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A Study on the Method of Safe Shiphandling in Violently Rough Sea by Typoon or Hurricane

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Abstract : *The object of this study is to develop the method of safe conducting of a vessel through stormy sea when we encounter typoon or hurricane on ocean. The scope of investigation in this paper will be limited to safe maneuvering related only with rolling motions of a vessel. The processes of investigations are as follows; Firstly, we decide a CPA(Closest Point of Approach) with the center of the storm and decide significant wave height(*$H_{1/3}$*) by SMB method and then calculate wave height of the highest of 1000 waves(*$H_{1/1000}$*) and other data. Secondly, we make mathematical model of rolling motions of the vessel on the stormy sea and calculate the biggest rolling angle of the vessel and etc. Thirdly, we decide the most safe maneuvering method to ride out the stormy sea. By the above mentioned method we are able to calculate the status of the stormy sea and ships motions to be encountered and ride out safely through violently rough sea.*

Key words : *safe maneuvering, rolling motion, rough sea, CPA, actual experiences*

1. Introduction

Oceanographers study and investigate about ocean waves and sea status of rough ocean under violent Typoon or Hurricane. Naval architects study ship building and investigate motions of a vessel that they build in a model basin. Masters sometimes must conduct and maneuver their vessels through violently rough sea riding out Typoon or Hurricane. But until nowadays, there has been no usable maneuvering manual guide composed of the two parts investigations to ride out Typoon or Hurricane except Buys Ballots Laws(U.S.N.H.O, 1966), that is a natural law discovered by the Dutch professor Buys Ballot to indicate position of the center of the storm to be encountered. To ride out storm safely a master must know not only the position of the storm center related to his vessel but also the exact status of sea roughness to be encountered and the motions of his vessel due to the degree of sea roughness. The objective of this study is to make a manual of safe maneuvering of a vessel through rough sea for the master. The method is to combine the degree of encountering sea roughness that can be decided from the results of investigations already made by oceanographers with the motions of the vessel got by computation on the basis of the master mariner's actual experiences.

2. Theoretical approach

2.1 Historical background of wave forecasting investigation

Studies on forecasting waves by theoretical method had begun in the first part of 1940's by Sverdrup and Munk(Korvin-Krokovsky, 1961) and later by Bretschneider in U.S.A. The government of U.S.A. invested much money in their study and at last they developed and made mathematical model for forecasting waves. The forecasting of waves according to their manual greatly contributed to the landing of invasion troops on Normandy and other places during the second world war. Within the wave generating sea area there always exist a large number of such trains of waves of different length, traveling with the wind or at small angles with the wind direction. From interference and criss-crossing there results an extremely irregular appearance of the sea surface. Because of the simultaneous presence of many trains, the wave characteristics have to be described by some statistical terms. For that purpose it has been found convenient to introduce the average height and period of the one-third highest waves. The waves defined in this manner are called "the significant waves, these quantities increase with the time and the distance over which the energy of the wind is transmitted to waves. The forecasting method of waves

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developed by Sveradrup, Munk and Bretschneider is called SMB method according to the head letter of their names.

2.2 Using the diagram of forecasting significant waves

On the base of SMB method, Wilson, B.W. developed more reliable mathematic model for forecasting waves and made wave forecasting diagram to be used easily and reliably(Ichiro, 2006). If you are provided with wind velocity, fetch and time of wind duration, you are able to find wave height($H_{1/3}$), and it's period($T_{1/3}$) by crossing the line of equivalent wind velocity with those of the fetch and the wind duration lines. If you find two waves by above mentioned method, smaller one is the correct wave.

2.3 Wave spectrum and heights of waves of particular seaway

2.3.1 Energy of an irregular seaway

To be able to define a seaway it is necessary to take sample records of waves over a period time. Although the wave pattern will never be repeated as same, the statistical characteristics of the sea state, that is, the energy spectrum will remain as same form and quantity. This is the advantage of statistical investigations. In other words, the sinusoidal components that approximate a record for a particular sea state are the same regardless of time and place and differ from one record to another only in the phase orientation, thereby keeping the energy of the wave system constant.

