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# A Proposed Standard of Stability for Passenger Ships

## (Part III : Ocean-going and Coasting Ships)

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Abstract

The authors have developed a standard of stability for passenger ships in Ocean-going and Coasting Services. This standard was worked out in a similar manner as that for Smooth Water Area and Small Crafts by the Ministry of Transportation with cooperation of Tokyo and Kyushu Universities, Nippon Kaiji Kyokai, etc.

In preparing this standard, investigations have been made on various elements of external forces affecting stability such as wind, waves, shipping of sea water, shift of weights aboard, steering, as well as metacentric height, dynamical stability, maximum righting arm, etc. : whereupon the method of comprehensive judgement of the stability has been developed as follows :

(1) Criterion by dynamical stability

Among external forces, effects of wind and waves have been considered. Let us assume that, a ship is listed under the statical transverse heeling moment due to steady wind, and the ship is subjected dynamically to a gust when the ship is at the maximum angle of roll due to waves windward. In order that the ship has sufficient dynamical stability,

$$\text{work ratio} \quad C > 1$$

(2) Criterion by maximum righting arm

As external forces, shipping of sea water, shift of heavy weights aboard, steering, etc. have been considered. $GZ_m$ must satisfy either of the following formulæ.

$$GZ_m \geqq 0.0215\,B \quad \text{or} \quad GZ_m \geqq 0.275 \text{ (m)}$$

(3) Criterion by metacentric height

As the criterion by GM is same as that for ships engaged in Smooth Water Area when wind pressure and shift of passengers have been taken into consideration.

$$GM \geqq (1.1\,Ah + \sum kn\bar{B})B/100\,f\varDelta, \quad f \leqq B/5.5.$$

## §1. Foreword

The authors have recently proposed standards of stability for passenger ships in Smooth Water Area [1] and for those of small size [2]. As a further extension of this series of work, the authors have successfully developed a standard for passenger ships in Ocean-going and Coasting Services, and they are pleased to present it in this paper.

The general task of working out standards of stability for passenger ships has thus been

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completed, at least tentatively, and the Ministry of Transportation is expected to incorporate these proposed standards into the Ships Safety Law and its related regulations.

The work has been drawn up by Ministry of Transportation's "Ships Safety Law and Its Related Regulations Revisory Panel" and then reviewed by a committee representing Tokyo and Kyushu Universities, Nippon Kaiji Kyokai (classification society), Japanese Shipowners' Association, Shipbuilders' Association of Japan, etc.

In the course of preparation of these standards, comprehensive investigations and analyses were carried out, and some of the works were made public previously by those responsible. [3], [4] and [5]. Referring to these papers, the authors attempt to give an account of the proposed standard and how it has been arrived at.

In other countries, the United States [6] and U.S.S.R. [7] have their own standards of stability, which do not however incorporate the effect of waves. The authors believe that theirs is the first to take such an effect into account. It does not of course follow that the authors regard this standard as consummate in itself. It is the authors' earnest hope that still better standards be developed, making this standard as a stepping stone.

## § 2. Principles

### (1) Classification of Ships

The current regulations classify the plying limits of vessels into Ocean-going, Greater Coasting, Coasting and Smooth Water Areas. For the purpose of applying a standard of stability, it is thought unfair to apply the same standard for Coasting ships to ships engaged in Seto Inland Sea service or those running only a short voyage out into Coasting Area. These ships should therefore be treated separately. On the other hand, Ocean-going ships and Greater Coasting ships encounter no noticeably different sea conditions so that they may be dealt with in the same category. Consequently, all ships, except those of Smooth Water Area, can be divided into the following three classes :

(i) Ocean-going (Regulations' Ocean-going and Greater Coasting)

(ii) Coasting-I (Regulations' general Coasting)

(iii) Coasting-II (Regulations' Coasting ships but navigating in Seto Inland Sea only, or with scheduled voyage less than 2 hours in the Coasting Area.)

