig.3-7, at any location O(r,θ) within a stationary typhoon region, the wind speed can be calculated from the following equation (3-17a)

$$V_{Ch}(r,\theta) = V_{Ch} = V_{\max} \frac{3(R_{\max} r)^{3/2}}{R_{\max}^3 + r^3 + (R_{\max} r)^{3/2}} \qquad (3\text{-}17a)$$

and its wind direction with an inward angle α (around 20) from its isobar tangent can be calculated as:

$$D_S(r,\theta) = \theta - 90° - \alpha \qquad (3\text{-}17b)$$

Finally, the wind-field of stationary typhoon can be determined by equations (3-17a) and (3-17b)

3-3-2 Wind-field due to the movement of typhoon

Wind-field due to the movement of typhoon (moving wind-field) is a large-scale wind-field relating to environmental atmosphere circulation. The magnitudes of the speed of moving wind-field are different from site to site within typhoon area. Several moving wind-field models of typhoon have been developed by researchers in the field, and the main of them are as follows:

Miyazaki model: $V_{SM} = V_S \exp(-\pi r/500)$ (3-18)

Jelesnianski model: $V_{SJ} = V_S[R_{\max} r/(R_{\max}{}^2 + r^2)]$ (3-19)

Uenomuhu model: $V_{ST} = V_S \exp\left(-\frac{\pi}{4}\frac{|r - R_{\max}|}{R_{\max}}\right)$ (3-20)

where, V_S is forward speed of typhoon, r and $R_{\max}$ are the same meaning with the foresaid.

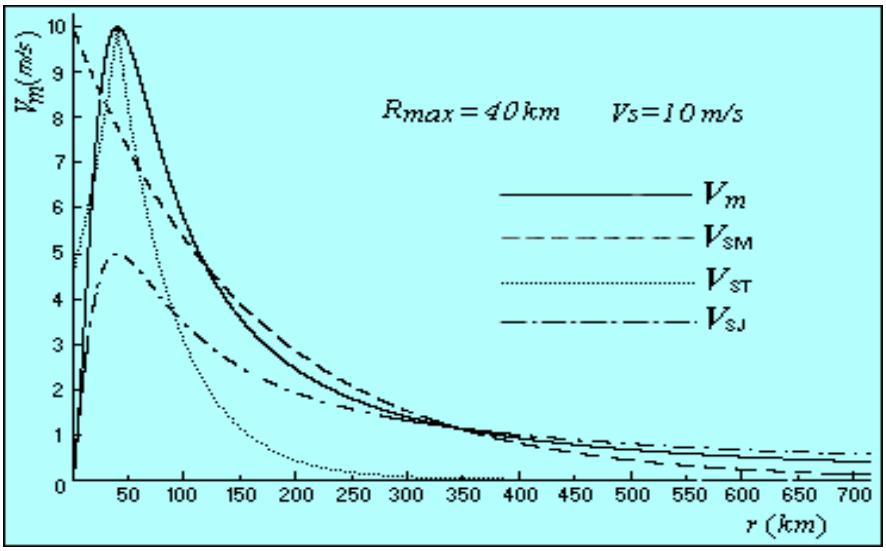


Fig.3-6 Some moving wind speed profiles

As shown in Fig.3-6, in V_{SM} curve, moving wind speed is maximum at typhoon center and equal to typhoon moving speed, and then, is reduced promptly, $0.53V_S$ at maximum radius, 4.3% of V_S at the distance 500km to center. In V_{SJ} curve, moving wind speed is zero at typhoon center, and achieves the maximum that is equal to the half of V_S at maximum radius, and then, decays very slow. In V_{ST} curve, at typhoon center, moving wind speed is $0.456V_S$, and achieves maximum value V_S at maximum radius, then decays promptly. So, these three moving wind-field models are not so reasonable, and with some problems somewhat. In view of this condition, at any location O(r,θ), a new model of wind speed of moving wind-field is proposed as follows:

$$V_m(r,\theta) = V_S \frac{3(rR_{\max})^{3/2}}{R_{\max}^3 + r^3 + (rR_{\max})^{3/2}}$$

(3-21a)

As shown in Fig.3-6, in V_m curve, moving wind speed is zero at typhoon center and, reaches maximum value (equal to V_s) at $r = R$, and then, decays at a moderate rate. So, this model is more reasonable than the others abovementioned.

The wind direction of moving wind-field at any site O(r,θ) within typhoon's region is always the same with the typhoon's forward direction. If the typhoon's forward direction angle is β, then:

$$D_m(r,\theta) = \beta \qquad (3\text{-}21b)$$

Finally, the wind-field due to the movement of typhoon can be determined by equations (3-21a) and (3-21b).

3-3-3 Wind-field model of typhoon

As shown in Fig.3-7, at any location O(r,θ) in typhoon region, providing that the wind vector of stationary typhoon is $\overrightarrow{OA}$, its speed and direction are determined by Equations (3-17a) and (3-17b) respectively, and the wind vector due to typhoon's movement is $\overrightarrow{AB}$, its speed and direction are determined by Equations (3-21a) and (3-21b) respectively, then the real resultant wind vector ($\overrightarrow{OB}$) thereafter can be expressed as:

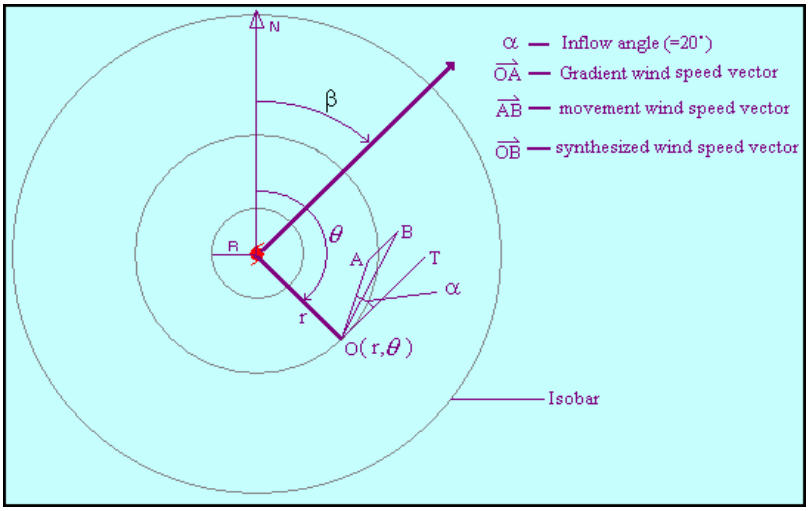


Fig.3-7 Wind speed synthesis

$$\overrightarrow{OB} = \overrightarrow{OA} + \overrightarrow{AB} \tag{3-23}$$

Hence, the wind speed $V(r,\theta)$ of $\overrightarrow{OB}$ can be calculated as follows:

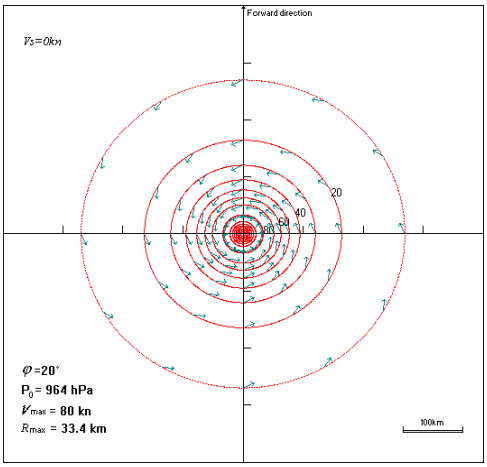
$$V(r,\theta) = \frac{3(rR_{\max})^{3/2}}{R_{\max}^3 + r^3 + (rR_{\max})^{3/2}} \sqrt{V_{\max}^2 + V_S^2 + 2V_{\max}V_S \sin(\theta - \alpha - \beta)} \tag{3-24}$$

and its direction $D(r,\theta)$ of $\overrightarrow{OB}$ can be calculated as follows:

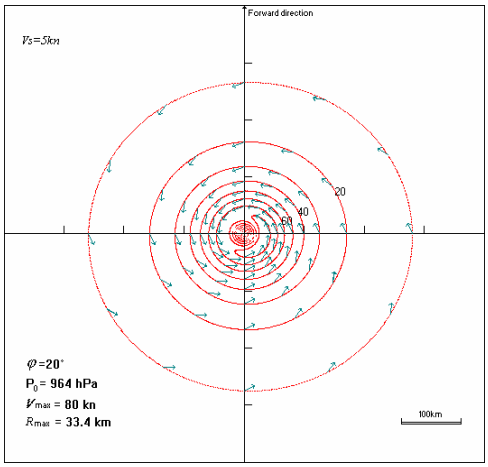
$$\tau(r,\theta) = \tan^{-1}\left(\frac{V_S \sin\beta - V_{\max}\cos(\theta-\alpha)}{V_S \cos\beta + V_{\max}\sin(\theta-\alpha)}\right) \tag{3-25}$$

Finally, the wind-field of typhoon can be determined by Eq.(3-24) and Eq.(3-25).

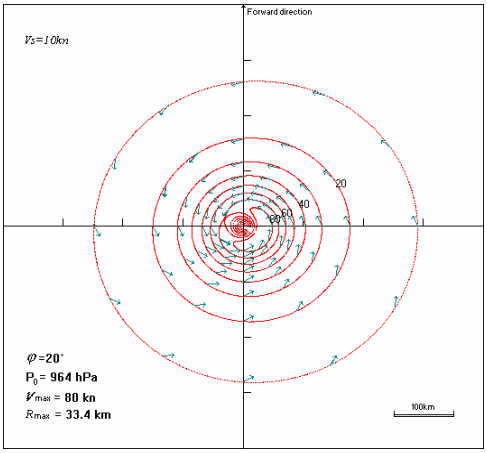
(a)


Forward direction
Vs=0kn
20
40
60
80
φ=20°
P0= 964 hPa
Vmax = 80 kn
Rmax = 33.4 km
100km

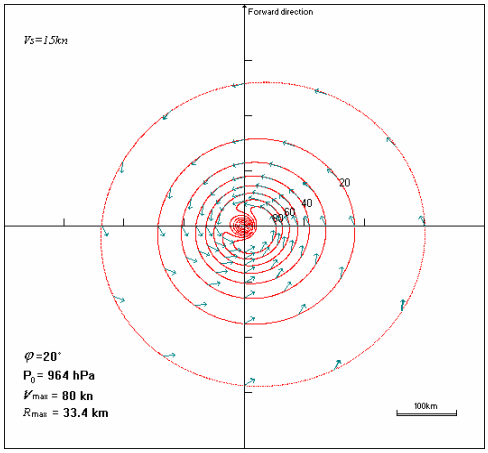
(b)


Forward direction
Vs=5kn
20
40
60
80
φ=20°
P0= 964 hPa
Vmax = 80 kn
Rmax = 33.4 km
100km

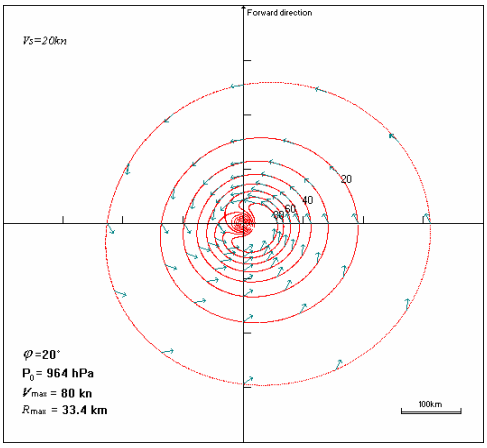
(c)


Forward direction
Vs=10kn
20
40
60
80
φ=20°
P0= 964 hPa
Vmax = 80 kn
Rmax = 33.4 km
100km

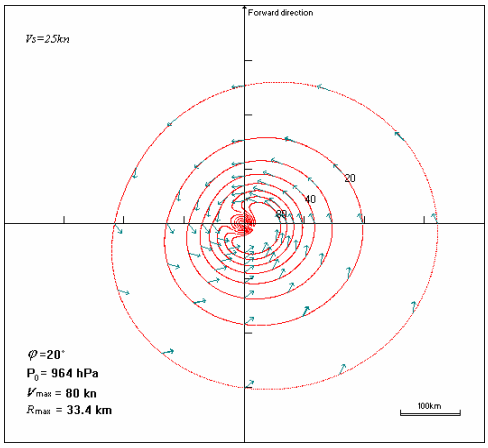
(d)


Forward direction
Vs=15kn
20
40
60
80
φ=20°
P0= 964 hPa
Vmax = 80 kn
Rmax = 33.4 km
100km

(e)


Forward direction
Vs=20kn
20
40
60
80
φ=20°
P0= 964 hPa
Vmax = 80 kn
Rmax = 33.4 km
100km

(f)


Forward direction
Vs=25kn
20
40
60
80
φ=20°
P0= 964 hPa
Vmax = 80 kn
Rmax = 33.4 km
100km

(g)

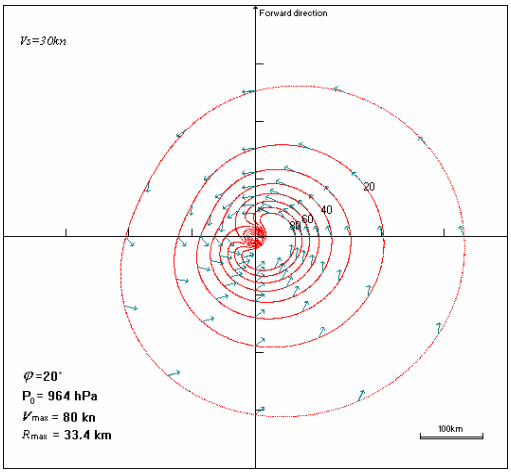


Fig.3-8 Examples of wind-fields

Fig.3-8(a)~(g) are examples of wind-fields of typhoons with the same characteristics but different forward speeds. From these series of images, the following are learned:

1) The wind-field distribution is circular symmetric as shown in image (a) if typhoon's forward speed is zero.

2) Owing to the effects of typhoon movement being added to the symmetric wind-field caused by pressure gradient, the wind-field becomes asymmetric. Moreover, the degree of asymmetry of wind-field distribution gradually gets more and more distinct with the forward speed increasing, just as shown in images (b)~(g) in Fig.3-8. Namely, when a typhoon moves slowly, considerably wide area of strong winds are located in the right front quadrant as well as in the right rear quadrant, while strong wind area gradually shifts towards the rear as the forward speed increases. That is to say, in the former case the area of strong winds is wider in the right semi-circle than in the left semi-circle, while in the later case it is wider in the rear semi-circle than in the front semi-circle. In a word, the winds in the right of forward direction are stronger than those in the left and, the winds in the rear right quadrant are strongest.

By verifying such wind-field model through observed data, we found that its average of the absolute values of the relative error of prediction results is 13.5%, and such prediction error rate can be permitted and accepted for our purpose.

3-4 Wave-field model of typhoon

The wave model, generally adopted by the weather agencies, such as WAM, hindcasts the typhoon wave not very well due to the swift change of wind velocity both in space and time. The coast engineers like to use hindcasting techniques based on SMB principles to hindcast typhoon waves, such as Ijima, Tang and Bretschneider's. Spectral models have been shown to provide accurate estimates of typhoon wave condition when driven by good wind-field information (Ward, Evans and Pompa 1977; Corson el at. 1982; Cardone 1992; Hubertz 1992; Nai, 2001).

In general, parametric prediction methods tend to work well applied to phenomena that have little or no dependence on previous states (i.e. systems with little or no memory). Waves depend not only on the present wind-field but also on earlier wind-field, pre-existing waves from other wind systems, and in general on the entire wave-generation process over the last 12 to 24 hours.

For our intention of developing a simulation system to avoid typhoon's strike at sea, and there are only past typhoon track data available for use, the basic characteristics of typhoon wind and wave fields are requested to simulate only, because this process will not influence the training effect largely. Owing to this, the empirical formulae are applied (Fang, 2003).

Fang Zhong-sheng processed the data associated with typhoons during years of 1974~1996 from "Ocean Data Buoy Stations of Japan Meteorological Agency" by using statistical method. Firstly, the data is classified into several classes according to typhoon central pressure P_0, the distance r from observation point (Buoy) to the typhoon center and the azimuth angle ψ from the direction of movement of the typhoon center, and then, the mean values of wind speed, wave height and period in each class are calculated. In order to derive the empirical relationship among the significant wave height, wind speed, and other parameters under typhoons, the regression analysis and dimensionless analysis are carried out

to deal with two sets of severest data composed from several classes of the classified data respectively. Finally, two empirical formulae are yielded by dimensionless analysis, and used to conveniently predict significant wave height due to typhoons by using the wind speed V_{10} and the radial distance r. The two empirical formulae are as follows:

$$H_S = 2.96\times10^{-3}V_{10}^{1.44}r^{0.279} \qquad if \quad P_0 \leq 955hpa \qquad (3\text{-}26)$$

$$H_S = 2.74\times10^{-3}V_{10}^{1.39}r^{0.305} \qquad if \quad P_0 > 955hpa \qquad (3\text{-}27)$$

Where, H_S ------ significant wave height (m),

V_{10} ------ wind speed at 10-meter high level (m/s),

r ------ radial distance from typhoon center (m).