2.3.2 Energy spectrum and wave spectrum

2.3.2.1 Energy spectrum

As the energy of a wave system is constant, the severity of a seaway is then measured by the total energy content of all waves present. The energy of a sinusoidal wave is given as $\frac{1}{2}\rho g\zeta_a^2$ per square meter of sea surface (where ζ_a is amplitude of the wave), the total energy per square unit of sea surface is given by(R.B., 1978),

$$E_T = \frac{1}{2}\rho g(\zeta_1^2 + \zeta_2^2 + \cdots\cdots\cdots + \zeta_n^2) \tag{1}$$

Thus any given seaway can be described by the energy distribution versus the different frequencies (angular velocities of waves). The distribution of energy versus angular velocity of waves is called the energy spectrum for the particular seaway and it has been found that a energy spectrum of a stormy sea follows a distribution form which is known as Rayleigh distribution as shown in Fig. 1.

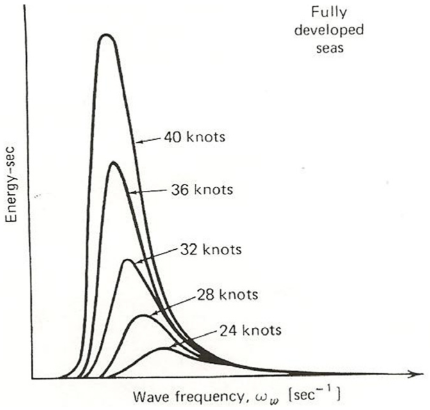

Fig. 1 Energy spectra of fully developed seas for various wind speeds

2.3.2.2 Wave spectrum and heights of waves of a seaway

We have seen that total energy quantity (E_T) per unit area of sea surface is represented by formula (1) and that area under the energy spectrum curve yields total energy quantity per unit sea area. Now, instead of drawing a spectrum that represents energy, $\frac{1}{2}\rho g$ is excluded out from formula (1), and the area under the curve of the new figure, generally denoted as m_0 , is later multiplied by $\frac{1}{2}\rho g$ to obtain the energy. The new figure is called the wave spectrum, and the ordinates are represented by the symbol $S_\zeta(\omega_w)$, which is called the spectral density of wave energy(Bhattacharyya, 1978).

$$\int_0^\infty S_\zeta(\omega_w)d\omega_w = m_0 = (\frac{1}{n})\sum_1^n \zeta_i^2 \tag{2}$$

If we define the meaning of m_0, $\sqrt{m_0} = \zeta$ is a hypothetic wave amplitude that has same energy as the complex seaway. When mathematic formula for the waves of a particular seaway, is not available, ITTC(International Towing Tank Conference) spectral formula will be used as follows(Bhattacharyya, 1978) :

$$S(\omega_w) = \frac{A}{\omega_w^5}exp(-B/\omega_w^4) \tag{3}$$

Where, ω_w : Circular frequency in radians per second

A : $8.10\times10^{-3}g^2$, where g is the acceleration of gravity in meter

B : $3.11/H_{1/3}^2$, where $H_{1/3}$ is the significant wave height

The relations between m_0 and wave height are given in table 1 for the Rayleigh distribution.

Table 1 Relation between m_0 and wave height

	Amplitude	Height
Average wave	$1.25\sqrt{m_0}$	$2.50\sqrt{m_0}$
Average of one-third highest waves	$2.0\sqrt{m_0}$	$4.0\sqrt{m_0}$
Average of one-tenth highest waves	$2.55\sqrt{m_0}$	$5.09\sqrt{m_0}$
Average of one-hundredth highest waves	$3.34\sqrt{m_0}$	$6.67\sqrt{m_0}$

Longuet-Higgins derived statistically the most probable largest amplitude in record of n waves as follows(R.B., 1978):

$$\sqrt{2LN(n)} \times \sqrt{m_0} \times CF \tag{4}$$

Where, CF : correction factor, however the CF is taken to be 1.0 when standard ITTC formula is used for wave spectrum for a given significant wave height, since it is assumed by ITTC that the wave height ($2\zeta_i$) histogram follows the Rayleigh distribution. It should be noted that there is a limit on the number of waves to be considered in obtaining the maximum wave height from the Rayleigh distribution. Although we may obtain a very high wave if the record is made for a very long time, the probability of occurrence for the extremely high wave is very low. Therefore often a record of 1000 waves is considered to be sufficiently representative for the determination of the wave spectrum and the most probable value of the one-thousandth highest wave amplitude is taken to be the most probable largest amplitude and it can be calculated by following formula;