### (2) Conditions of Ships

A ship must maintain ample stability in all service conditions. It is therefore sufficient to take the worst stability condition alone as the basis for criterion. However, it is difficult to define such a worst condition in a simple manner. On the other hand, calculation of stability in every possible service condition is a nuisance. The best solution therefore is to select several conditions of a ship and to see if the requirement is met in these conditions. The authors, giving due regard to size and plying limits of ships, have thought fit to designate the condi-

Table 1

| Condition of Ship | Ocean-going | Coasting-I and Coasting-II |
|---|---|---|
| Light | ○ | ○ |
| Ballast, at Departure | ○ | ○ |
| 〃 at Arrival | ○ | ○ |
| Full-load, at Departure | ○ | ○ |
| 〃 50% Consumed | ○ | — |
| 〃 80% Consumed | ○ | — |
| 〃 at Arrival | ○ | ○ |

tions given in Table 1. This question will be discussed further in §9.

(3) **Effective Buoyancy**

In stability calculation, it is necessary to define the limits of buoyancy. The authors have deemed it fit to adopt the following principles :

(i) Side-to-side erections and other similarly effective superstructures will be included in the buoyancy.

(ii) If there is an opening in a part of the ship included in the buoyancy, and if such an opening has ineffective means of closing whether in design, strength or watertightness, it is considered open to sea. When the ship inclines past the angle of immersion of the lower end of such an opening (hereinafter called the angle of flooding), the buoyancy of the ship is considered no longer effective. Consequently, the stability curve holds good only up to the angle fo flooding, as shown in Fig. 1.

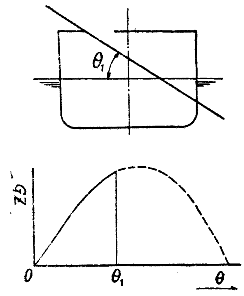


Fig. 1

## §3. External Forces and their Estimation

(1) **External Forces to be Considered**

As the external forces affecting the stability of a ship, the following factors may be considered :

(i) Wind
(ii) Waves
(iii) Shipping of sea water
(iv) Shift of weights aboard
(v) Steering
etc.

It is very difficult, if not impossible, under the present circumstances, to ascertain all the effects of these external forces and determine the stability required to withstand these effects. The authors have attempted to take into their account as much effects of these external forces, direct or indirect, as possible, and have finally adopted the methods given in (3), (4) and (5) below.

(2) **Elements of Stability to be Considered**

Stability of a ship comprises various elements. In usual practice, such elements as metacentric height, dynamical stability, maximum righting arm and vanishing angle of stability are given suitable values so as to insure ample stability for a ship in design. If any two of the last three elements, dynamical stability, maximum righting arm and vanishing angle of stability, are fixed, the third one may be approximated automatically. Thus, the following three elements were selected as the measures of stability :

(i) Dynamical stability ($S_d$)
(ii) Maximum righting arm ($GZ_m$)
(iii) Metacentric height (GM)

The authors have related these elements with the effects of external forces enumerated in (1) above, and have worked out the following three criteria (3), (4) and (5), to all of which a ship must conform.

(3) **Criterion by Dynamical Stability**

Among external forces, effects of wind and waves are considered primarily in the calculation. Let us assume that, as shown in Fig. 2, a ship is listed $\theta_s$ under the statical transverse heeling moment (due mainly to steady wind), and rolls $\theta_0$ and $\theta_0'$ from side to side about $\theta_s$, and then the ship is subjected to a gust when the ship is at the maximum angle of roll $\theta_0$ win-

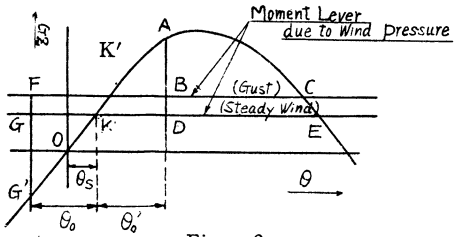


Fig. 2

dward. In order that the ship does not capsize,

Area ABC > Area BFGD

or Area AK'C > Area K'FG'

Let Area AK'C $=b$, Area K'FG' $=a$, and

$$C=b/a \tag{1}$$

It follows then that this $C$ must be greater than unit, if the ship is not to capsize. It contains, however, so many elusive factors that it is not amenable to calculation. It is therefore practicable to determine the critical value of $C$ empirically from available data of sunken and existing ships. It may be in order to add here that the authors are aware of other express ions of $C$ suggested in the past, [4], [8], [9] and [10], which were thoroughly examined before adopting the expression (1) above.