Periods of significant waves (T_S) can be calculated as follows (Yang, 2000):

$$T_S = 3.83\sqrt{H_S} \quad \text{(Sec)} \qquad (3\text{-}28)$$

Eq.(3-28) was originally yielded by Bretschneider (1957) based on statistical analysis of large numbers of observed data, so its accuracy can meet our requirement.

The wave directions in typhoon region are very complicated, for simplicity, we consider that the wave direction is same with the direction of the corresponding wind roughly.

The value of V_{10} can be calculated according to Eq.(3-24), and then, the significant wave heights H_S can be predicted according to Eq.(3-26) or Eq.(3-27). The average of the absolute value of the relative error of predicted results is 0. 15 by using whether Eq.(3-26) or Eq.(3-27). By verifying it through other observed wave data, both equations can be used to predict typhoon wave height rationally on the whole.

Provided that the parameters of typhoon are the same as those in Fig.3-8 (d), the

significant wave filed is shown as Fig.3-9.

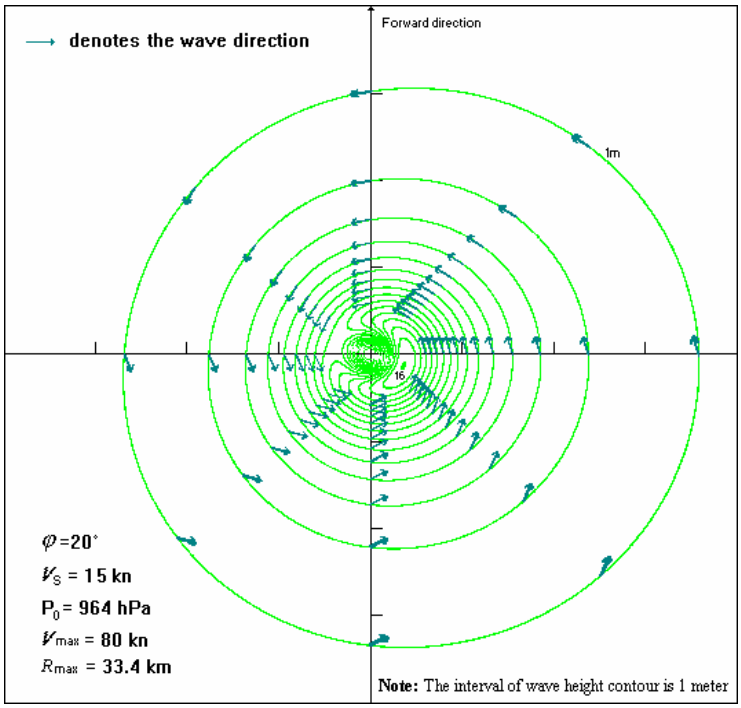


Fig.3-9 Wave-field in typhoon

It is clear that the wave height is the greatest in the right rear quadrant and the smallest in the left front quadrant, while the great difference is not found between the wave height in the right front quadrant and that in the left rear quadrant. Comparing the right semi-circle of the typhoon with the left semi-circle, we may consider the following items as the causes of such distribution of waves:

1) As is known universally, winds blow with greater velocity in the right (dangerous) semi-circle than in the left (navigable) semi-circle.

2) In the right semi-circle waves move in a direction near to that of the typhoon's movement; therefore, the fetch and duration of winds become longer than those in the left semi-circle.

3) Generally speaking, the wind velocity at a point on the sea surface increases more and more as the typhoon approaches, while it decreases less and less after the typhoon center passed there. Accordingly, the mean wind velocity taken for a certain length of duration is greater when it is located in the rear semi-circle than when it is located in the front semi-circle, even if the distance from the point to the typhoon center is equal in both cases.

4) In the rear semi-circle there exist remarkable swells which are originated in the front semi-circle and were left behind. Consequently, wind waves generated in the rear semi-circle are superposed on and raised by these swells. Particularly, in the rear region not so distant from the typhoon center, mountainous and pyramidal waves are apt to be raised when the typhoon passed by with a speed beyond a certain level.

5) The rate of decrease of the wave height comes down distinctly with the distance from the typhoon center. Moreover, strictly speaking, the rate of decrease of the wave height differs among quadrants in a typhoon.

The form of Fig.3-9 is similar to the wave field of hurricane developed by Bretschneider in 1957 as shown in Fig.3-10. The wave-field model of Bretschneider has been adopted by “Shore Protection Handbook” of U.S.A. (Traffic Ministry of P.R.C., 2001).

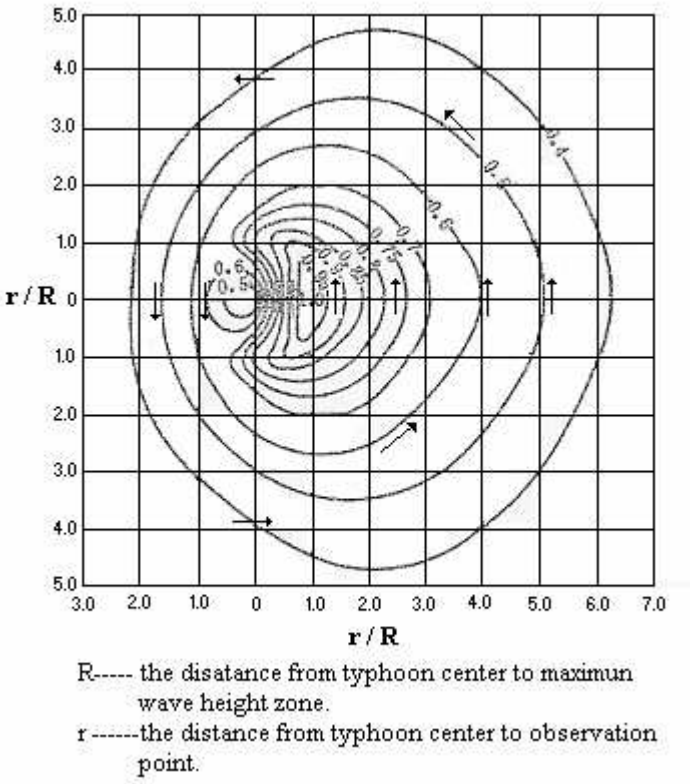


Fig.3-10 Wave-field by Bretschneider

3-5 Experiment and discussion

We applied No.14 typhoon formed on 17th August of 1997 to these wind-field model and wave field model. Fig.3-11 is an example screen which shows wind speed and wave height at some locations in the typhoon region. Actually, in our software, the information of wind and wave at any location within typhoon region can be shown to mariners at the right down corner of the computer screen as shown in Fig.3-11 while the mouse is moving. It is very intuitional and convenient for mariners to take avoiding actions.

In this chapter, we proposed a simple parametric model for calculating wind speed & direction and wave height & direction at any location around the typhoon at sea. The proposed

wind-field model is asymmetric, and consists of a circular symmetric wind-field caused by the pressure gradient of stationary typhoon and a moving wind-field caused by the movement of typhoon. An empirical method with the regression analysis and dimensionless analysis was applied to produce the wave-field of typhoon by using only wind speed and radial distance. By verifying this model through observed data, we found that it is accurate enough to develop the simulation system for training students and seafarers so as to take appropriate actions while facing a typhoon at sea.

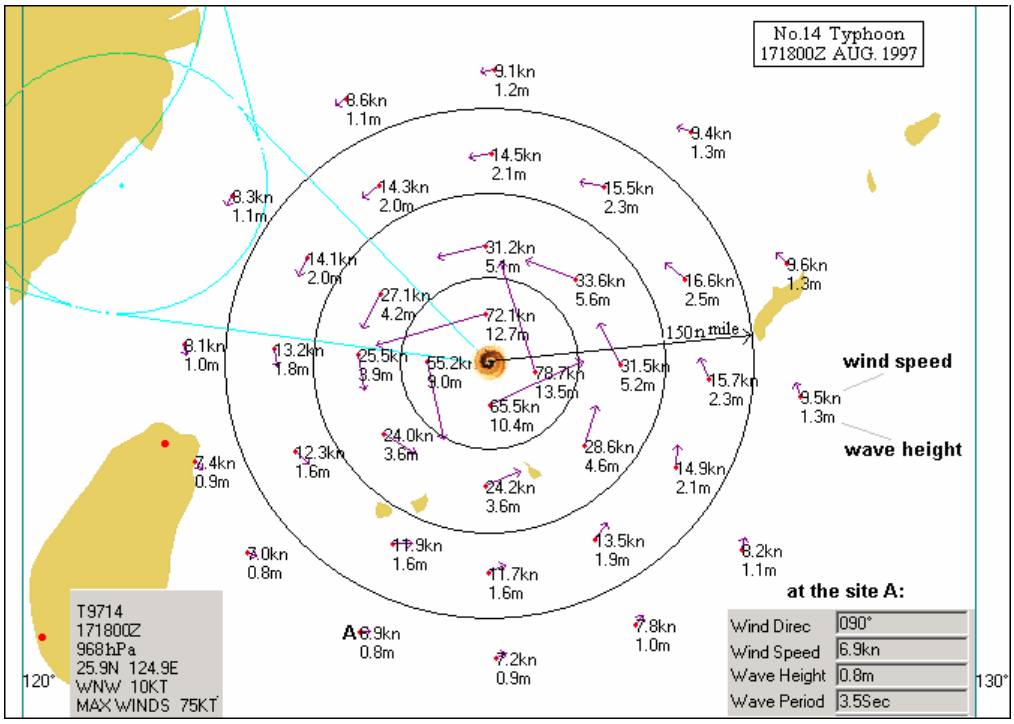


Fig.3-11 A captured screen frame of winds and waves within the typhoon region

Chapter 4

Evaluation of Navigation Safety

The foresaid chapters have developed the wind-field model, the wave-field model and the track prediction model of typhoon, whereupon it becomes possible that ship operators are aware of the weather condition (mainly, strong wind and rough sea) around typhoon and the situation that they are facing, and take some actions on preventing typhoon's strike. But they do not know whether those actions are appropriate, effective, and safe enough. In view of this, we shall carry out an evaluation of their performances in order to advance their abilities through our simulation training.

Ship operators shall take grip with the extent of navigational safety, especially in facing with a threat of typhoon. It is necessary to evaluate the degree of navigation safety while ship is navigating at waters near a typhoon, and Fig.4-1 shows the evaluation process simply (Kong Gil-Young, 2002).

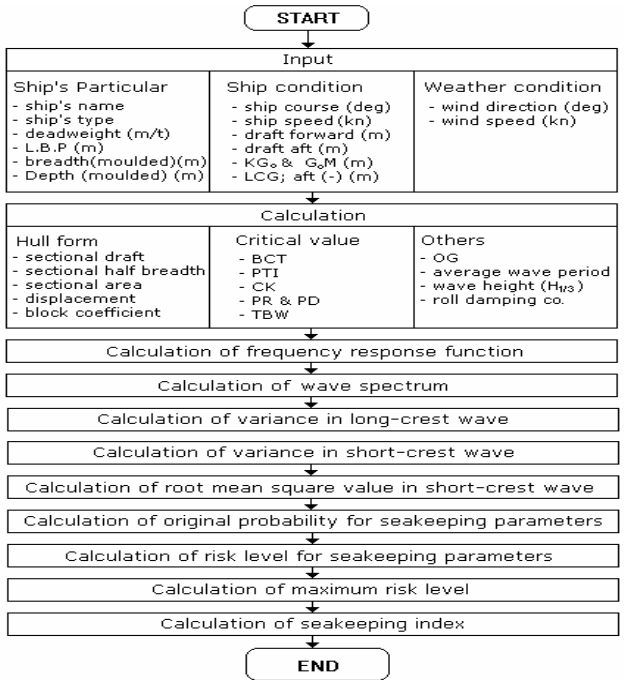


Fig.4-1 Flow Chart of Navigation Safety Evaluation

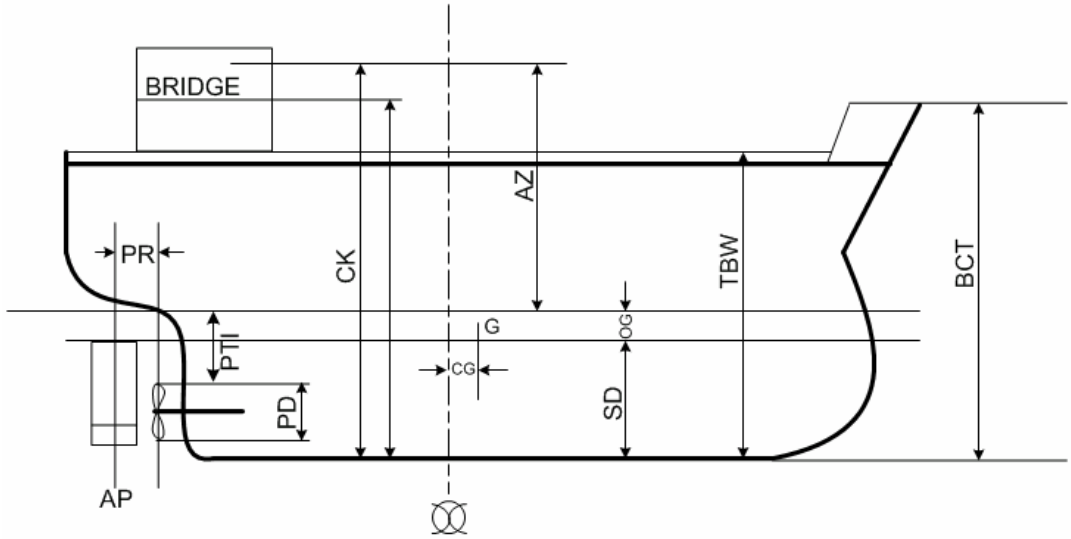


Fig.4-2 Sketch of critical parameters

In this module of navigation safety evaluation, there needs inputting three kinds of data as the following: the ship's particular, ship condition, weather condition (chiefly winds and waves calculated from the wind-field and wave-field above-mentioned.), and then calculate the hull form and critical values as shown in Fig.4-2, finally, make a series of calculations of frequency response function, wave spectrum, variances in long-crest and short-crest waves, root mean square value in short-crest wave, original probability for seakeeping parameters, risk level for seakeeping parameters, maximum risk level and the seakeeping performance index (SPI). Consequently, we can judge the navigational safety according to the SPI, that is, if the SPI exceeds 1, then the ship is in danger, or vice versa.

4.1 Ship motions in waves

In order to analyze the response values of ship motions in irregular waves, it is necessary to learn the response function of ship motions in regular waves above all. For mastering the ship's forces from waves and measuring the motion and forces in regular waves, the strip theory is mainly applied.

The strip theory which assumes two dimension flow in transverse planes at each section

of the ship holds good only if the wavelength is small compared with the ship length. Firstly, by cutting the body into several strips and calculating the two dimensional fluid forces employed on each strip, the fluid forces employed on three-dimensional body can be calculated. The research is based on space coordinates with uniform motion and, calculates the response function of body by using systematized OSM (Ordinary Strip Method).