$$\sqrt{2LN(n)} \times \sqrt{m_0} = 3.72\sqrt{m_0} \tag{5}$$

Where, CF=1

2.4 Numerical calculation of a seaway

If we are able to know the value of the significant wave height of a seaway or m_0 of the spectrum of it, we can calculate the average wave height, H_0, significant wave height $H_{1/3}$, one-tenth wave height $H_{1/10}$, one-hundredth wave height $H_{1/100}$ and one-thousandth wave height $H_{1/1000}$ which is the largest wave height of the seaway and also we can calculate the probability of wave distribution of the sea status by following formula(Yoon, 1982) ;

$$P(h > H_i) = \mathrm{Exp}(-H_i^2/\overline{H^2}) \tag{6}$$

Where, h : wave height higher than H_i

H_i : designated wave height

$\overline{H}$: root mean square of wave heights

2.4.1 Numerical value of various heights of waves

$$\begin{aligned}
&1)\ H_0 = 2.50\sqrt{m_0} \quad \text{or} \quad \frac{2.50}{4.0} \times H_{1/3} = 0.63H_{1/3}\\
&2)\ H_{1/3} = 4.0\sqrt{m_0}\\
&3)\ H_{1/10} = 5.09\sqrt{m_0} \quad \text{or} \quad \frac{5.09}{4.0} \times H_{1/3} = 1.27H_{1/3}\\
&4)\ H_{1/100} = 6.67\sqrt{m_0} \quad \text{or} \quad \frac{6.67}{4.0} \times H_{1/3} = 1.67H_{1/3}\\
&5)\ H_{1/1000} = 7.44\sqrt{m_0} \quad \text{or} \quad \frac{7.44}{4.0} \times H_{1/3} = 1.86H_{1/3}
\end{aligned} \tag{7}$$

2.5 Actual rolling motion of a vessel on stormy sea

When a big merchant vessel encounter with a heavy sea, the vessel rolls irregularly with rolling of 10 degrees more or less, but sometimes she encounter with a extraordinarily big and steep(seemingly like a coming cliff) wave which appears suddenly and the vessel rolls 30 or 40 degrees at the instant of impacting with the swiftly coming wave, which also disappear suddenly after the impact and the vessel rolls again with ordinary roll angles no sooner than passing the big wave. Such a phenomenon can be explained by wave theory that a very big wave is composed of many sinusoidal waves the phase originations of which are different each other.

3. Making mathematic model for rolling motion of a vessel onstormysea

3.1 Mathematic model

When a vessel starts to roll with a big impact force that appears and disappears suddenly, the mathematic model can be made as follows:

$$(I_x + i_x)\frac{d^2\theta}{dt^2} = C\delta(t) - N\frac{d\theta}{dt} - W \cdot GM \cdot \theta \tag{8}$$

where, I_x : moment of inertia through x axis

i_x : added moment of inertia

θ : roll angle

C : coefficient of unit impact force $\delta(t)$

$\delta(t)$: unit impact force that appears at an instant and suddenly disappears
N : coefficient of resisting moment due to angular velocity $\dot{\theta}$
W : displacement(ton)

Resisting moment(M_{tR}) is composed of two parts, that is, $M_{tR} = N_1\dot{\theta} + N_2\dot{\theta}^2$, but we can approximate and abbreviately represent it as $N\dot{\theta} \approx N_1\dot{\theta} + N_2\dot{\theta}^2$ to make formula(8) linear.

We can compute the value of N from actual ships roll record. Now, if we can solve formula (8) numerically, we can predict the biggest roll angle to be encountered and take preliminary actions in advance for the safety of our vessel. We can simplify formula(8) and solve it as follows:

$$\frac{d^2\theta}{dt^2} + N'\frac{d\theta}{dt} + \omega_s^2\theta = C'\delta(t) \qquad (8.1)$$

Operating laplace transformation and inverse laplace transformation to formula(8.1), we solve it and get formula(9) as follows:

$$\theta(t) = \theta_0 e^{-0.5N't}\sin\omega_s' t \qquad (9)$$

where, $\theta_0 = \frac{C'}{\omega_s'}$

Formula (9) is for beam sea or nearly beam sea.