(4) **Criterion by Maximum Righting Arm**

In giving an adequate value for the maximum righting arm, to ascertain all the external forces and calculate the theoretical value is not an easy task. Here, therefore, an attempt will be made to relate the maximum righting arm, in abstract terms, with such other external forces than wind and waves that are covered in (3) above, as shipping of seawater, shift of heavy weights aboard, steering, etc.

Let us consider the case when a ship rolled to a swing end. Let absolute angle of roll be $\theta'$, relative angle of roll $\theta_a'$, displacement $\varDelta$, and moment of inertia $I$, then

$$I\frac{d^2\theta'}{dt^2}=-\varDelta \mathrm{GZ}(\theta_a')$$

Let $B$=breadth of ship, $k_1B$=radius of gyration, $\alpha_p$=accelaration of a point P at a distance $k_2B$ from the ship's centerline, and $g$=gravitational acceleration, then

$$I=\frac{\varDelta}{g}k_1^2B^2, \quad \frac{d^2\theta'}{dt^2}=\frac{\alpha_p}{k_2B}$$

Therefore,

$$\frac{\alpha_p}{g}=-\frac{k_2}{k_1^2}\frac{\mathrm{GZ}(\theta_a')}{B}$$

This equation implies that $\alpha_p$ depends on $\mathrm{GZ}(\theta_a')/B$, and also that the greater the value of $\mathrm{GZ}(\theta_a')/B$, hence $\alpha_p$, the better the ship's righting ability from a swing end. The latter may be expressed as :

$$\frac{\mathrm{GZ}(\theta_a')}{B}>k_3 \tag{2}$$

Assuming that a ship has listed $\theta_a'$, and received a sudden heeling moment of $M$, the following condition is required for the ship to remain stable :

$$\varDelta \mathrm{GZ}(\theta_a')>M \tag{3}$$

As $M$, let us take the moment due to shipping of seawater or shift of weights aboard the ship. Then the arm length of this type of moment is relative to the athwartship dimension of the ship, and hence may be expressed as $k_4B$. If the moment is caused by a force $F$,

$$M=k_4FB$$

Magnitude of shipped seawater and moving weights may be assumed relative to the size of a ship. Thus,

$$F=k_5\varDelta$$

Therefore.

$$M=k_4k_5\varDelta B=k_6\varDelta B$$

Substituting this into equation (3), we have

$$\frac{\mathrm{GZ}(\theta_a')}{B}>k_6 \tag{4}$$

Thus we have the same type of equation as (2). It may be said therefore that the righting ability of a ship has an important relation with the degree of its safety.

The value of $\theta_a'$ must be chosen when the ship has the least GZ and at the greatest possible angle of heel. Specifically, it seems suitable to take the maximum angle of heel when the moment due to wind pressure and rolling due to waves act simultaneously. It is not however so easy and simple to obtain $\theta_a'$ among irregular waves. As $\theta_a'$ is close to $\theta_m$ (angle of heel at $GZ_m$), and the form of GZ-curves does not seem to differ much from each other in different ships, it seems safe to determine $GZ_m/B$ in place of $GZ(\theta_a')/B$.

$$\frac{GZ_m}{B} > k_6' \qquad (5)$$

As the critical value of $k_6'$ is not readily amenable to theoretical calculation, it must be derived from data of actual ships.

Next, as another type of $M$, let us take the moment due to steering. Let the force acting upon the rudder be $F$, and the distance from the ship's C.G. to the center of effort $F$ be $h$, then,

$$M = Fh$$

Therefore,
$$\frac{GZ(\theta_a')}{B} > \frac{Fh}{\varDelta B}$$

In actual cases, the calculated values of this criterion are far smaller than the critical values of $GZ_m$ which is given by equation (5) above and described further in §7. Thus, it is thought unnecessary to take this factor into consideration, except for high-speed ships.