Moreover, the coordinates of ship motions in waves are as follow:

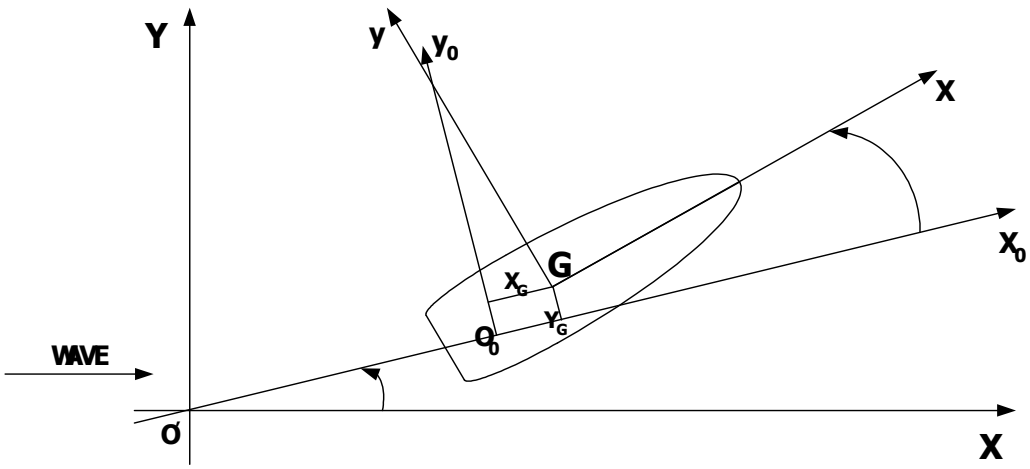
O'-XYZ : stationary space coordinates,

$O_0 - x_0y_0z_0$: space coordinates with uniform motion,

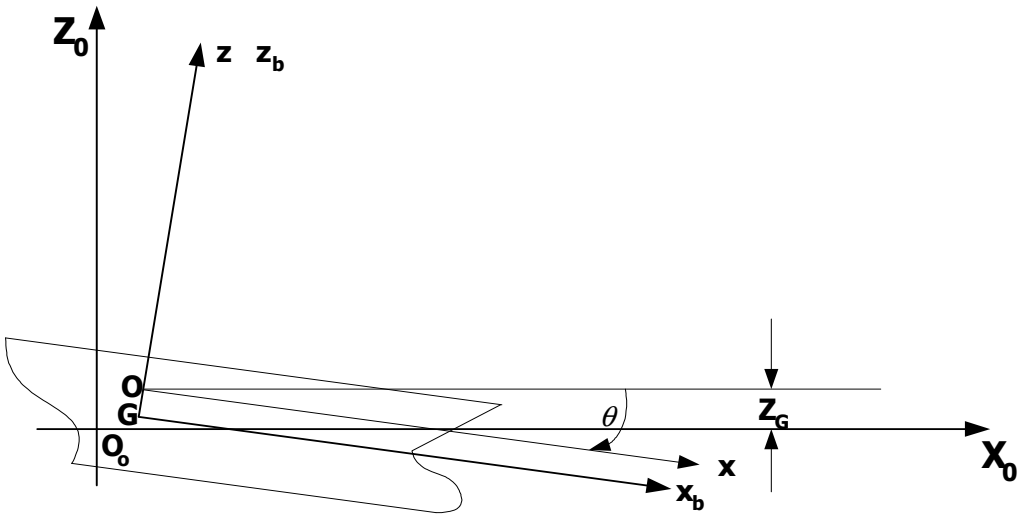
O - xyz : body fix coordinates originated at stationary free surface,

G- $x_by_bz_b$: body fix coordinates originated at the gravity center of ship.

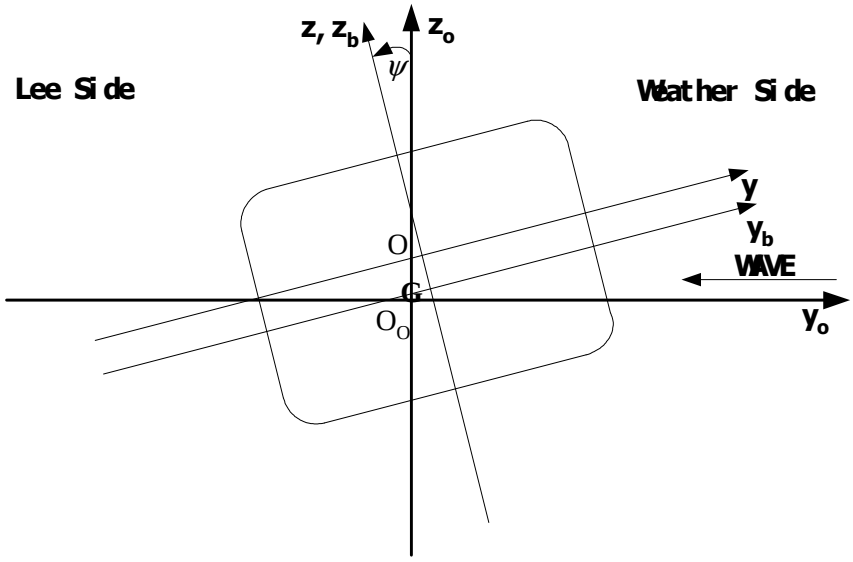
Providing that the ship is sailing with a velocity *V* and a heading that is inclined at an angle *x* to the direction of wave traveling and, in the vicinity of the average position O_0, the gravity center *G* act an oscillation with a small amplitude along the directions of axes and around the axes. Phase angle is based up on the time when the wave crest is on the middle of the central line of the body, and its forward direction is marked using "+".



(a)



(b)



(c)

Fig.4-3 Coordinate System

4.2 Ocean wave spectrum

We may consider that the irregular sea state is superposed through many small waves with different values of amplitudes, directions of wave traveling, frequencies and phases. Against an instant time when these small waves superpose to cause the irregular waves, the change of wave heights has the form of Gauss distribution, and its extreme value has the form of Rayleigh distribution. With respect to such irregular ocean wave, we may grasp its characteristics by using spectrum analysis. During developing in this research, ocean wave spectrum with long-crest have been adopted by International Ship Structure Congress is employed, and the format of this spectrum is as follows:

$$S_{\xi}(\omega) = \frac{1}{2\pi} 0.11 (H_{1/3})^2 T_0 (\frac{T_0}{2\pi}\omega)^{-5} exo\left\{ -0.44 (\frac{T_0 \omega}{2\pi})^{-4} \right\} \qquad (4\text{-}1)$$

where, T_0 : average wave period,

$H_{1/3}$: significant wave height,

ω : wave angular frequency.

ω

Additionally, in order to reflect the actual sea state precisely, on the consideration of directional spectrum of component waves in Eq.(4-1), the spectrum can be expressed by using the irregular wave caused by short-crest wave as follows:

$$S_{\xi}(\omega, \theta) = \frac{2}{\pi} S_{\xi}(\omega) \cos^2 \theta \qquad (-\pi/2 \leq \theta \leq \pi/2)$$

$$= 0 \qquad \text{(otherwise)}$$

where, θ is the angle between the average direction of wave traveling and that of a component wave.

When a ship is navigating with encounter angle x and speed V, between the encounter

frequency (ω_e) and wave frequency (ω), there exists the relation: $\omega_e = \omega(1-\frac{\omega V}{g}\cos x)$, the wave spectrum $S_\xi(\omega,\theta)$ expressed by ω can be transformed into the wave spectrum $S_\xi(\omega_e,\theta)$ expressed by ω_e according to the following expression:

$$\frac{d\omega_e}{dw} = 1-\frac{2\omega V}{g}\cos x$$
$$d\omega_e = (1-\frac{2\omega V}{g}\cos x)d\omega \tag{4-3}$$

The areas under wave spectrums with the wave frequency (ω) and the encounter frequency (ω_e) respectively shall be same, and such relation can be expressed as the following:

$$S_\xi(\omega,\theta)d\omega = S_\xi(\omega_e,\theta)d\omega_e$$
$$S_\xi(\omega_e,\theta) = S_\xi(\omega,\theta)\frac{d\omega}{d\omega_e} \tag{4-4}$$

Therefore, the following expression can be yielded:

$$S_\xi(\omega_e,\theta) = \frac{S_\xi(\omega,\theta)}{1-(2\omega V/g)\cos x} \tag{4-5}$$

4-3 Evaluated factors of seakeeping performance

In order to evaluate the degree of navigational safety of a ship with special consideration to the people on board, ship's body and cargo on board, which is navigating at rough and irregular sea, the following factors are considered for the evaluation (Kong Gil-Young, 2002):

(1) Deck wetness
(2) Propeller racing
(3) Slamming
(4) Rolling
(5) Vertical acceleration
(6) Lateral acceleration

Once each of evaluated factors exceeds the given critical value and its probability exceeds the given critical occurrence probability, a ship navigating at rough sea may loss its control and becomes dangerous. The systemic combination of those evaluated factors has the form of serial combination. If the probability of occurrence of just one factor exceeds the critical probability, then the overall seakeeping performance fails and the ship may be endangered.

In this study, model ship is passenger ship, in order to develop the database of the degree of danger, and all evaluated factors and their critical occurrence probability are listed in the following Table 4-1:

Table 4-1 The critical values and the critical occurrence probabilities

Evaluated factors	Critical values	Critical occurrence probabilities
Deck wetness	Effective freeboard at F.P.	2×10^{-2}
Propeller racing	1/3 of the top blade of propeller is exposed	10^{-1}
Slamming	At 8 $\frac{1}{2}$ of S.S. when bottom exposes and wave inrushes, the relative acceleration exceeds critical acceleration (Threshold velocity), Threshold velocity=0.09 $\sqrt{gL}$ (g=9.80m/sec^2)	5×10^{-2}
Rolling	At bulwark top of weather side on body's center, the condition that seawater inrushes is critical condition. On static water, the altitude from waterline to bulwark top.	10^{-3}
Lateral acceleration	The lateral acceleration at the bridge exceeds 0.38g	10^{-3}
Vertical acceleration	The vertical acceleration at the bridge exceeds 0.56g	10^{-3}

4.4 Variance of navigation safety evaluated factors

When a ship is navigating at sea which has single wave distance and irregularity and is keeping constant course (χ) and speed (V), spectrum $S_{x_i}(\omega_e,\chi)$ is as follows if we put $X_i(t)$ (the random process of evaluation factors calculated from the response function of ship's motion according to OSM) as $H_{x_i}(\omega_e,V,\chi-\theta)$:

$$S_{x_i}(\omega_e,\chi)=\int_{-\pi/2}^{\pi/2}\left|H_{x_i}(\omega_e,V,\chi-\theta)\right|^2 S_\zeta(\omega_e,\chi)d\theta \tag{4-6}$$

Variance $\sigma_{x_i}^2$ of evaluated factors is as the following:

$$\sigma_{x_i}^2(\chi,V,S)=\int_0^\infty S_{x_i}(\omega_e,\chi)d\omega_e \tag{4-7}$$

The variables that let the variance in formula (4-7) change are the meeting angle of the ship and wave, the ship's speed and the condition of the sea state (S). While calculating the value of variance with consideration to components of directional waves, we may approximately apply the relation between variances (σ_S) of short-crested waves and that (σ_L) of long-crested waves as follows:

$$\left.\begin{aligned}
\sigma_S^2(0^\circ)&=\frac{1}{9}\left\{4\sigma_L^2(0^\circ)+3\sigma_L^2(30^\circ)+2\sigma_L^2(60^\circ)\right\}\\
\sigma_S^2(30^\circ)&=\frac{1}{9}\left\{1.5\sigma_L^2(0^\circ)+5\sigma_L^2(30^\circ)+1.5\sigma_L^2(60^\circ)+\sigma_L^2(90^\circ)\right\}\\
\sigma_S^2(60^\circ)&=\frac{1}{9}\left\{\sigma_L^2(0^\circ)+1.5\sigma_L^2(30^\circ)+4\sigma_L^2(60^\circ)+1.5\sigma_L^2(90^\circ)+\sigma_L^2(120^\circ)\right\}\\
\sigma_S^2(90^\circ)&=\frac{1}{9}\left\{\sigma_L^2(30^\circ)+1.5\sigma_L^2(60^\circ)+4\sigma_L^2(90^\circ)+1.5\sigma_L^2(120^\circ)+\sigma_L^2(150^\circ)\right\}\\
\sigma_S^2(120^\circ)&=\frac{1}{9}\left\{\sigma_L^2(60^\circ)+1.5\sigma_L^2(90^\circ)+4\sigma_L^2(120^\circ)+1.5\sigma_L^2(150^\circ)+\sigma_L^2(180^\circ)\right\}\\
\sigma_S^2(150^\circ)&=\frac{1}{9}\left\{\sigma_L^2(90^\circ)+1.5\sigma_L^2(120^\circ)+5\sigma_L^2(150^\circ)+1.5\sigma_L^2(180^\circ)\right\}\\
\sigma_S^2(180^\circ)&=\frac{1}{9}\left\{2\sigma_L^2(120^\circ)+3\sigma_L^2(150^\circ)+4\sigma_L^2(180^\circ)\right\}
\end{aligned}\right\} \tag{4-8}$$

Moreover, for any evaluated factor, when the spectrum is same with Eq.(4-6), the random process $X_i(t)$ is calculated as follows:

$$X_i(t) = \int_0^{\infty} \cos(\omega_e t + \psi_i)\sqrt{2S_{x_i}(\omega_e, x)d\omega_e} \tag{4-9}$$

where, $\psi_i = \varepsilon_i(\omega) + \gamma_i$

γ_i = phase angle distributed uniformly between 0 and 2π

4-4-1 Deck wetness

At the position F.P. on the central line of body, the displacement can be expressed as the following:

$$D(t) = \xi_w(t) - [Z(t) - l_D \cdot \theta(t)] = D_0(t)\cos(\omega_e t + \varepsilon_D) \tag{4-10}$$

while, $D_0(t) = \sqrt{D_c^2 + D_s^2}$

$$D_c = \xi_a \cos(k \cdot l_D \cdot \cos x) - Z_a \cdot \cos\varepsilon_z + l_D \cdot \theta_a \cdot \cos\varepsilon_\theta$$

$$D_s = -\xi_a \sin(k \cdot l_D \cdot \cos x) - Z_a \cdot \sin\varepsilon_z + l_D \cdot \theta_a \cdot \cos\varepsilon_\theta$$

$$\varepsilon_D = \tan^{-1}\left(\frac{D_s}{D_c}\right)$$

$l_D = \frac{L}{2} - Mid.G$, Mid.G: the direction of ship's heading (+)

$$\omega_e = \omega - \left(\frac{V_s}{g}\right) \cdot \omega^2 \cdot \cos x$$

Then, the response function $H_D(t)$ of the relative displacement $D(t)$ at the bow can be expressed as follows:

$$H_D(t) = \frac{D(t)}{\xi_a} = \sqrt{D_a^2 + D_b^2} \cdot \cos(\omega_e t + \varepsilon_D) \tag{4-11}$$

while, $D_a = \cos(k \cdot l_D \cdot \cos x) - \left(\frac{Z_a}{\xi_a}\right) \cdot \cos\varepsilon_z + k \cdot l_D \cdot \left[\frac{\theta_a}{(k \cdot \xi_a)} \cdot \cos\varepsilon_\theta\right]$

$$= \cos(k \cdot l_D \cdot \cos x) - H_z \cdot \cos\varepsilon_z + k \cdot l_D \cdot H_\theta \cos\varepsilon_\theta$$

$$D_b = -\sin(k \cdot l_D \cdot \cos x) - H_z \cdot \sin\varepsilon_z + k \cdot l_D \cdot H_\theta \sin\varepsilon_\theta$$

$$\varepsilon_D = \tan^{-1}\left(\frac{D_b}{D_a}\right), \quad H_\theta = \frac{\theta_a}{k \cdot \xi_a} \quad , \quad H_z = \left(\frac{Z_a}{\xi a}\right)$$

If the frequency response function is expresses as $H_D(\omega_e)$, the spectrum $S_D(\omega_e)$ of $D(t)$ is as follows:

$$S_D(\omega_e) = \int_{-\pi/2}^{\pi/2} \left|H_D(\omega_e)\right|^2 \cdot S_\xi(\omega_e, \theta) d\theta \tag{4-12}$$

The variance σ_D^2 of $D(t)$ is as follows:

$$\sigma_D^2 = \int_0^\infty S_D(\omega_e) d\omega_e \tag{4-13}$$

4-4-2 Propeller racing

The body's relative displacement $R(t)$ at the position of propeller on the central line is expressed as the following equation:

$$R(t) = \xi_w(t) - [Z(t) - l_D \cdot \theta(t)] = R_0(t)\cos(\omega_e t + \varepsilon_R) \tag{4-14}$$

while, $R_0(t) = \sqrt{R_c^2 + R_s^2}$

$$R_c = \xi_a \cos(k \cdot l_p \cdot \cos x) - Z_a \cdot \cos\varepsilon_z + l_p \cdot \theta_a \cdot \cos\varepsilon_\theta$$

$$R_s = -\xi_a \sin(k \cdot l_p \cdot \cos x) - Z_a \cdot \sin\varepsilon_z + l_D \cdot \theta_a \cdot \cos\varepsilon_\theta$$

$$\varepsilon_R = \tan^{-1}\left(\frac{R_s}{R_c}\right)$$

$$l_P = -(\frac{L}{2} - Mid.G)$$, Mid.G: the direction of ship's heading (+)