3.2 Calculation of roll damp coefficient N'

In a model basin they test rolling of various model vessels assuming various cases of circumstances. But when an actual big vessel maneuvers running with considerable speed on a stormy sea of a Typoon, the roll damp coefficient got from model basin tests seems not usable due to inappropriate to actual circumstances. Therefore we can get the value of damp coefficient N' from the results of actual vessels roll records, that is as follows:

$$\theta(t) = \theta_0 e^{-0.5N't}\cos\omega_s' t \qquad (9.1)$$

$$N' = -\frac{L_n\beta}{0.25\,T_s'} \qquad (9.2)$$

where β : roll degree decreasing coefficient

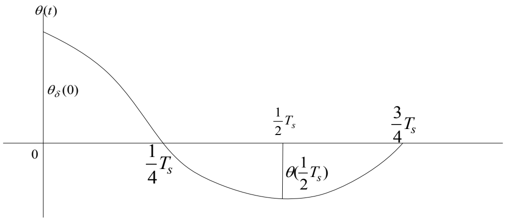

Fig. 2 damped rolling on stormy sea

The author checked and recorded great rollings on bridges of three vessels on actual stormy sea, and found for example if first rolling degree was 30^o more less, the next rolling degree(after 0.5 T_s passed) 15^o more less, that is the value of β is 0.5 more or less on the average.

4. Deciding CPA(Closest point of approach) distance to the center of Typoon

4.1 General precautions for riding out a storm safely

When a vessel is to be encountered with a tropical cyclone during her ocean sailing the master of the vessel must decide the distance of CPA to the center of the storm for riding out the storm safely. The CPA distance would be variable according to the strength of the typoon, the size of the vessel, loaded cargoes on her, the hull strength of the vessel and etc,. For example, when a vessel loaded with iron ore cargo encounters storm, she had better avoid heavy pitching motion, receiving waves from beam sea but on the other hand a vessel loaded with logs or timbers or heavy cargoes on the deck must avoid heavy rolling receiving big waves on the bow.

4.2 Evaluating numerical values of mathematic model and certifying the safety of the maneuvering vessel

4.2.1 An example of a vessel loaded with grain cargo of corn

A vessel sailing from Panama canal for Yokohama Japan is encountering with a Typoon(see fig 3 for details) about 900 miles off on SW direction. The master of the vessel intends to pass 260 mile line of CPA off the center of the Typoon on the right semi-circle of it. Where, given conditions, that is, the particular of the vessel and other data etc. are as follows:

vessel	M/V Lucky Star
G/T	10,000ton
cargo	15,650ton grain corn
$L \times B \times d(m)$	$144 \times 21 \times 10$
Fully loaded draft	8m
GM_T	1.5m
Full ahead speed	18kts
Heave to with speed of 12kts(half ahead) and wave incident angle 30^o more less	
Radius of gyration through x axis $k_x = 0.335B$	
Maximum permissible roll angle $\leq 30^o$ if possible	

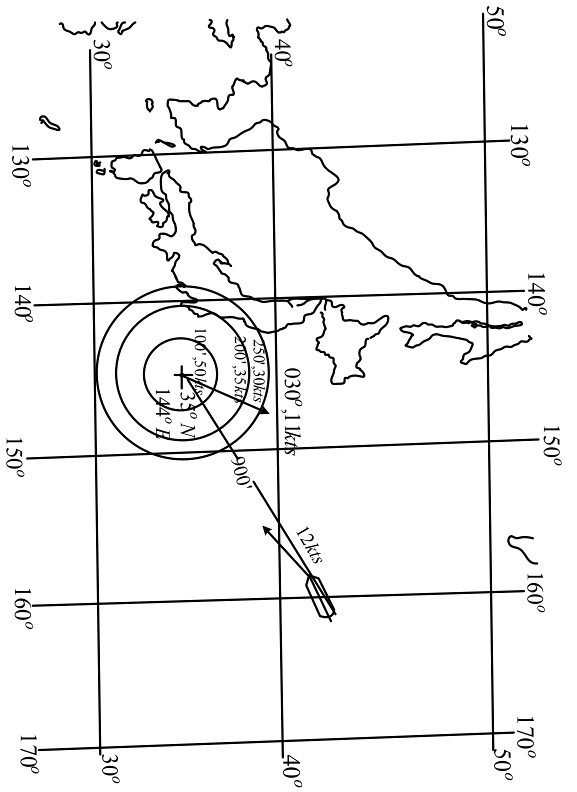

Fig. 3 example of a vessel loaded with grain cargo of corn

4.2.2 Answer

1. Significant & the highest wave height ($H_{1/3}$ and $H_{1/1000}$) calculations

a. Average wind velocity = 38.33kt

b. Fetch = 260mile = 482km

c. Duration of time = distance 900 mile/relative speed(11+12) = 39.13 hour

$H_{1/3} = 6.5m$, from formula(7), $H_{1/1000} = 12.1m$

2. maximum roll angle(θ_0) to be expected (see attached sheet 1) $\theta_0 = 30.4^o$