(5) **Criterion by Metacentric Height**

Ocean-going and Coasting ships must of course conform to the basic requirements for ships in Smooth Water Area [1]. As external forces, wind pressure and shift of passenger are considered in a similar manner to arrive at a suitable value of GM.

## §4. Values of Wind Velocity and Angle of Roll to be Used in Criteria

(1) **Type of Ocean Winds to be Used for Each Plying Limit**

Ocean winds may be divided, according to the paper [3], into the following types by their cause :

(i) Barometric gradient
(ii) Front
(iii) Lows
(iv) Typhoons

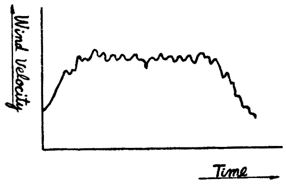


Fig. 3

As depicted in Fig. 3, barometric gradients and fronts blow for a relatively long duration, but their strength is not so great, being 10 to 15 m/sec at the strongest. These types of wind occur very frequently, and are likely to attack ships near the coast without warning. It may be recalled that, for small craft [2], barometric gradient of 10 m/sec (In the standard for small crafts, moment due to wind pressure is not considered directly, but comes in the form of a margin for maximum angle of heel.), and for smooth water vessels [1], front of 15 m/sec have been assumed. It seems in order then to take the front for Coasting-II class of ships.

In lows and typhoons, as shown in Fig. 4, wind force is the strongest at their center, where the direction is reversed, and after that the trailing steady wind continues to blow. At their centers, the wind velocity reaches as high as 32 m/sec in lows,

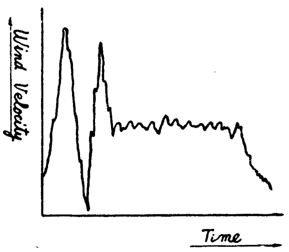


Fig. 4

and 50 m/sec in typhoons. In the trailing steady wind, it may be up to 15 m/sec in lows and 20 m/sec in typhoons and accelerates the growth of the sea. It seems appropriate to set the standard of stability, for Coasting-I class ships as to withstand lows, and for Ocean-going class ships to hold against typhoons, because the latter sometimes may have to run into typhoons even though aware of such warnings.

From the foregoing discussions, the type of wind and its approximate velocity to be used for each plying limit may be summarized as shown on Table 2.

Table 2.

| Cause or Type of Wind | Average Velocity of Trailing Steady Wind (m/sec) | Maximum Wind Velocity at Center (m/sec) | Applicable Class of Ships |
|---|---|---|---|
| Barometric gradient | 10 | —— | Small crafts [2] |
| Front | 15 | —— | Smooth Water ships [1] and Coasting-II class ships |
| Low | 15 | 32 | Coasting-I class ships |
| Typhoon | 20 | 50 | Ocean-going class ships |

(2) **Sea Conditions in Storms and Their Effect on the Critical Angle of Roll**

Apart from barometric gradients and fronts as shown in Fig. 3, lows and typhoons of the type as shown in Fig. 4 give rise to a question as to where it is the most dangerous to ships and thus the standard should be based on. Let us suppose that a typhoon passes through a ship's position. At the center of the typhoon, the wind is very strong, but it soon changes its direction 180 degrees, thus causing the waves to interfere and become very irregular, in which the rolling of the ship is not so violent. As the typhoon center moves away, the wind velocity decreases somewhat, but the waves grow and become increasingly regular, incurring heavier rolling to the ship. Amongst the trailing steady wind, the waves become highly developed, but the wind velocity continues to decrease. This relation is illustrated in Fig. 5, where $\theta_0$ is the angle of rolling and $\theta_{syn}$ is the angle of synchronous rolling among the waves that could have been developed and regularized by the wind force at such a position.