Then, the response function $H_R(t)$ of wave amplitude is as follows:

$$H_R(t) = \frac{R(t)}{\xi_a} = \sqrt{R_a^2 + R_b^2} \cdot \cos(\omega_e t, \varepsilon_R) \tag{4-15}$$

while, $$R_a = \cos(k \cdot l_P \cdot \cos x) - \left(\frac{Z_a}{\xi_a}\right) \cdot \cos\varepsilon_z + k \cdot l_P \cdot \left[\frac{\theta_a}{(k \cdot \xi_a)} \cdot \cos\varepsilon_\theta\right]$$

$$= \cos(k \cdot l_P \cdot \cos x) - H_z \cdot \cos\varepsilon_z + k \cdot l_P \cdot H_\theta \cos\varepsilon_\theta$$

$$R_b = -\sin(k \cdot l_P \cdot \cos x) - H_z \cdot \sin\varepsilon_z + k \cdot l_P \cdot H_\theta \sin\varepsilon_\theta$$

$$\varepsilon_R = \tan^{-1}\left(\frac{R_b}{R_a}\right)$$

If the frequency response function of $R(t)$ is $H_R(\omega_e)$, the spectrum $S_R(\omega_e)$ of $R(t)$ is

$$S_R(\omega_e) = \int_{-\pi/2}^{\pi/2} \left|H_R(\omega_e)\right|^2 \cdot S_\xi(\omega_e, \theta) d\theta \tag{4-16}$$

and the variance σ_R^2 of $R(t)$ is as the following equation:

$$\sigma_R^2 = \int_0^\infty S_R(\omega_e) d\omega_e \tag{4-17}$$

4-4-3 Rolling

At the middle of ship's body, the change $L(t)$ of the relative water level on shipboard side can be expressed as the following equation:

$$L(t) = \xi_w(t) - [Z(t) - l_G \cdot \theta(t)] = L_0(t)\cos(\omega_e t + \varepsilon_L) \tag{4-18}$$

while,

$$L_0(t) = \sqrt{L_c^2 + L_s^2}$$

$$L_c = \xi_a \cos(k \cdot l_G \cdot \cos x - k \cdot b \cdot \sin x) - Z_a \cdot \cos\varepsilon_z + l_G \cdot \theta_a \cdot \cos\varepsilon_\theta + b \cdot \phi_a \cdot \cos\varepsilon_\phi$$

$$L_s = -\xi_a \sin(k \cdot l_G \cdot \cos x - k \cdot b \cdot \sin x) - Z_a \cdot \sin\varepsilon_z + l_G \cdot \theta_a \cdot \cos\varepsilon_\theta + b \cdot \phi_a \cdot \cos\varepsilon_\phi$$

$$\varepsilon_L = \tan^{-1}(\frac{L_s}{L_c})$$

$l_G = Mid.G)$, Mid.G: the direction of ship's heading (+)

Then, the response function $H_L(t)$ of wave amplitude is as follows:

$$H_L(t) = \frac{L(t)}{\xi_a} = \sqrt{L_a^2 + L_b^2} \cdot \cos(\omega_e t, \varepsilon_L) \tag{4-19}$$

while, $L_a = \cos(k \cdot l_G \cdot \cos x - k \cdot b \cdot \sin x) - H_z \cdot \cos\varepsilon_z$

$$- k \cdot l_G \cdot H_\theta \cdot \cos\varepsilon_\theta + k \cdot b \cdot \cos\varepsilon_\phi$$

$$L_b = -\sin(k \cdot l_G \cdot \cos x - k \cdot b \cdot \sin x) - H_z \cdot \cos\varepsilon_z$$

$$- k \cdot l_G \cdot H_\theta \cdot \sin\varepsilon_\theta + k \cdot b \cdot \sin\varepsilon_\phi$$

$$\varepsilon_L = \tan^{-1}\left(\frac{L_b}{L_a}\right)$$

If the frequency response function of $L(t)$ is $H_L(\omega_e)$, the spectrum $S_L(\omega_e)$ of $L(t)$ is

$$S_L(\omega_e) = \int_{-\pi/2}^{\pi/2} \left|H_L(\omega_e)\right|^2 \cdot S_\xi(\omega_e, \theta) d\theta \tag{4-20}$$

and the variance σ_L^2 of $L(t)$ is as the following equation:

$$\sigma_L^2 = \int_0^\infty S_L(\omega_e) d\omega_e \tag{4-21}$$

4-4-4 Vertical acceleration

At the central line of ship's body, the vertical acceleration $A_v(t)$ can be expressed as the following equation:

$$A_v(t) = Z_G(t) - l_D \cdot \theta(t) = A_{v_0}(t)\cos(\omega_e t + \varepsilon_{A_v}) \tag{4-22}$$

where, $A_{v_0}(t) = \sqrt{A_{v_c}^2 + A_{v_s}^2}$

$$A_{v_c} = -\omega_e^2 (Z_a \cdot \cos\varepsilon_z - l_D \cdot \theta_a \cdot \cos\varepsilon_\theta)$$

$$A_{v_s} = -\omega_e^2 (Z_a \cdot \sin\varepsilon_z - l_D \cdot \theta_a \cdot \sin\varepsilon_\theta)$$

$$\varepsilon_{A_v} = \tan^{-1}\left(\frac{A_{v_s}}{A_{v_c}}\right)$$

then, the response function $H_{Av}(t)$ of wave amplitude is as follows:

$$H_{A_v}(t) = \frac{A_v(t)}{\xi_a \cdot (g/L)} = \sqrt{A_{v_a}^2 + A_{v_b}^2} \cdot \cos(\omega_e t, \varepsilon_{A_v}) \tag{4-23}$$

where, $A_{v_a} = (-\omega_e^2/(g/L))(H_z \cdot \cos\varepsilon_z - k \cdot l_D \cdot H_\theta \cdot \cos\varepsilon_\theta)$

$$A_{v_b} = (-\omega_e^2/(g/L))(H_z \cdot \sin\varepsilon_z - k \cdot l_D \cdot H_\theta \cdot \sin\varepsilon_\theta)$$

$$\varepsilon_{A_v} = \tan^{-1}(A_{v_b}/A_{v_a}) = \tan^{-1}(A_{v_s}/A_{v_c})$$

If the frequency response function of $A_v(t)$ is $H_{Av}(\omega_e)$, the spectrum $S_{Av}(\omega_e)$ of $A_v(t)$ is

$$S_{A_v}(\omega_e) = \int_{-\pi/2}^{\pi/2} \left| H_{A_v}(\omega_e) \cdot (g/L) \right|^2 \cdot S_\xi(\omega_e, \theta) d\theta \tag{4-24}$$

and the variance $\sigma_{A_v}^2$ of $A_v(t)$ is as the following equation:

$$\sigma_{A_v}^2 = \int_0^\infty S_{A_v}(\omega_e) d\omega_e \tag{4-25}$$

4-4-5 Lateral acceleration

The lateral acceleration of ship's body at the point with the distance Z_p above the central line is calculated from the following equation:

$$\begin{aligned} A_T(t) &= Y_G(t) + l_s \cdot \dot{\phi}(t) - l_z \cdot \dot{\phi}(t) + g \cdot \dot{\phi}(t) \\ &= A_{T_o}(t)\cos(\omega_e t + \varepsilon_{A_t}) \end{aligned} \tag{4-26}$$

where, $A_{T_0}(t) = \sqrt{A_{T_c}^2 + A_{T_s}^2}$

$$\begin{aligned} A_{T_c} &= -\omega_e^2 (Y_a \cdot \cos\varepsilon_y - l_s \cdot \phi_a \cdot \cos\varepsilon_\phi \\ &\quad - l_z \cdot \phi_a \cdot \cos\varepsilon_\phi - \left(\frac{g}{\omega_e^2}\right) \cdot \phi_a \cdot \cos\varepsilon_\phi) \end{aligned}$$

$$\begin{aligned} A_{Ts} &= -\omega_e^2 (Y_a \cdot \sin\varepsilon_y - l_s \cdot \phi_a \cdot \sin\varepsilon_\phi \\ &\quad - l_z \cdot \phi_a \cdot \sin\varepsilon_\phi - \left(\frac{g}{\omega_e^2}\right) \cdot \phi_a \cdot \sin\varepsilon_\phi) \end{aligned}$$

$$\varepsilon_{A_T} = \tan^{-1}\left(-\frac{A_{T_s}}{A_{T_c}}\right)$$

then, the response function $H_{Av}(t)$ of wave amplitude is as follows:

$$H_{A_T}(t) = \frac{A_T(t)}{\xi_a \cdot (g/L)} = \sqrt{A_{T_a}^2 + A_{T_b}^2} \cdot \cos(\omega_e t, \varepsilon_{A_T}) \tag{4-27}$$

where, $A_{T_a} = (-\omega_e^2/(g/L))(H_y \cdot \cos\varepsilon_y - k \cdot l_s \cdot H_\phi \cdot \cos\varepsilon_\phi - k \cdot H_\phi \cdot \cos\varepsilon_\phi (l_z + g/\omega_e^2))$

$A_{T_b} = (-\omega_e^2/(g/L))(H_y \cdot \sin\varepsilon_y - k \cdot l_s \cdot H_\phi \cdot \sin\varepsilon_\phi - k \cdot H_\phi \cdot \sin\varepsilon_\phi (l_z + g/\omega_e^2))$

$\varepsilon_{A_t} = \tan^{-1}(A_{T_b} / A_{T_a})$

If the frequency response function of $A_T(t)$ is $H_{A_T}(\omega_e)$, the spectrum $S_{A_T}(\omega_e)$ of $A_T(t)$ is

$$S_{A_t}(\omega_e) = \int_{-\pi/2}^{\pi/2} \left| H_{A_t}(\omega_e) \cdot (g/L) \right|^2 \cdot S_\xi(\omega_e, \theta) d\theta \tag{4-28}$$

and the variance $\sigma_{A_T}^2$ of $A_T(t)$ is as the following equation:

$$\sigma_{A_T}^2 = \int_0^\infty S_{A_t}(\omega_e) d\omega_e \tag{4-29}$$

4-4-6 Slamming

Slamming is a phenomenon that occurs at the position of S.S. $8\frac{1}{2}$ while the relative speed exceeds a certain critical value at the time that ship's bottom is out of water.

In this condition, if the relative displacement and the relative speed are expressed as S(t) and $\dot{S}(t)$ respectively, its random process and variance can be expressed as follows:

(1) Relative displacement at the position of S.S.$8\frac{1}{2}$

If $H_s(t)$ denotes the modulation response function of waves S(t),

$$H_s(t) = S(t)/\xi_a = \sqrt{S_a^2 + S_b^2} \cdot \cos(\omega_e t + \varepsilon_s) \tag{4-30}$$

where, $S_a = \cos(k \cdot l_s \cdot \cos x) - H_z \cos\varepsilon_z + k \cdot l_s \cdot H_\theta \cdot \cos\varepsilon_\theta)$

$$S_a = \sin(k \cdot l_s \cdot \cos x) - H_z \sin\varepsilon_z + k \cdot l_s \cdot H_\theta \cdot \sin\varepsilon_\theta)$$

$$\varepsilon_s = \tan^{-1}(S_b / S_a)$$

$$l_s = Mid.S - Mid.G = 0.35 \cdot L - Mid.G$$

If $H_s(\omega_e)$ denotes the frequency response function of $S(t)$, the spectrum $S_s(\omega_e)$ of $S(t)$ is as follows:

$$S_s(\omega_e) = \int_{-\pi/2}^{\pi/2} \left| H_s(\omega_e) \right|^2 \cdot S_\xi(\omega_e, \theta) d\theta \tag{4-31}$$

and its variance $\sigma_{A_T}^2$ of $A_T(t)$ is as the following equation:

$$\sigma_s^2 = \int_0^\infty S_s(\omega_e) d\omega_e \tag{4-32}$$

(2) Relative speed at the position of S.S. 8 $\frac{1}{2}$

The relative speed $\dot{S}(t)$ can be yielded by calculating the first-order differential coefficient of the relative displacement $S(t)$ for time t, as the following:

$$\dot{S}(t) = \xi_\omega(t) - [\dot{Z}_G(t) - l_s \cdot \dot{\theta}(t)] = \dot{S}_0(t) \cos(\omega_e t + \varepsilon_{\dot{S}}) \tag{4-33}$$

where, $S_0(t) = \sqrt{\dot{S}_c^2 + \dot{S}_s^2}$

$$\dot{S}_c = \omega_e(-\xi_a \sin(k \cdot l_s \cdot \cos x) - Z_a \cdot \sin \varepsilon_z + l_s \cdot \theta_a \cdot \sin \varepsilon_\theta)$$

$$\dot{S}_s = \omega_e(-\xi_a \cos(k \cdot l_s \cdot \cos x) - Z_a \cdot \cos \varepsilon_z + l_s \cdot \theta_a \cdot \cos \varepsilon_\theta)$$

$$\varepsilon_{\dot{S}_s} = \tan^{-1}(\dot{S}_s / \dot{S}_c) = \tan^{-1}(S_a / S_b)$$

then, if $H_{\dot{S}}(t)$ denotes the amplitude response function of waves, it can be expressed as following equation:

$$H_{\dot{s}}(t) = \dot{S}(t) / \xi_a \sqrt{g / L} = \sqrt{\dot{S}_a^2 + \dot{S}_b^2} \cdot \cos(\omega_e t + \varepsilon_{\dot{s}}) \tag{4-34}$$

where, $\dot{S}_a = -\dfrac{\omega_e^2}{g / L} \cdot \sin(k \cdot l_s \cdot \cos x) - H_z \sin \varepsilon_z + k \cdot l_s \cdot H_\theta \cdot \sin \varepsilon_\theta) = \dfrac{\omega_e}{\sqrt{g / L}} \cdot S_a$

$$\dot{S}_b = -\frac{\omega_e^2}{g / L} \cdot \cos(k \cdot l_s \cdot \cos x) - H_z \cos \varepsilon_z + k \cdot l_s \cdot H_\theta \cdot \cos \varepsilon_\theta) = \frac{\omega_e}{\sqrt{g / L}} \cdot S_b$$

$$\varepsilon_{\dot{s}} = \tan^{-1}(\dot{S}_b / \dot{S}_a) = \tan^{-1}(-S_a / S_b)$$

If $H_{\dot{S}}(\omega_e)$ denotes the frequency response function of $\dot{S}(t)$, the spectrum $S_{\dot{s}}(\omega_e)$ of $\dot{S}(t)$ is as follows:

$$S_{\dot{s}}(\omega_e) = \int_{-\pi/2}^{\pi/2} \left| H_{\dot{s}}(\omega_e) \cdot \sqrt{g/L} \right|^2 \cdot S_{\xi}(\omega_e, \theta) d\theta$$

$$= \int_{-\pi/2}^{\pi/2} \left| \omega_e \cdot H_S(\omega_e) \right|^2 \cdot S_{\xi}(\omega_e, \theta) d\theta \qquad (4\text{-}35)$$

and its variance $\sigma_{\dot{s}}^2$ of $\dot{S}(t)$ is as the following equation:

$$\sigma_{\dot{s}}^2 = \int_0^{\infty} S_{\dot{s}}(\omega_e) d\omega_e \qquad (4\text{-}36)$$

4-5 Occurrence probabilities and critical standard variances of the factors of seakeeping performance

The change of the modulation width against an instant time of the $X_i(t)$ has the form of Gauss distribution and its extreme value has the form of Rayleigh distribution. Once the variance $\sigma_{x_i}^2$ is acquired, then Q_{X_i} (which means the probability that the extreme value of $X_i(t)$ exceeds a constant value X_1) is as follows:

$$Q_{X_i} = \int_{X_1}^{\infty} \left(\frac{X_i}{\sigma_{X_i}}\right) \exp\left(-\frac{X_i^2}{2\sigma_{X_i}^2}\right) dX = \exp\left(-\frac{X_1^2}{2\sigma_{X_i}^2}\right) \qquad (4\text{-}37)$$

And then σ_{x_i} can be expressed as:

$$\sigma_{X_i} = \sqrt{-\frac{X_1^2}{2\ln Q_{X_i}}} \qquad (4\text{-}38)$$

When we consider critical probability $Q_{X_{iC}}$ (i.e. the probability of exceeding X_{iC}), then variance $\sigma_{X_{iC}}$ that is a value of danger can be found:

$$\sigma_{X_{iC}} = \sqrt{-\frac{X_{ic}^2}{2\ln Q_{X_{iC}}}} \qquad (4\text{-}39)$$

4-6 Evaluation values and risk of the evaluated factors

The extreme value of the evaluated factors characterizes the form of Rayleigh distribution and the occurrence probability is expressed as $Q(\overline{X_i})$. In this case E_{X_i} is defined as the evaluation value of X_i factors and is expressed as an inverse number with non-dimension.

$$E_{X_i} = \frac{1}{\sqrt{-2\ln\{Q(\overline{X_i})\}}} = \frac{\sigma_{X_i}}{X_i} \tag{4-40}$$

When the evaluation value E_{X_i} becomes zero, then the reliability level of the random factor (X_i) is 1.0, and when the evaluation value E_{X_i} becomes infinite then the reliability level of the random factor (X_i) is zero.