3. Time interval between max. waves = 2.2hours

About twice encountering during one watch time of deck officer(Refer. Attached sheet 1)

4. Probability of sea state that the height of wave is higher than that of significant wave 13.6% of all rough sea state(Refer. Attached sheet 1)

5. Degree of safety

A little bit unsafe. Recommend CPA to be about 300 miles

5. Conclusions

When we sail on rough sea of a storm, we often experience highly dangerous situation comes from the impact of a extraordinary big wave. Therefore we can conclude as follows:

(1) We are able to avoid such a dangerous situation by taking sufficiently safe CPA distance from the center of storm after computation of the sea state.

(2) In a shipyard when they complete building of a vessel, the shipyard will be able to prepare storm maneuvering guide manual appropriate for the vessel by the method mentioned above.

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ATTACHED SHEET Ⅰ

Exciting moments, moment of inertia and the other data for ships roll motion calculations etc.

1 Exciting moment C calculation(M_{T1})

(1) Moment due to free surface slope

On a rough sea of a storm sometimes an extraordinary big wave suddenly appears, seemingly like a coming steep cliff, and it gives the vessel a great impact and disappears suddenly. So we can assume the surface water slope 30 degrees more or less.

$$M_{T1} = W \cdot GM_T \tan 30^o \qquad (1.1)$$

$M_{T1} = 18{,}598 \times 1.5 \times \tan 30^o = 16106\text{ton·m}$

(2) Moment due to drifting force(F_d and M_{T2})

$$F_d = \frac{1}{2}\rho_w g \zeta_a^2 R^2 \sin\alpha \qquad (2.1)$$

$F_d = 0.5 \times 0.105 \times 9.8 \times 6.05^2 \times 154 \times 0.4^2 = 464\text{ton}$

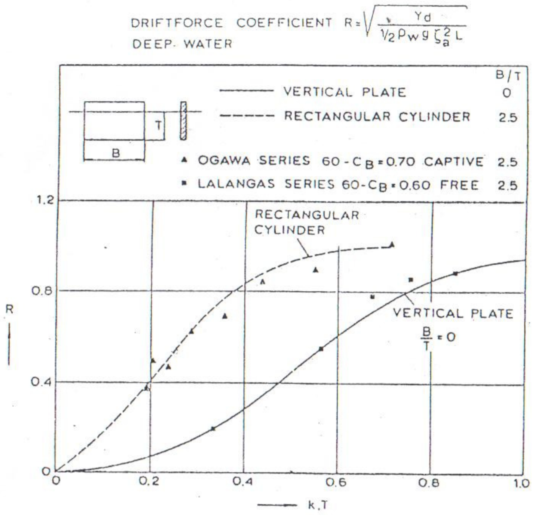

Fig. 1.1 Drift force coefficient in beam waves

(3) moment due to water particles velocities of orbit circles F_w and M_{T3}

$$\triangle F_w = \frac{1}{2}\rho_w L d_r (r\omega_w)^2 \sin^2\alpha \qquad (3.1)$$

where, α : wave incident angle $\approx 90^o$

$$F_w = \frac{1}{2}\rho_w L \omega_w^2 \int_{-r}^{r} r^2 dr$$

$= 0.3333 \times 0.105 \times 154 \times (0.4486)^2 \times 6.1^3 = 246\text{ton·m}$

$M_{T3} = 246 \times 5 = 1230\text{ton·m}$

(4) moment due to wind velocity(M_{T4})(Yoon, 1987, 2009)

$M_{T4} = 53 \times 10 = 530\text{ton·m}$

(5) moment due to wind generated current force (M_{T5})

$M_{T5} = 36 \times 5 = 180\text{ton·m}$

(6) unknown rough sea factor (M_{T6})

No matter how hard we try to compute correct sea state of rough sea, it is impossible to compute exact values of a natural seaway. So we had better add unknown safety factor to the computed C value by 30% of it.