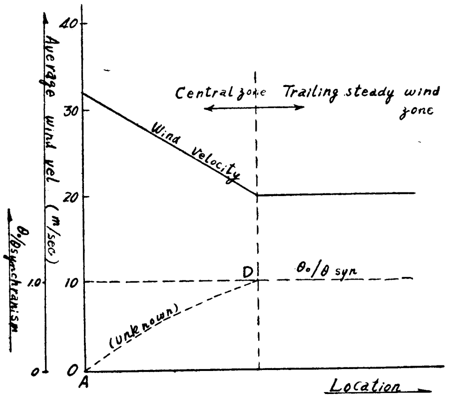



Fig. 5

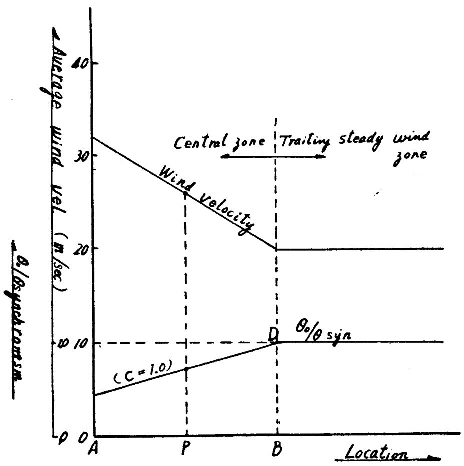



Fig. 6

It is impossible to find how the critical angle of inclination under the combined effects of wind and rolling, or $C$ $(=b/a)$ given in equation (1), should vary unless it is known how the irregularity of waves varies as the center moves away. However, in order for the vessels having the value of $C=1$ in the trailing steady wind to manitain the condition of $C=1$ at higher wind velocity, calculations based on a few examples indicate that the critical angle of rolling must be reduced as shown in Fig. 6. If the angle of rolling due to irregular waves is less than that of Fig. 6, namely, if Fig. 5's AD-curve comes below Fig. 6's AD-curve, it follows that the standard of stability may be determined by the two points, center A and periphery B, or by one mid-point P. The paper [4] chooses points A and B, but here the authors have chosen the other alternative of a point in the middle of points A and B, where the wind force is a little stronger than that in the trailing wind but the critical angle of rolling is a little smaller than that in the regular waves.

## § 5. Standard Value of Wind Velocity

### (1) Steady Wind

As mentioned in § 4, the standard value of the statically inclining steady wind velocity is selected at the middle point between the center of typhoon or low, and the trailing steady wind zone. Firstly, from actual ship's data described later in § 7, and secondly from the worst possible condition that may be encountered by a ship, the standard value of 26 m/sec for Ocean-going and 19 m/sec for Coasting-I have been adopted. For Coasting-II, it was taken at 15 m/sec.

Inclining arm due to steady wind pressure will be calculated in the same manner as before : Namely, assuming that the wind blows transversely, it is given by

$$D_w = 0.76 \times 10^{-4}\, V^2 Ah/\Delta \qquad (6)$$

Where, $D_w$ = Inclining arm due to wind pressure (m)

$V$ = Standard wind velocity (m/sec)

$A$ = Lateral area of the part of the ship above water line ($m^2$)

$h$ = Vertical height of C. G. of A above the half-draft point (m)

$\Delta$ = Displacement of the ship (T)

In addition, the effects of the angle of inclination is neglected here.

### (2) Gustiness

As shown in Fig. 2, the criterion by dynamical stability assumes that a ship receives a gust at the swing end to windward. For this purpose, the degree of fluctuation in the wind velocity, or the "gustiness," must be determined. Fig. 7 shows the ratio of gustiness over the

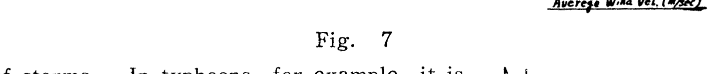



Fig. 7

whole range of storms. In typhoons, for example, it is 1.7 at the maximum, and on the average it is 1.23. But this value represents, of the minute features of fluctuation as shown in Fig. 8, only $(\bar{V}_{max}-\bar{V})/\bar{V}$, which is made up of the average fluctuation of a relatively long duration. In actual cases, however, the fluctuations that may cause a ship to capsize are the ones of a duration half the rolling period of ships, or specifically 3 to 8