We define $E_{X_{iC}}$ as the critical evaluation value done on critical occurrence probability of random factor of X_i and, μ_{X_i} is defined as the risk of X_i and expressed as follows:

$$\mu_{X_i} = \frac{E_{X_i}}{E_{X_{iC}}} = \frac{[\overline{X_i}/\sigma_{X_{iC}}]}{[\overline{X_i}/\sigma_{X_i}]} = \frac{\sigma_{X_i}}{\sigma_{X_{iC}}} \tag{4-41}$$

where, $\sigma_{X_{iC}}$ is the value of danger of factor X_i

On the other hand, when $\mu_{X_i} \geq 1.0$, X_i (the factor of seakeeping performance) becomes dangerous, and when $\mu_{X_i} < 1.0$, it shows that the ship is safe.

4-7 Relative risk

Providing that the risks of factors X_i and X_j are μ_i and μ_j respectively, based on μ_i as a datum, the ratio μ_{ij} of μ_j to μ_i is defined as the relative risk as the following equation:

$$\mu_{ij} = \frac{\mu_j}{\mu_i} = \frac{\dfrac{X_i}{\sigma_{X_i}}}{\alpha_{ij} \cdot \left[\dfrac{X_j}{\sigma_{X_j}}\right]} = \frac{\sigma_{X_{ic}}}{\sigma_{X_{jc}}} \cdot \frac{\sigma_{X_j}}{\sigma_{X_i}} \tag{4-42}$$

while α_{ij} is the ratio of the critical evaluation values of factor i^{th} to that of jth factor, as follows:

$$\alpha_{ij} = \frac{E_{X_{ic}}}{E_{X_{jc}}} = \frac{\left[\dfrac{X_{ic}}{\sigma_{X_{ic}}}\right]}{\left[\dfrac{X_{jc}}{\sigma_{X_{jc}}}\right]}$$

where, when $\mu_{ij} > 1.0$, then factor X_j is more danger than factor X_i, and vice versa.

On the other hand, the values of the above-mentioned relative risks of the vertical acceleration risk and each of other 5 evaluated factors are different with the condition of ship's load, the encounter angle with wave, the condition of sea, ship's speed and so on. In this condition, the encounter angle with wave is calculated as the angle between ship's course and the direction of real wind.

4-8 Definitions of seakeeping performance index

With respect to a ship navigating at rough and irregular sea, when the value of each seakeeping performance factor exceeds the given critical value and its critical occurrence probability exceeds the given critical occurrence probability, the ship loss its control and becomes dangerous.

But, in the existing research above-mentioned definitely, the critical occurrence probabilities of the evaluated factors are different, and the systemic combination of those evaluated factors has the form of serial combination. Consequently, in order to evaluate the navigation safety by using existing evaluated factors of seakeeping performance, all of those factors shall be measured. But, it is impossible to install all sensors for measuring the characteristic of each factor, and the evaluation by installing sensors of all factors will be in problem in the economy.

Hence, in this research, there is no relation to ship's kind, loading condition and so on, and under a certain navigation condition only one seakeeping evaluation factor relating to the whole safety of ship is measured, and one proposal has to be made concerning SPI that can be evaluated with integration. By using SPI proposed, with different ship's course according to different sea condition, we can carry out the integrated seakeeping performance evaluation, and then show the corresponding information on the evaluation chart.

Setting a critical occurrence probability to each evaluated factor of seakeeping performance, it means that, the degrees that factors with the same degree of danger become dangerous are same. This condition is the same with that in reliability engineering, that means, when the failure occurrence probability of each factor of the whole system is same, the failure probability becomes same with it. Therefore, if each evaluated factor of seakeeping performance has the same degree of danger, by means of transforming them into the corresponding same occurrence probabilities, we can develop a SPI to evaluate the navigational safety of the whole system of ship. Only if we figure out one of the evaluated factors of seakeeping performance, the maximum danger degree of the whole system with 6 evaluated factors can be acquired. Moreover, in spite of not figuring out all of 6 factors, we can evaluate the navigation safety of the overall system of ship. In addition, when the degrees of danger of 6 existing factors are less than 1.0, if we adopt the maximum degree of danger, by supplementing some that the overall system had been evaluated for safety, and then integrating 6 evaluated factors of seakeeping performance, then it is possible to evaluate the navigation safety.

4-8-1 Transformed evaluation value of the evaluated factors of seakeeping performance

According to the study up to now, we know that the critical occurrence probabilities of factors, which can be evaluated for the overall seakeeping performance of ship that is navigating at rough and irregular sea, can be set with different values. Therefore, comparing with the evaluated factors with great critical occurrence probabilities, the factors with small

critical occurrence probability are often neglected while evaluating seakeeping performance of ship, and the danger condition is evaluated as the safe one. In order to supplement this deficiency, the occurrence probability of each evaluated factor achieves its critical occurrence probability; its degree of danger is converted and evaluated by using the same value while the critical occurrence probability achieves the largest one (i.e. Q_{Pc}=0.1) of propeller racing. That is, the degree of danger of each evaluated factor is same with that of propeller racing, and its occurrence probability is same with that of propeller racing. The transformed evaluation value $\tilde{E}_i$ of the evaluation value E_i of each evaluated factor of seakeeping performance is calculated from the following equation:

(1) In case of 'propeller racing'

$$\tilde{E}_p = \frac{E_p}{\alpha_{pp}} = E_p \cdot \frac{E_{pc}}{E_{pc}} = E_p \tag{4-43}$$

where, E_P: evaluation value of propeller racing $\left(\frac{\sigma_p}{X_p^*} = \frac{1}{\sqrt{-2\ln(Q_p)}} \right)$

$\tilde{E}_p$: transformed evaluation value of propeller racing

E_{Pc}: critical evaluation value of propeller racing $\left(\frac{\sigma_{pc}}{X_p^*} = \frac{1}{\sqrt{-2\ln(0.1)}} \right)$

(2) Other than 'propeller racing'

$$\tilde{E}_i = \frac{E_i}{\alpha_{pi}} = E_i \cdot \frac{E_{pc}}{E_{ic}} = E_{pc} \cdot \mu_i \tag{4-44}$$

where, α_{pi} : critical evaluation value ratio of ith factor to propeller racing

μ_i : dangerousness of ith factor

In Equations (4-42) and (4-43), when the degrees of danger are the same, then transformed values remain the same, and the occurrence probabilities shall have the same

values.

$$\mu_i = \mu_j \rightarrow \tilde{E}_i = \tilde{E}_j, \tilde{Q}_i = \tilde{Q}_j \tag{4-45}$$

4-8-2 Definition of seakeeping performance index

By using the transformed evaluation value of propeller racing above-mentioned and, analyzing the conceptions of the transformed evaluation value $(\tilde{E}_T)$ of the ship's overall system consisted of *n* evaluated factors of seakeeping performance and the critical evaluation value (E_{Tc}), the definition of SPI is proposed.

The transformed evaluation value $(\tilde{E}_T)$ of the ship's overall system is expressed as follows:

$$\tilde{E}_T = \frac{1}{\sqrt{-2\ln(1-\tilde{P}_T)}} \tag{4-46}$$

where, $\tilde{P}_T = \prod_{i=1}^{n} \tilde{P}_i$

The reliability function $\tilde{P}_i$ of the evaluated factors of seakeeping performance can be used and calculated from the following equation:

$$\begin{aligned}
\tilde{P}_i &= 1 - \exp\left\{-\frac{1}{2}\left(\frac{1}{\tilde{E}_i}\right)^2\right\} \\
&= 1 - \exp\left\{-\frac{1}{2}\left(\frac{\alpha_{pi}}{E_i}\right)^2\right\} \\
&= 1 - \exp\left\{-\frac{1}{2}\left(\frac{\alpha_{pi} \cdot X_i^*}{\sigma_i}\right)^2\right\} \\
&= 1 - Q\left(X_i^*\right)^{\alpha_{pi}{}^2}
\end{aligned} \tag{4-47}$$

Where, $Q(X_i) = \exp\left\{-\frac{1}{2}\left(\frac{X_i}{\sigma_i}\right)^2\right\}$

In addition, the overall evaluation value of the ship's overall system is expressed as follows:

$$E_{Tc} = \frac{1}{\sqrt{-2\ln(1-P_{Tc})}} \tag{4-48}$$

where, $P_{Tc} = \prod_{i=1}^{n} P_{ic}$

$$P_{ic} = 1 - \exp\left\{-\frac{1}{2}\left(\frac{X_i^*}{\sigma_{ic}}\right)^2\right\} = 1 - Q_{ic} \tag{4-49}$$

P_{Tc} : reliability function of seakeeping performance

Q_{ic} : critical occurrence probability of each factor (Rayleigh distribution)

In order to find out the overall degree of danger of the system, the ratio of Eq.(4-48) to Eq.(4-46) can be expressed as $\tilde{\mu}_T$:

$$\tilde{\mu}_T = \frac{\tilde{E}_T}{E_{Tc}}\sqrt{\frac{\ln(1-P_{Tc})}{\ln(1-\tilde{P}_T)}} \tag{4-50}$$

If $\tilde{\mu}_T$ is great than 1.0, the overall system is judged to be in danger. When just one factor of $\tilde{\mu}_T$ becomes more than 1.0, $\tilde{\mu}_T$ tends to be greater than 1.0.

Moreover, this $\tilde{\mu}_T$ is one of the evaluation factors of seakeeping performance, if its degree of danger is greater than 1, then $\tilde{\mu}_T$ becomes greater than 1. It means that, only if one factor is measured, the approximate value of the maximum dangerousness of all evaluation factors can be yielded. So, we consider that there are many advantages of producing simple and convenient hardware.

$$\mu_T \approx \mu_m(x,V,S) = \text{Maximum}[\mu_i(x,V,S)] \tag{4-51}$$

4-8-3 Navigation safety evaluation of any one factor

The reliability function $\tilde{P}_i$ of seakeeping performance evaluation factors can be figured out only if the relative dangerousness μ_{ij} of just one seakeeping performance evaluation factor is done. By using this method, the SPI μ_T, with which the navigational safety of a ship that is navigating at rough and irregular sea can be evaluated, can be calculated as the following equation:

$$\begin{aligned}
\tilde{P}_i &= 1 - \exp\left\{-\frac{1}{2}\left(\frac{\alpha_{P_i} X_{im}}{\beta_i \sigma_i}\right)^2\right\} \\
&= 1 - \exp\left\{-\frac{1}{2}\left(\frac{\alpha_{P_i} X_{im}}{\alpha_{P_i} \mu_{ij} \sigma_i}\right)^2\right\} \\
&= 1 - \exp\left\{-\frac{1}{2}\left(\frac{E_{ic}}{E_{Pc}} \cdot \frac{E_{ic}}{E_{ic}} \cdot \frac{X_{im}}{\mu_{ij} \sigma_i}\right)^2\right\} \\
&= 1 - \exp\left\{-\frac{1}{2}\left(\frac{\alpha_{P_i}}{\mu_{ij}} \cdot \frac{X_{im}}{\sigma_i}\right)^2\right\} \\
&= 1 - Q\left(X_{im}\right)^{\left(\frac{\alpha_{pi}}{\mu_{ij}}\right)^2}
\end{aligned} \tag{4-52}$$

where, X_{im} : any evaluated factor of seakeeping performance to be calculated

$\beta_i = \alpha_{ij} \cdot \mu_{ij}$

μ_{ij} : relative dangerousness of jth factor relative to i^{th} factor

α_{Pi} : critical evaluation value ratio of ith factor to ‘propeller racing’

4-8-4 Navigation safety evaluation by calculating vertical acceleration

SPI μ_T defined in the above is an index with which the overall navigation safety can be evaluated by calculating only one of existing seakeeping evaluation factors. Accordingly, in this sector, the ship’s overall navigation safety is evaluated by calculating only vertical

acceleration factor of existing seakeeping evaluation factors, which is easy to be calculated and is directly influential on the safety of cargo, seafarers' work, and so on. $\tilde{P}_i$ of Eq.(4-52) can be yielded by calculating the vertical acceleration, and then the SPI can be figured out according to the following equation:

$$\begin{aligned}
\tilde{P}_i &= 1 - \exp\left\{-\frac{1}{2}\left(\frac{\alpha_{P_i} X_{Av}}{\beta_i \sigma_{Av}}\right)^2\right\} \\
&= 1 - \exp\left\{-\frac{1}{2}\left(\frac{\alpha_{P_i} X_{Av}}{\alpha_{P_i} \mu_{Avi} \sigma_{Av}}\right)^2\right\} \\
&= 1 - \exp\left\{-\frac{1}{2}\left(\frac{E_{ic}}{E_{Pc}} \cdot \frac{E_{Avc}}{E_{Avc}} \cdot \frac{X_{Av}}{\mu_{Avi} \sigma_{Av}}\right)^2\right\} \\
&= 1 - \exp\left\{-\frac{1}{2}\left(\frac{\alpha_{P_{Av}}}{\mu_{Avi}} \cdot \frac{X_{Av}}{\sigma_{Av}}\right)^2\right\} \\
&= 1 - Q\left(X_{Av}\right)^{\left(\frac{\alpha_{pAv}}{\mu_{Avi}}\right)^2}
\end{aligned} \tag{4-53}$$

where, $Q(X_{Av}) = \exp\left\{-\frac{1}{2}\left(\frac{X_{Av}}{\sigma_{Av}}\right)^2\right\}$

$\beta_i = \alpha_{Avi} \cdot \mu_{Avi}$

μ_{Avi} : relative dangerousness of each factor to vertical acceleration

α_{Pav}: critical evaluation value ratio of vertical acceleration to propeller racing

Hence, the critical occurrence probabilities of propeller racing and vertical acceleration are $Q_{Pc} = 10^{-1}$ and $Q_{AVc} = 10^{-3}$, then the value $\alpha_{PAv} = 1/\sqrt{3}$. Consequently, Eq.(4-53) can be simply expressed as the following equation:

$$\tilde{P}_i = 1 - Q(X_{Av})^{\frac{1}{3}\left(\frac{1}{\mu_{Avi}}\right)^2} \tag{4-54}$$

The foresaid sections in this chapter are mainly described referring to the master paper (Zhao, 2000) of Korea Maritime University.

4-9 Experiment & Discussion

Professor Gil-Young Kong and Doctor Yun-Sok Lee in Korea Maritime University have developed the application for evaluating the navigational safety according to the data of the training ship, HANNARA. There are three files as the input data of this application. The first is HANNSM1.dat that is mainly about the ship's particular, such as Length between fore and aft poles, Breadth, Draft, and so on. The second is NSM2.dat that is about the medial parameters for the calculation, such as the encounter angle of wave, the Froude number, and so on. The third is whp.dat that contains the weather information, such as wind speed and direction, wave height and period. If we provide that the wind velocity is 25 knots, the wave height is 3.0 meters, and the wave period is 6.0 seconds, the calculation result of the application are outputted into the file CAL.OUT, the corresponding evaluation values are shown in the following table:

Table 4-2 A calculation result of navigational safety evaluation

EA (°)	**Fn**	**DW**	**PR**	**SL**	**RO**	**VA**	**LA**	**SPI**
180	0.204	0.449	0.784	0.540	0.497	0.984	0.211	0.971
180	0.238	0.464	0.713	0.578	0.507	1.078	0.213	1.035
180	0.273	0.475	0.637	0.610	0.525	1.163	0.215	1.104
180	0.290	0.478	0.572	0.622	0.536	1.198	0.215	1.135
150	0.204	0.427	0.763	0.511	0.525	0.949	0.301	0.933
150	0.238	0.443	0.695	0.549	0.536	1.043	0.306	0.998
150	0.273	0.455	0.622	0.580	0.553	1.126	0.311	1.068
150	0.290	0.458	0.557	0.593	0.563	1.161	0.313	1.098
120	0.204	0.367	0.720	0.432	0.594	0.886	0.455	0.867
120	0.238	0.380	0.661	0.461	0.618	0.959	0.486	0.919
120	0.273	0.392	0.594	0.489	0.653	1.030	0.535	0.981
120	0.290	0.397	0.534	0.501	0.677	1.061	0.571	1.012
90	0.204	0.259	0.651	0.297	0.679	0.607	0.605	0.697

90	0.238	0.268	0.583	0.315	0.683	0.651	0.610	0.696
90	0.273	0.275	0.514	0.331	0.719	0.694	0.664	0.746
90	0.290	0.278	0.458	0.338	0.744	0.714	0.707	0.785
60	0.204	0.241	0.648	0.237	0.687	0.412	0.624	0.695
60	0.238	0.244	0.572	0.246	0.711	0.428	0.656	0.704
60	0.273	0.248	0.494	0.255	0.793	0.449	0.777	0.819
60	0.290	0.250	0.435	0.257	0.849	0.459	0.866	0.912
30	0.204	0.255	0.707	0.192	0.667	0.170	0.628	0.715
30	0.238	0.254	0.623	0.175	0.592	0.160	0.485	0.610
30	0.273	0.254	0.538	0.157	0.628	0.154	0.513	0.600
30	0.290	0.255	0.476	0.148	0.656	0.152	0.558	0.625
0	0.204	0.270	0.718	0.191	0.627	0.122	0.516	0.695
0	0.238	0.268	0.644	0.168	0.596	0.099	0.442	0.626
0	0.273	0.269	0.563	0.145	0.645	0.081	0.511	0.619
0	0.290	0.270	0.499	0.137	0.680	0.073	0.574	0.649

Here, EA – Encounter Angle of Wave, Fn – Froude Number, DW – Deck Wetness, PR – Propeller Racing, SL – Slamming, RO – Rolling, VA – Vertical Acceleration, LA – Lateral Acceleration, SPI – Seakeeping Performance Index

The relation between Froude number (*Fn*) and ship's speed (*V*) is as follows:

$$Fn = \frac{V}{\sqrt{gL}} \tag{4-55}$$

where, g is the gravity acceleration (m/s^2)

L is the ship's length between fore and aft poles (m).