$M_{T6} = 0.3 \times$ computed C value

Total C value = 1.3(16106+2320+1230+530+180)
= 26,476ton·m

2. moment of inertia($I_x + i_x$)

$$I_x + i_x = \frac{18598}{9.8} \times (0.335 \times 21)^2 = 93922\text{ton·m}$$

3. C' value calculation

$$C' = \frac{C}{(I_x + i_x)} = 0.2819/\text{sec}$$

4. Ship's roll frequency (ω_s) calculation

ω_s=0.545rad/sec

5. ω_s' calculation

$$\omega_s' = \sqrt{\omega_s^2 - (0.5N)^2} = 0.5315/\text{sec}$$

6. maximum roll angle(θ_0) calculation

$$\theta_0 = \frac{C'}{\omega_s'} \times 57.3^o = 0.5304 \times 57.3^o = 30.4^o$$

7. calculation of time interval between two maximum waves

Average wave height = $\frac{2.5}{4.0} \times H_{1/3} = 4.1m$

$T_{1/3} = 7.9\text{sec}$, $7.9 \times 1000 = 7900\text{sec}$

$7900 \div 3600 = 2.2hour$

8. calculation of probability

$$P(h > H_i) = \text{Exp}(-H_i^2/\overline{H^2})$$

$H_i = 6.5m$, $\overline{H} = 4.6m$, $P = e^{-1.997} = 0.136$

Percentage = $0.136 \times 100 = 13.6\%$ of all rough sea state

ATTACHED SHEET II

Disastrous maritime accidents that occurred due to extraordinary great waves are as follows:

1. Tanker World Concord fracturing(Yoon, 2009)

(1) ship's particular & etc.

1) $L\times B\times D=223\times 31.7\times 17.3(m)$

2) G/T : 33,768ton

3) D/W : 54,271 ton

4) cargo tanks : No. 1, 3, 5 full
No. 2, 4 empty

(2) Time & place

1954. 11. 27. at dawn(0125) offshore sea of Seilly Islands

(3) Accident

The hull broke into two parts and parted off with an explosive sound of a cannon firing.

(4) Encountered waves

Two successively coming big waves of about 11m high from st'd bow.

2. Ore Carrier M/V Haedang Hwa missing

(1) ship's particular & etc.

1) $L\times B\times D=259\times 39.6\times 19.7(m)$

2) G/T : 56,861ton

3) D/W : 102,805 ton

4) cargo : Iron ore 98,802 L/T of Australia

(2) Time & place

1980. 7. 23. afternoon,
60 mile off east coast of Mindanao, Philippines

(3) Accident

Missing

(4) Encountered heavy sea within 100miles of Typhoon Kim 965 hpa

3. Ore Carrier M/V Derbyshire missing

(1) ship's particular & etc.

Almost same as M/V Haedang Wha.

(2) Time & place

1980. 9. 10. afternoon,
Near east coast of Okinawa, Japan

(3) Accident

Missing

(4) Development of accident

Loaded iron ore bulk cargo of 100,000 ton at Canada Port and sailed for Tokyo via Cape Town. At noon of 10th, sept. she reported "650 miles to destination. Now maneuvering heave to amidst Typhoon Kim". After the report she was missed and about 20 years after she had been found fractured at no. 1 hatch coaming.

4. Bulk Carrier M/V Onomichi-maru destruction and sinking

(1) ship's particular & etc.

1) $L\times B\times D=218\times 31.7\times 17.3(m)$

2) D/W : 56,341 ton

3) cargo : Fully loaded bulk coal

(2) Time & place

1980. 12. 30. 1400hours,
About 900 miles east of Nojimasaki, Japan.

(3) Accident

Destructed and sank

(4) Development of accident

M/V Onomichi-maru sailed from east coast of U.S.A. for Japan fully loaded with bulk coal. She maneuvered heave to with 5kts receiving waves of 8 or 9 meter high about 20^o from port bow. At about 1400 hours an extraordinary big wave of 13 meter more or less struck port bow and she did great slamming and her bow dived deeply into water that made about 5 degree bucking of bow part of no. 1 cargo hold upward and the bow part parted off from main hull after about 2 hours. She sunk during being towed by an ocean tug. All crew were saved.

5. Container vessel M/V Hanjin-Inchon missing

(1) ship's particular & etc.

1) $L\times B\times D=200.6\times 23.8\times 14.0(m)$

2) G/T : 17,676ton

3) cargo capacity : 1150 TEU(Twenty foot equivalent unit)

4) cargoes : Fully loaded in holds and on decks.

(2) Time & place

1987. 2. 13., between 0200~0300 hours

(3) Accident

Missing

(4) Development of accident

M/V Hanjin-Inchon sailed from Seattle, west coast of U.S.A. for Busan, Korea. She encountered with an extratropical cyclone of 980 hpa and received extraordinary big waves from st'd beam sea and capsized and sank near the southern end of Kamchatka Perinsular.

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