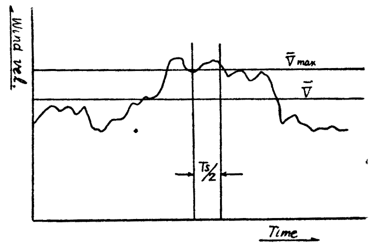



Fig. 8

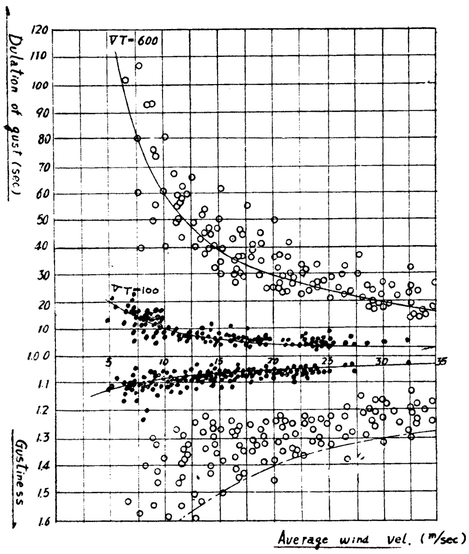


Fig. 9

seconds. It is apparently too rigorous to take $(\bar{V}_{max}-\bar{V})/\bar{V}$ as the gustiness of a gust in Fig. 2. From this view point, duration and intensity of gust are plotted along the base of average wind velocity and presented in Fig. 9. On the upper section is shown the duration of gust, and on the lower section the corresponding gustiness, or relative intensity. This plot indicates that

(i) Duration of gust may be divided roughly into two groups :

$VT=600$ and $VT=100$.

(ii) Gusts of longer duration are stronger in intensity.

(iii) As the average velocity increases, the gustiness decreases.

These findings suggest that, for the gustiness of a gust for the purpose of Fig. 2, relatively small value should be assumed.

Furthermore, considering the tendency that, under gusts, the center of reaction of a ship rises above the statical center under steady wind pressure, thus reducing the value of $h$ in equation (6), and also that the relative wind velocity decreases due to drift of the ship, the gustiness ratio of $\sqrt{1.5}$ ($\doteqdot 1.23$) has been specified. Consequently, the fluctuation in inclining arm due to wind pressure becomes, from equation (6),

$$\delta D_w/D_w=1.5 \qquad (7)$$

## §6. Waves and Rolling of Ships

### (1) Relation between Wind and Wave

According to the famous paper by H. U. Sverdrup and W. H. Muuk [11], the relation between wave steepness $\delta$ and wave age $\beta$ is given as shown in Fig. 10. This figure can be expressed by the dotted lines in Fig. 11 on the basis of wave period when the wind volocity is taken as a parameter.

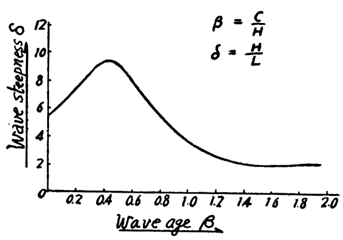


Fig. 10

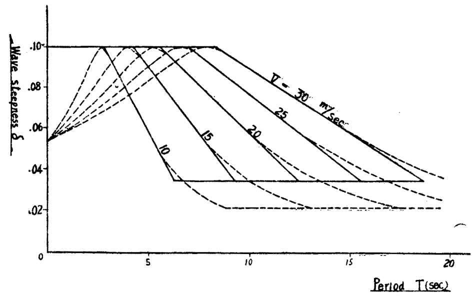


Fig. 11

Assuming that a ship, having the period of rolling $T_S$, encounters with a wave originated by a wind of certain velocity, the severest rolling of this ship may take place when she synchronizes with the wave, that is, when she encounters with the wave of the period $T_S$. Therefore the steepness of this wave can be obtained from Fig. 11. In constant wind velocity, the ship having longer period of rolling may only synchronize with the wave of greater age, that is, of smaller steepness.

The authors adopt, as a standard, the wave steepness corresponding to the rolling period of the ship and standard wind velocity obtained by Fig. 11. In this case, the following assumption is put forth for the convenience's sake.