As shown in Fig.4-3, an encounter angle (E.A.) is defined as the angle between the direction of ship's heading and the direction of waves, and its value of E.A. ranges from 0° to 180°.

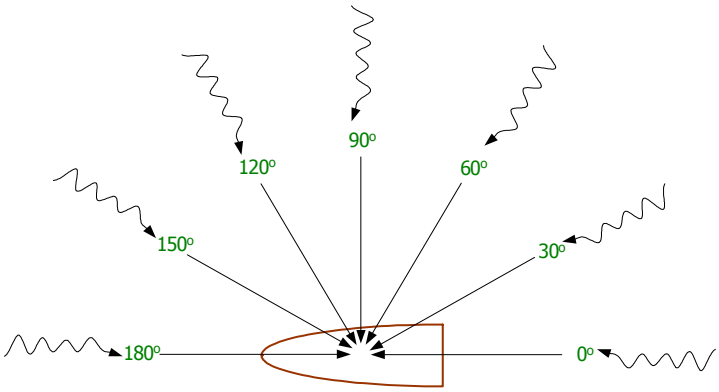


Fig.4-4 Encounter Angle of Waves

As shown in Table 5-2, the interval of E.A. is 30°, and the *Fn* has only four rates. For a specific E.A. and *Fn*, how to get the corresponding evaluation values? For this purpose, based on the results like Table 5-2, using the method of polynomial interpolation, we can get the evaluation values for any encounter angle and Froude number (related to the ship's speed). According to the values in the table 5-2, and using this method, the evaluation values for E.A.=135° and *Fn*=0.261 (its corresponding ship's speed is 15 knots) are as following table:

Table 4-3 Polynomial interpolation values of the evaluation values

EA (°)	**FN**	**DW**	**PR**	**SL**	**RO**	**VA**	**LA**	**SPI**
135	0.261	0.437	0.651	0.546	0.605	1.107	0.434	1.066

Obviously, according to the foresaid principal, the ship is in danger under this condition.

Here, we applied No.14 typhoon formed on 14th August of 1997 to this navigation safety evaluation, as shown in the following Fig.4-4, we found that, at 1800 hours on 12th, No.1 ship was in danger because the value (1.059) of total dangerousness is greater than 1.0.

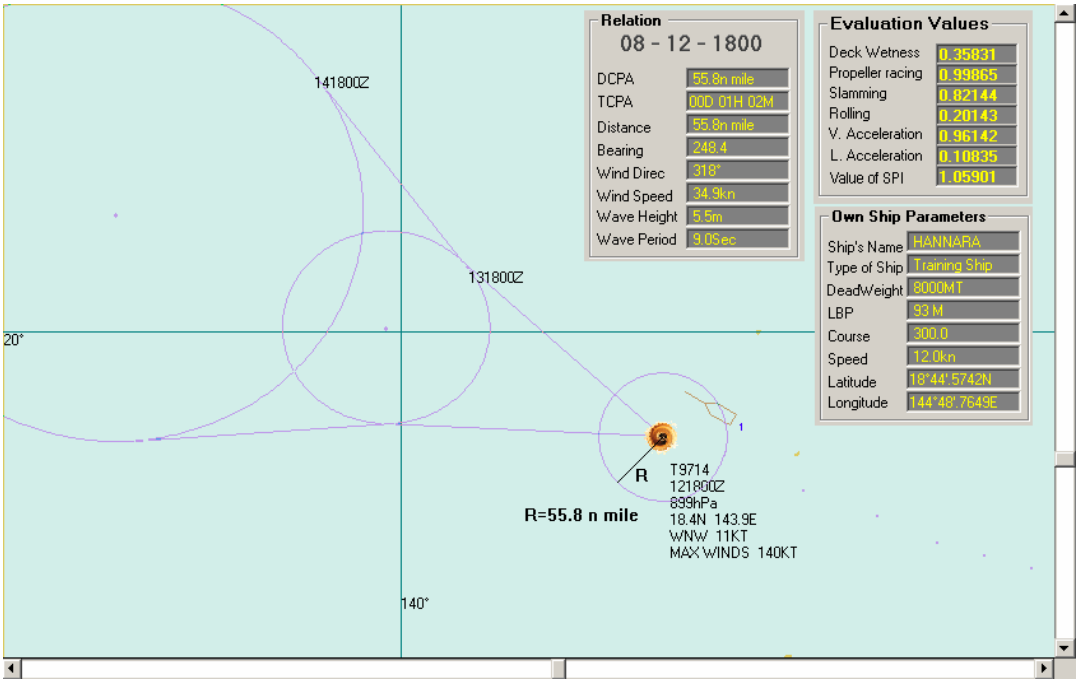


Fig.4-5 An experiment of evaluating the degree of navigation safety

In this condition, the evaluation values of all evaluated factors are shown in the following table 4-4.

Table 4-4 An example of navigation safety evaluation

DW	PR	SL	RO	VA	LA	SPI
0.358	0.999	0.821	0.201	0.961	0.108	1.059

In this chapter, we mainly described the basic theory of navigation safety evaluation roughly, and carried out an experiment of navigation safety evaluation. Additionally, we can yield the evaluation values for any value of encounter angle and any value of *Fn* using the method of polynomial interpolation. Hence, in our simulation training system, we can evaluate the degree of navigation safety at any time, and consequently, the effect of actions that is taken to avoid typhoon by the trainee can be checked.

Chapter 5

Design of the system and its corresponding operations

5-1 Overview of the system

This system aims at training students and seafarers to prevent typhoon's striking at sea, which is designed based on the Client/Server mode on Local Area Network (LAN). Here, the clients mean the trainees, and the server means the instructor. They are connected using hub and can perform data exchange interactively based on TCP/IP protocol. The framework of the system is shown in the following Fig.5-1.

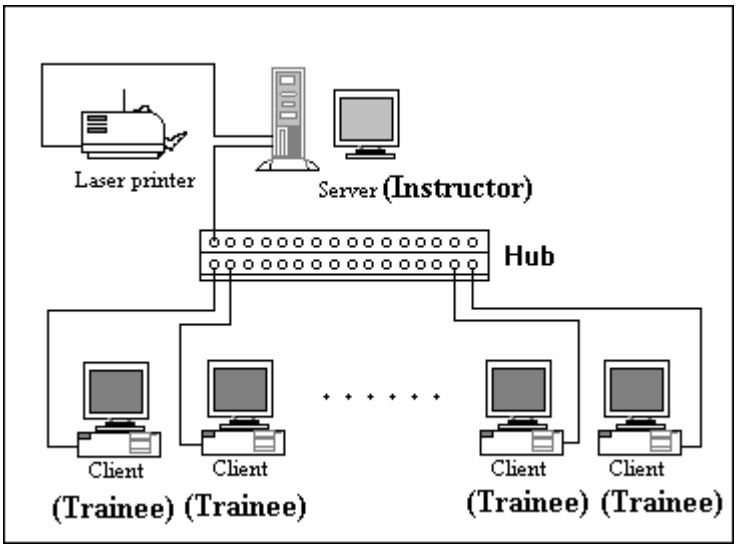


Fig.5-1 Framework of the system

Correspondingly, the software of this system includes two applications running on the server's computer and on the clients' computers respectively. The instructor shall, through the Server's application, set up the scenario of training, which includes setting up the training waters, the parameters of ships and the time ratio of simulation, and choosing a sample of past typhoons, and controlling the training process if needed, and send these information to all

trainees (clients) through LAN. Before starting to run, the trainees may set up ship's course, ship's speed and ship's position, but after running, the trainees cannot change the ship's parameters other than ship's course and/or speed.

The application running on the server are almost same with that running on the client, and so are their interface, but the one on the server has more functions than that on the client. Here, we mainly describe the details of the server application, which consists of nine functional modules as follows:

(1) Electronic chart module
(2) Assistant navigational mark module
(3) Deck-reckoning plot module
(4) Typhoon animation demonstration module
(5) Typhoon track prediction module
(6) Typhoon wind and wave calculation module
(7) Navigation safety evaluation module
(8) Information display module
(9) Communication module of LAN

These nine modules are integrated into the program, and the main function of each module is described in the next subsections.

The following Fig.5-2 is the simple flow chart of the program running on the server. Its rough processes are described as follows: (1) Choose the year and the number of the past typhoon to be simulated (through this step, the database is opened.); (2) Set the ship's position, ship's course and ship's speed; (3) Set the time ratio of simulation; (4) Start to run the system; (5) Then the program is running with some loops: the first is Dead-reckoning of ship's track; the second is typhoon's track forecasting; the third is calculating of typhoon's wind-field and wave-field; the fourth is ship's navigational safety evaluation; the last is calculating of DCPT, TCPA, Distance and Bearing between ship and typhoon; (6) The program is outputting: ship's

state, typhoon's state, typhoon's forecast positions, the winds and waves at ship's position and the relation between ship and typhoon; (7) While the number of present typhoon's position is equal to the total number of this typhoon's track positions, the program ends.

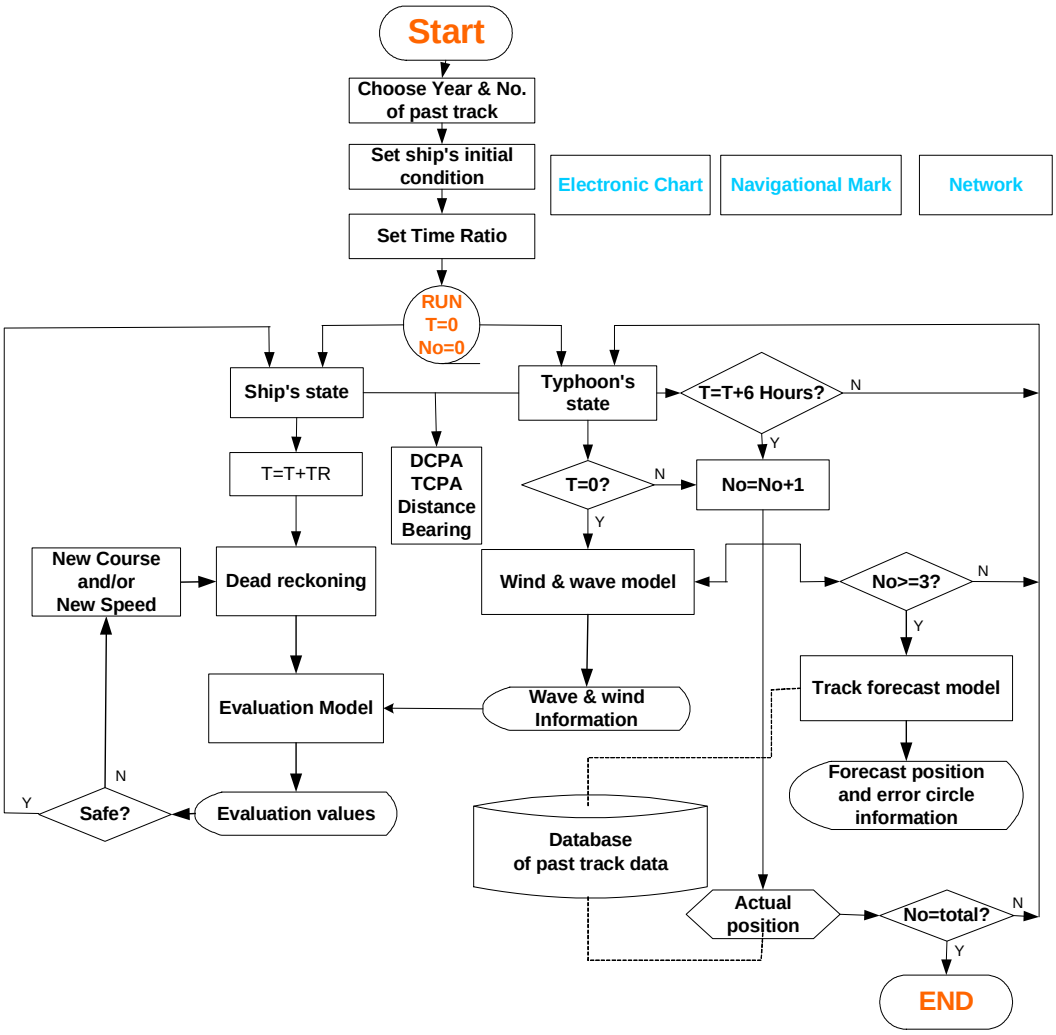


Fig.5-2 Flow chart of the program running on the server

5-1-1 Electronic chart module

Strictly speaking, the electronic chart in our system is not a real electronic chart but a very simple and special purpose one. That is to say, it is designed specially for our system. It

only contains the grids of latitude and longitude lines, coastlines and marks of some big cities. Its scale ranges from 100°E to 180° of longitude and from 5°N to 50°N of latitude. But it can be freely zoomed in and out, and freely shifted up and down, left and right as required. The values of longitude and latitude of any position within the chart area can be displayed on the Status Bar while the mouse is moving on the screen.

5-1-2 Assistant navigational mark module

There are three navigational marks: Line, Circle, and Circle with a Line. It is very easy to draw these marks using the mouse, and their corresponding bearing and distance values are displayed on the Status Bar. These marks cannot be erased when the electronic chart scale is changing, but they can be erased one by one from the last to the beginning using the Eraser tool. Therefore, we can conduct a route planning on the electronic chart through the determined waypoints or directly through the mouse. This function is required in our system. Moreover, the distance and the bearing between any two points on the electronic chart can be measures.

5-1-3 Dead-reckoning plot module

The departure point can be set by dragging the mark of the vessel on the electronic chart or by inputting the values of longitude and latitude through the Input Dialog Window. The initial course and speed are also set through the Input Dialog Window. After being set a departure position (the values of longitude and latitude), a course and a speed to a vessel, the vessel can be running on the electronic chart by dead reckoning at various different time intervals as required. During the period of dead reckoning, the vessel’s dynamical parameters (position, course and speed) can be changed as required at any time through the Input Dialog Window. The positions of vessel past track can be saved at 1-hour interval, and the past track may be chosen to display or not by simply clicking a switch button.

5-1-4 Typhoon animation demonstration module

In order to show the movement of the typhoon vividly, we use the skill of animation. For this purpose, we make an animation file and load this file into the animation control. This animation has two kinds of movement: one is translation, and the other is twist. The translation is made along with the typhoon's track at 6-hour interval, and the twist shows the spiral movement of atmosphere within typhoon. And the rate of twist changes with the maximum wind of typhoon, that is, the stronger the maximum wind, the higher the rate. And the animation may be visible or invisible by simply clicking a switch button.

5-1-5 Typhoon track prediction module

According to the month and the date, the forward speed and direction, the present position and the position at 12 hours before of the existing typhoon, this module searches the similar tracks in the database of past track data based on three similarity criteria, and calculates the forecast positions in future 48 hours at 6-hour interval, and computes the error radii of 24-hour and 48-hour forecast positions, finally, shows the values of forecast positions and display two forecast error circles at 24 hours and 48 hours in graphic on the electronic chart. This process repeats once every 6 hours, and correspondingly the latest information of the existing typhoon is shown to the trainees.

5-1-6 Typhoon wind and wave calculation module

According to the present position, maximum wind and central pressure of typhoon, this module calculates the wind-field and wave-field within typhoon region. The wind and wave information at the vessel's position is displayed at the right down corner of the screen, and such information at any other location with distance less than 500 n miles is also displayed on the screen while the mouse is moving around the typhoon on the electronic chart.

5-1-7 Navigation safety evaluation module

This module makes reference to the program of navigation safety evaluation developed by Professor Gil-Young Kong of Korea Maritime University. The program needs to be inputted three kinds of data: the first is the current weather information of the area where the ship is navigating, such information mainly includes wind speed, wind direction, wave height and wave period, which can be calculated from the developed wind-field model and wave-field model of typhoon; the second is vessel's principal dimension and the condition of the body of the vessel; the third is intermediate parameters, such as the encounter angle of waves and the value of FN (Froude Number). And then, through a series of computations, the program outputs the evaluation values of the evaluated factors of seakeeping performance and the SPI. Finally, we can evaluate the degree of vessel navigation safety according to the index value of seakeeping performance, that is, while the index value is smaller than 1, the vessel is safe, and while the index value is greater than or equal to 1, the vessel becomes dangerous.

5-1-8 Information display module

This module is designed for displaying various data relating to typhoon's dynamical state and vessel's dynamical state. It mainly includes four parts: the forecast results of typhoon, the vessel's parameters, the latest information of typhoon, the relation between vessel and typhoon. The rectangle frame in the indicator shows the scale of geographical area that is displaying in the electronic chart. The past typhoon track that we choosed for the present exercise is also displayed in the indicator, and the client status where it shows that a client is on line or not and shows the number of the ship whose information are being displayed on the interface.

5-1-9 Network communication module between the instructor and the trainees

A WinSock control allows us to connect a remote machine and exchange data using either the User Datagram Protocol (UDP) or the Transmission Control Protocol (TCP). Both

protocols can be used to create client and server applications. Like the Timer control, the WinSock control doesn't have a visible interface at run time.

In this module, we use the Winsock control to carry out data exchange between instructor and trainee, which is based on TCP protocol. These instructions are mainly described as follows:

Table 5-1 Data formats of the instructions between Instructor and Trainee

Instruction	Format	Transfer direction
Typhoon YearNo	“YN” + str(YearNo) (6*String)	Instructor → Trainee
Ship’s Position	“PO”+format(y, “00000.00”)+format(y, “00000.00”) (18*String)	Instructor ⇆ Trainee
Ship’s Course	“CO” + format(course, “000”) (5*String)	Instructor ⇆ Trainee
Ship’s Speed	“SP” +format(speed, “00.0”) (6*String)	Instructor ⇆ Trainee
Ship’s Position, Course and speed	“AL” + Lat. + Lon. + Cou. + Spd (28*String)	Instructor ⇆ Trainee
Time Ratio	“TR” + format(TimeRatio, “0000”) (6*String)	Instructor → Trainee
Run	“RN” (2*String)	Instructor → Trainee
Pause	“PS” (2*String)	Instructor → Trainee
NewExercise	“NE” (2*String)	Instructor → Trainee
On/Off line	“NF” (2*String)	Instructor → Trainee
Initial Own-Ship	“IO” (2*String)	Trainee → Instructor

As shown in the above table, the first two characters of each instruction string are the identification code that indicates what parameters will be transferred, such as “YN”, “PO”, and so on. While some instructions only have the identification codes without any parameter, and the identification codes themselves are right the complete instructions, such as “RN”, “PS”, and so on.

5-2 Introduction of the application’s interface

Just like a common window program, the whole interface of the program is well designed. It is friendly, and easy to operate, as shown in the following Fig.5-3.

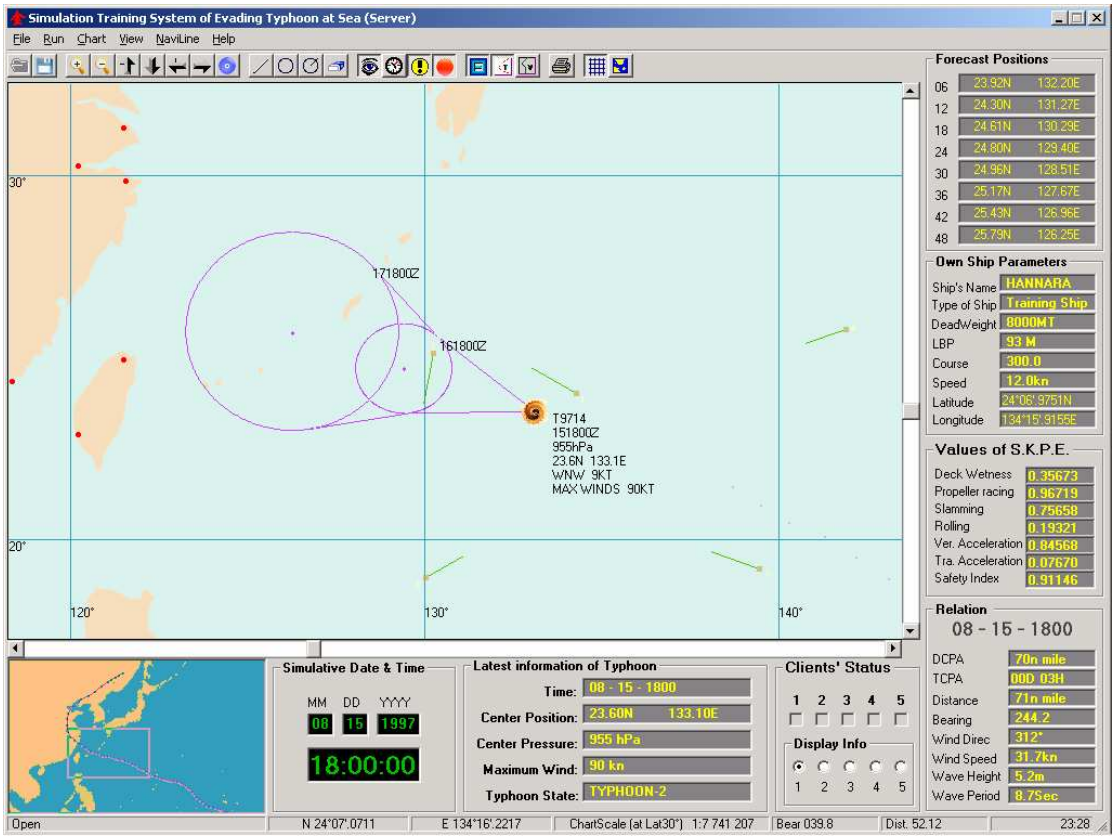


Fig.5-3 The program's interface

The interface has some functional zones described as follows:

(1) The Title bar,

(2) The Menu bar

(3) The Toolbar

(4) The Electronic chart window

(5) The information display frames

(6) The Status bar

5-2-1 The Title bar

The Title bar includes the System menu, the Title of this application and System buttons. The System menu has four submenus: Restore, Move, Size, Minimize and Close. The Title of the application window is Simulation Training System of Evading Typhoon at Sea. The System Buttons include three buttons: Minimize, Maximize and Close.

5-2-2 The Menu bar

The Menu bar has six menus: File, Run, Chart, View, NaviLine and Help. Each of these menus is described as follows.

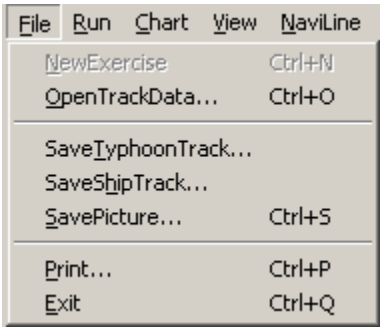


Fig.5-4 File Menu

(1) File menu

File menu has seven submenus: NewExercise, OpenTrcacData, SaveTyphoonTrack, SaveShipTrack, SavePicture, Print and Exit. The function of each submenu is described as follows:

NewExercise: Reset the system (Initialize all variables and arrays, and restore the electronic chart to the original size), and start a new exercise.

OpenTrcacData: Open a sample file of track data of past typhoon for training. After clicking this menu, “Select a sample” window is appeared for selecting a track data file. Before you

determine to select a track data, you may click **Preview** button to display the track on the **Indicator** in order to make sure whether it is suitable the exercise.

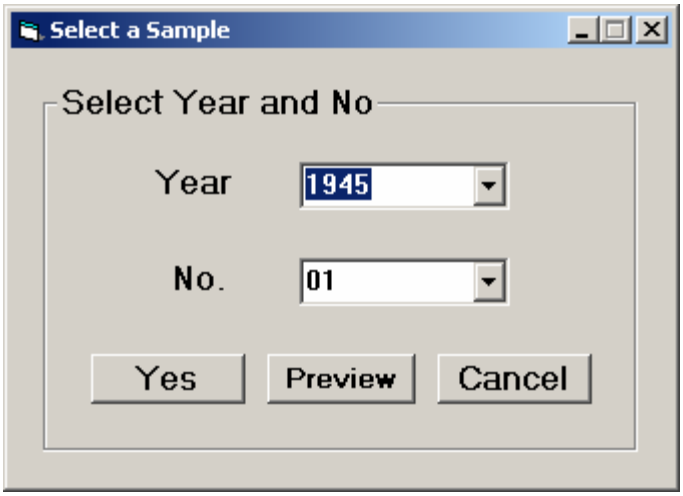


Fig.5-5 Window of **Select a Sample**

SaveTyphoonTrack: Save the track positions of the typhoon selected in the exercise into a file in format of Latitude, Longitude and Time. The time interval is six hours.

SaveShipTrack: Save the track positions of the current ship in the exercise into a file in format of Latitude, Longitude and Time at one-hour interval. If you want to designate a ship as a current ship, click one of grouped options captioned by ship's numbers in the **Clients' Status** frame.

SavePicture: Save the image of the training scenario into a file in BMP format.

Print: Print the image of the training scenario. After clicking the menu, a **Print** window appears as shown in the following figure. In this window, you can select the size of print area and the print orientation as required. If you chose "Select Area", you can use the mouse to drag a rectangle area to be printed as you need.

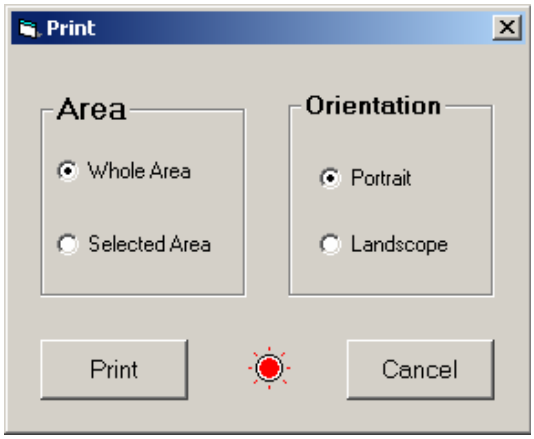


Fig.5-6 Window of **Print**

Exit: Exit the application.

(2) **Run** menu

The **Run** menu has four submenus: Start, Pause, Reset and Ratio. The function of each submenu is described as follows:

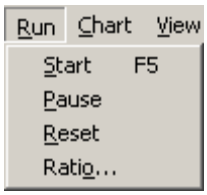


Fig.5-7 **Run** menu

Start: After setting up the various parameters of vessel and typhoon, we start an exercise to perform the training.

Pause: Stop the running of the program temporally if needed.

Reset: Reset the system to the original state.

Ratio: Set up the ratio of real time to simulative time. Because that, in practice, it takes several days to avoid typhoon's strike at sea, but it is not necessary to take so long time on the

simulation training, for this purpose we design this function for this purpose.

(3) **Chart** menu

The **Chart** menu has seven submenus: ZoomOut, ZoomIn, Up, Down, Left, Right and Original. The function of each submenu is described as follows:

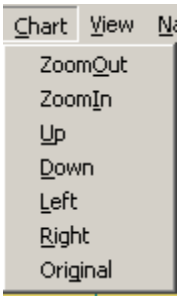


Fig.5-8 Chart Menu

ZoomOut: Decrease the image size of the electronic chart in order to display wider geographical area, and the chart scale decreases too.

ZoomIn: Enlarge the image size of the electronic chart in order to display smaller geographical area, and the chart scale increases too.

Up: Move the electronic chart upward while keeping the chart scale fixed.

Down: Move the electronic chart downward while keeping the chart scale fixed.

Left: Move the electronic chart leftward while keeping the chart scale fixed.

Right: Move the electronic chart rightward while keeping the chart scale fixed.

Original: Restore the electronic chart to the original state (i.e., display the whole area ranged from 100°E to 180° of longitudes and from 5°N to 50°N of latitudes.)

(4) **View** menu

The **View** menu has six submenus: ToolBar, Info, ForecastArea, TyphoonTrack, ShipTrack and Input. The function of each submenu is described as follows:

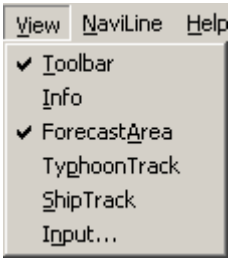


Fig.5-9 View Menu

ToolBar: It is a check style menu to control the ToolBar's visibility. If this menu is marked as "✓", the ToolBar is lain out on the top of the form, otherwise, the ToolBar is hide.

Info: It is a check style menu to control that whether the present information of typhoon is displayed on the electronic chart. When it is marked as "✓", this information is displayed.

ForecastArea: It is a check style menu to control that whether the predicted circles of 24 hours and 48 hours are displayed. When it is marked with "✓", they are displayed.

TyphoonTrack: It is a check style menu to control that whether the past track of typhoon is displayed at 6-hour interval. When it is marked with "✓", it is displayed.

ShipTrack: It is a check style menu to control that whether the past track of the current Ship is displayed at one-hour interval. When it is marked with "✓", it is displayed. (Note: if you want to set the current ship, please click the **Option** marked with the ship's No. in the **Client's Status** frame.)

Input: Set up the dynamical parameters of ships, including the ship's position, course and speed. The Input Window is shown in Fig.5-10. Before inputting data, choose the ship's number (1-5) firstly. Please input the data in the formats as remarked. The **Reset** button is used to blank all input fields for inputting new data.

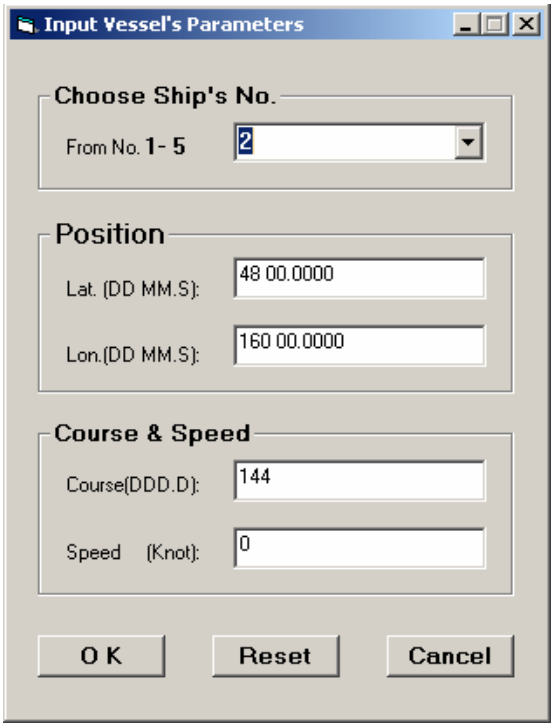


Fig.5-10 The window of Input Vessel's Parameters

(5) **NaviLine** menu

The NaviLine menu has five submenus: Line, Circle, LineCircle, Clear and Null. The function of each submenu is described as follows:

Fig.5-11 **NaviLine** Menu

Line: Draw a line on the electronic chart by moving the mouse with the left button down, and its distance and bearing between the beginning and the end points are shown in the Status Bar

simultaneously.

Circle: Draw a circle on the electronic chart by d moving the mouse with the left button down, and the distance of its radius are shown in the Status Bar simultaneously.

LineCircle: Draw a circle and a line simultaneously by moving the mouse with the left button down as shown in the following Fig.5-12, and the bearing of the line and the distance of the circle's radius are shown in the Status Bar simultaneously.

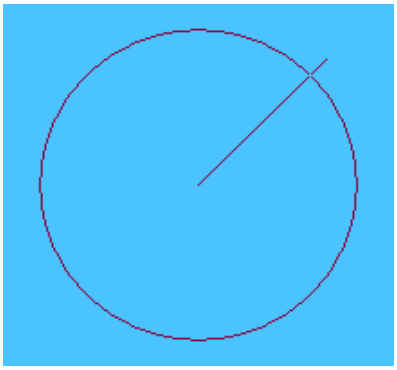


Fig.5-12 NaviLine of LineCircle

Erase: Erase the drawn NaviLines one by one according to the adverse sequence of drawing them by clicking this menu.

Null: Make nothing to be drawn by dragging the mouse.

(6) **Help** menu

This menu is the same as other windows applications. There are two submenus: **Manual** and **About**, and their functions are not described here.

5-2-3 The Toolbar

The Toolbar, which is located just below the Menu bar, has twenty-one buttons as shown in Fig.5-13. It provides quick access to file operations, electronic chart status change, naviline

drawing, and so on.

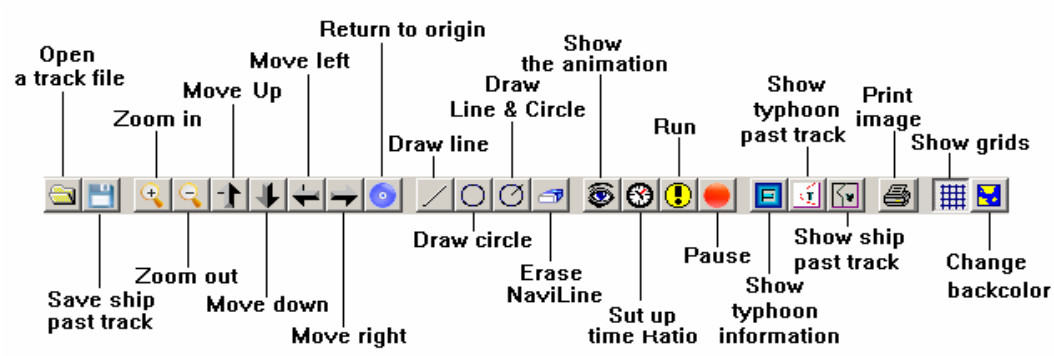


Fig.5-13 Toolbar

Each button in the toolbar has the corresponding menu item, which has the same function as that of button itself.

5-2-4 The window for displaying electronic chart

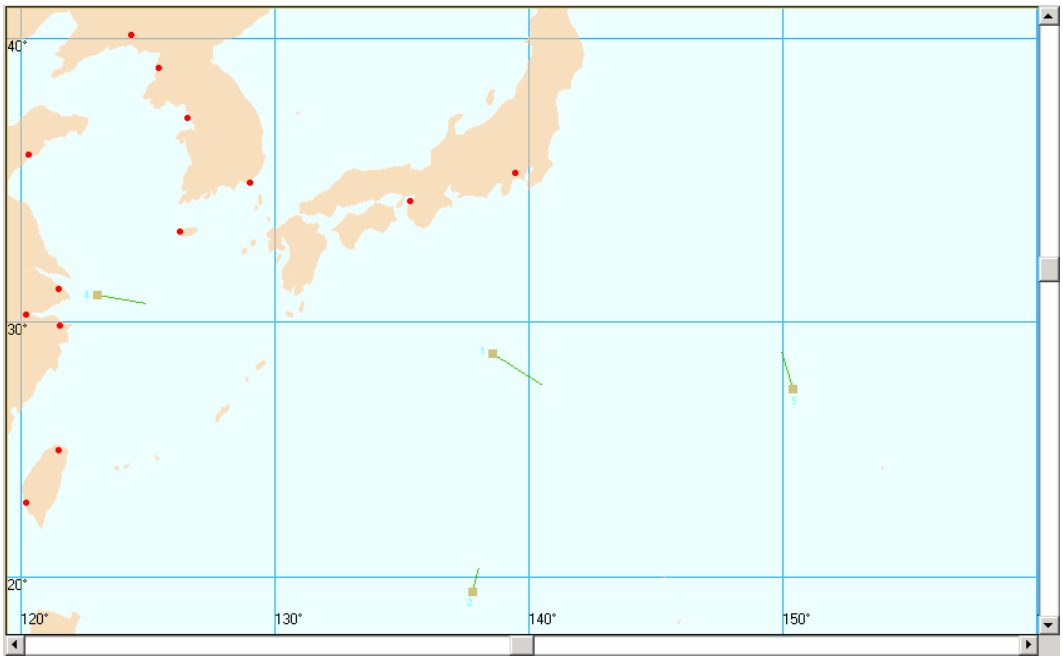


Fig.5-14 The window for displaying the electronic chart

The window for displaying electronic chart is shown as the following Fig.5-12. This window has the vertical scroll bar and the horizon scroll bar. The window is fixed, but the geographical range displayed is changed by changing the chart scale and shifting the central position.

The geographical range to be displayed can be changed by using **Chart** menu, the corresponding buttons of the **Toolbar** as the above-mentioned. Additionally, we can zoom in and out the chart by the middle roll of the mouse, and shift the chart by two scroll bars on the left side and on the bottom of the window respectively. In practice, we can display the suitable geographical area according to the specific training exercise.

5-2-5 The information display panels

This part includes seven frames: **Latest Information of Typhoon**, **Forecast Positions**, **Own-ship Parameters**, **Relation** between ship and typhoon, **Indicator**, **Clients' Status**, and **Date & Time**. And each frame has some items of interest.

The trainees shall pay attentions to this information, and take the corresponding actions to avoid the typhoon. The rectangle frame in the **Indicator** shows the geographical area displayed in the electronic chart window.

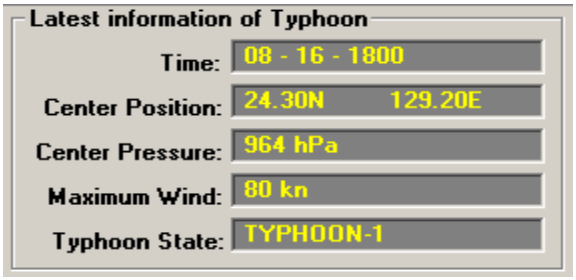


Fig.5-15 Latest information of typhoon

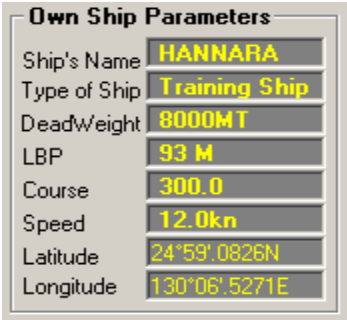


Fig.5-16 Own Ship Parameters

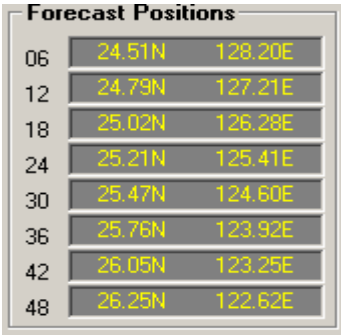


Fig.5-17 Forecast position

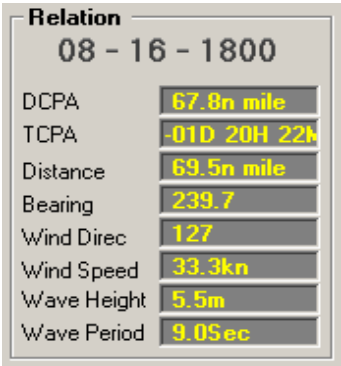


Fig.5-18 Relations between typhoon and own ship

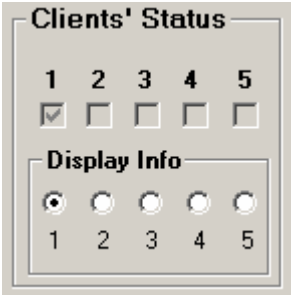


Fig.5-19 Clients' Status

Fig.5-20 Indicator for the electronic chart and past typhoon track

Fig.5-21 Present time on simulating

5-2-6 The Status bar

The Status bar includes some panels of Prompt, Geographical position at the mouse point, Present chart scale, Parameters of the present NaviLine and System time. The detail of the

Status bar is shown in the following Fig.5-22.

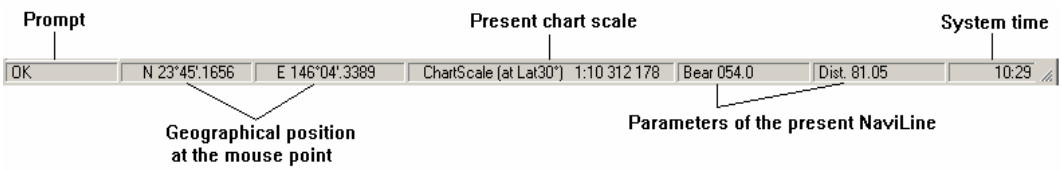


Fig.5-22 Status bar

5-3 Operations to the application program

5-3-1 How to start an exercise from the beginning.

1. Firstly run the server application program on the server machine, then the initial interface appears as shown in Fig.5-3.
2. Run the client application program on all client machines.
3. Confirm that the connection of data communication between the server and clients is established by checking the **CheckBox**es in the frame of **Clients' Status**.
4. Choose **File /OpenTrackData**, and then a window of **Select a sample** as shown in Fig.5-5 appears.
5. In this window, select the **Year** and the **No**. of the typhoon for training, click **OK**.
6. Plan a ship's route by drawing NaviLine according to the specific typhoon selected in the step 5 (if necessary).
7. Choose **View /Input**, and then a window of **Input Vessel's Parameters** appears as Fig.5-10.
8. In this window, set up the initial conditions for all ships, including the latitude and longitude of departure position, the initial course and the initial speed. (Note the formats of the input data.). We can also set up the departure position by dragging the vessel's mark on the electronic chart. (A client stands for a trainee and the ship under his control.)
9. Choose **Run/Ratio**, and then a window of **Set up the Time Ratio** appears.

10. In this window, select a suitable value of time ratio as needed, then click **OK**
11. Adjust the electronic chart to make the chart scale and the displayed geographical area suitable for the specific exercise.
12. Choose **Run/Start**, then the program starts to run, all ships and the typhoon begin to move on the chart, the various information are dynamically displayed on the interface.
13. The trainees shall watch the dynamic of typhoon and the ship display being displayed on the interface of client program, and take the corresponding actions promptly, that is to say, adjust the ship's course and/or speed.
14. During simulating, the instructor can pause the whole system's running if necessary by clicking the **Pause** button in the Toolbar, and can adjust any ship's state if necessary. If click one more time, the whole system will restore into running.
15. When the typhoon disappears, the program stops running automatically, and the exercise is over.

(Note: we may perform these operations using the corresponding buttons of the Toolbar or short-access keys)

5-3-2 How to switch to a new exercise

1. Choose **File/NewExercise**, and then appears a window of **Select a sample** as Fig.5-5.
2. Select a new sample of typhoon.

The next steps are the same as the above-mentioned in the sector 5-3-1.

CHAPTER 6

Conclusion

In the first place, we collected the past track data of typhoons covered from 1945 to 2001. By analyzing these data, we built a database of past typhoon tracks using the tool of Microsoft Access. We defined three criteria for judging whether a past typhoon track is similar to the track of existing typhoon. Based on these criteria and the database, we proposed a mathematical model for forecasting a typhoon's movement with the forecast error circle. Then, we carried out a simulation forecast on No.14 typhoon in 1997, and found that the forecasted results of the proposed model were reasonable and it is suitable for a simulation system for training mariners and students so that they can take appropriate actions to evade a typhoon at sea.

In the second place, based on the precedent researches by other scholars, we proposed simple parametric models for calculating wind speed & direction and wave height and period at any location around the typhoon region at sea. The proposed wind-field model is asymmetric, and consists of a circular symmetric wind-field caused by the pressure gradient of typhoon and a moving wind-field caused by the movement of typhoon. An empirical method with the regression analysis and dimensionless analysis was applied to build a wave-filed of typhoon by using only factors of wind speed and radial distances. By verifying this model through observed wave data, we found that it is accurate enough to develop the simulation system for training students and seafarers to take appropriate actions while they face a typhoon's threat at sea.

In the third place, we may evaluate the degree of ship navigation safety in order to confirm whether the actions are appropriate, effective, and safe enough, which are taken to prevent typhoon's strike according to the winds, the waves and the forecast track of typhoon calculated from the three models above-mentioned. In the period of training, we can, at any time, calculate the values of six evaluated factors and the SPI and, show this information to the

instructor so that he can evaluate the training effects of trainees. If the total index value is smaller than 1.0, the ship is safe, otherwise, if it is greater than or equal to 1.0, the ship becomes dangerous.

Finally, according to the above-mentioned ideas, we designed the simulation training system based on the Client/Server mode using the TCP/IP protocol. Hence, we developed two application programs running on the server machine and the clients' machines respectively. The server application program has the following functions:

(1) Electronic chart module
(2) Assistant navigational mark module
(3) Deck-reckoning plot module
(4) Typhoon animation demonstration module
(5) Typhoon track prediction module
(6) Typhoon wind and wave calculation module
(7) Navigation safety evaluation module
(8) Information display module
(9) Communication module of LAN

The client application program has the most functions of the server's, the main difference is that the server application program has the function of supervising ships' states of all clients and controlling the whole system's running. The interfaces of the applications are friendly and easy to operate. The whole system runs steadily.

In future, we will continue to engage in this research. We'll try to improve the accuracies of the wind-field, wave-field and typhoon track forecast models, advance the quality of the electronic chart, increase the types of client ship and the number of clients (presently, there are only 5 clients available).

References

[1] Gao Cong-Qin (1996), “Weather and Marine Disaster”, Weather, Vol.22, No.10, 1996, pp. 54-57.

[2] Hope, J.R. and C.J. Newmann (1969), “An operation technique for relating existing tropical cyclone to past track”, the sixth AMS Conference on Hurricanes, Miami, USA.

[3] Hope, J.R. and C.J. Neumann (1970), “An operation technique for relating the movement of existing tropical cyclones to past track”, *Mon. Wea. Rev.*, 98(12).

[4] Goerss, C.R. Sampson, and J.Gross (2004), “A history of Western Pacific tropical cyclone track forecast skill”, *Wea.* Forecasting 2004.

[5] Wang Zhi-Lie and Fei Liang (1987), “ Typhoon forecast Manual” Meteorological Publisher, China, pp. 184-187.

[6] Chen Lian-Shou and Ding Yi-Hui (19790, “General review of typhoon in West Pacific”, Meteorological Publisher, China, pp.388-391.

[7] Chen Lian-Shou and Shu Jia-Xin (1980), “A review of typhoon research and operational prediction in China”, Symposium on Typhoons, Shanghai, China, pp.189-195.

[8] Fujida (1987), “Wave conspectus”, Japan Meteorological Association”, pp.100-105.

[9] Chen (1994), “A Computation Method for Typhoon Wind-field”, TROPICAL OCEANOLOGY, Vol.13, No.2, pp.41-48.

[10] Zhu Shou-Xian (2002), “An Asymmetric Wind-field Model of Typhoon Near Shore”, Journal of East China Normal University (Natural Science), No.3, 2002, pp.66-71.

[11] H.E. Willoughby and M.E. Rahn (2003), “The Climatology of Hurricane Wind Profiles”, 26th Conference on Hurricane and Tropical Meteorology.

[12] Greg Holland (1997), “Horizontal Wind Structure”, Bureau of Meteorology Research Center, Melbourne.

[13] Liang Kuang-Nai (2001), “A Simple Typhoon Wave Hindcast and Swell Prediction Model”, (http://sol.oc.ntu.tw/omisar/wksp.mtg/woml.97c/rep/rep1-1-2.htm).

[14] Fang Zhong-Sheng and Jin Cheng-Yi (2003), “Statistical Analysis on Wave Height,

Wind Speed and Other Parameters Due to Tropical Cyclones in the North Pacific Area", Journal of Ship Mechanics, Vol.7, No.5, 2003, pp.1-10.

[15] Yang Bo-Ren (2000), "Study on the Development of Net-cage Fish-farming in Taiwan", Master Thesis of National Zhongshang University.

[16] Traffic Ministry of P.R.C. (2001), "Design Handbook of Habour Engineering", pp80-85.

[17] Gong Gil-Young (2002), "On the Development of An Information Service System for Navigation Safety of Seagoing vessels", the Symposium on Marine Industry of Korea Maritime University, No.12, 2002.

[18] Zhao Yi-Shun (2000), "A basic study for the development of Integrated Seakeeping Performance Evaluation System on Board the Ship", Master These of Korea Maritime University, 2000.

[19] Atkinson and Holliday (1977), http://www.tmd.go.th/~marine/thesis/proceding1.html

[20] Hsu, S.A., "Estimating hurricane-induced maximum sustained wind speed at 10m from its central pressure at sea", Mariners Weather Log, 2003.

Acknowledgements

I would like to express my deep gratitude to my advisor, Prof. Chae-Uk Song, who gave me much financial support and essential academical guidance during the past three years when I studied Doctor course at Korea Maritime University.

I appreciate all professors of the supervisory committee, who are Prof. Zhong-Hui Yun, Prof. Byeong-Deok Yea, Prof. Dong-Il Seol, Prof. Gil-Yeong Gong. I am indebted to them for their many important suggestions.

And I would also like to thank Prof. Chao-Jian Shi in Shanghai Maritime University for his encouragement and much help.

I also want to thank my close friends, Mr. LiRui, Miss Xiao-Ling Zhang, Miss Cai-Rong Zhen, Mr. LiYu, Miss Shan-shan Wu, and Pin-Jian Liu who is studying doctor course at Kobe University of Japan, for their zealous help

Lastly, I would like to acknowledge my wife, Zhen-Rong Wang, and my parents-in-law, for their great spiritual supports.