(i) In the sea area where the wind of certain velocity blows, the wave originated by the wind of smaller velocity can be co-existed. In other words, for all periods smaller than those corresponding to the maximum values of $\delta$-curves, maximum value of $\delta$ is taken as the value of $\delta$.

(ii) Although Fig. 11 indicates that the steepness of the waves of longer period becomes very small, 0.035 ($\doteqdot$1/30) is taken as the minimum wave steepness taking into account the swell transmitted from other sea area and the irregularity of waves.

(iii) $\delta$-curves between the maximum and minimum wave steepnesses thus determined according to (i) and (ii) may be regarded as straight lines as obviously shown in Fig. 11.

From the above assumptions, the wave steepness to be used for the standard is derived given by solid lines in Fig. 11 according to the rolling period of actual ships and the standard wind velocity.

(2) **Synchronized Rolling Angle amongst Regular Waves**

The synchronised rolling angle of the ship amongst regular waves can be desermined by the following formula.

$$\theta_{\text{syn}}=\sqrt{\frac{\pi\gamma\Theta_w}{2N}} \qquad (8)$$

Where, $\Theta_w$ = Surface wave slope = $\pi\delta$

$\gamma$ = Effective wave slope coefficient

$N$ = Bertin's extinction coefficient

Although the precise formula of $\gamma$ has been developed by Y. Watanabe [14] and [15], in this paper the value of $\gamma$ is calculated by the following formula for the sake of simplification, taking into account the fact that the calculated values of $\gamma$ as to 60 actual ships are as shown in Fig. 12.

$$\gamma=0.73+0.60\frac{OG}{d} \qquad (9)$$

Where, $d$ = Draft of ship (m)

OG = Vertical distance from the water line to the center of gravity of the ship (m) (Positive above water line)

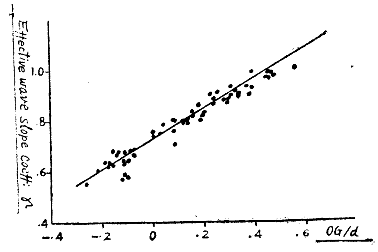



Fig. 12

Concerning $N$, since there is no reliable formula or curve at present, it is taken as 0.02 provisionally for ships of ordinary form having bilge keel.

In determining $\delta$ from Fig. 11, $T_s$ is obtained by H. Kato's presumption method [16] and [10] or by Rollzahl method where it is unknown.

(3) **Irregularity of Waves**

As both period and height of ocean waves are irregular, the rolling of ships amongst them are not uniform. With regard to the irregularity of waves, it is known that there are a few statistical laws; that is, as ascertained by Jr. G. Neuman [17], when the wave frequency is taken as $\omega$ and the amplitude $r(\omega)$, the spectrogram of the wave $[r(\omega)]^2$ has approximately constant distribution as far as the fully arisen sea is concernened as exemplified in Fig. 14. It has also been ascertained by M. S. Longuet-Higgins [18] that between the area of this $[r(\omega)]^2$ curve, $R(\omega)=\int_0^\infty[r(\omega)]^2d\omega$ (which is called as cumulative energy density), and the statistical quantity of the irregularity of waves the relation indicated by Table 3 exists.

Table 3.

| | |
|---|---|
| Average height of waves | $0.886\sqrt{R}$ |
| Height of the wave most frequently encountered | $0.707\sqrt{R}$ |
| Significant wave height (average value out of 1/3 from the highest wave) | $1.416\sqrt{R}$ |
| Average wave height out of 1/10 from the highest wave | $1.800\sqrt{R}$ |

On the other hand, when observing a series of waves, exceptionally big waves may occasionally come, the height of which varies according to the number of waves passing by; and the height of the biggest wave included in the group of the waves usually increases as the number of waves passing by increases. This relation is indicated in Table 4.

Table 4.

| | |
|---|---|
| Maximum wave height within 20 waves | $1.87\sqrt{R}$ |
| Maximum wave height within 50 waves | $2.12\sqrt{R}$ |
| Maximum wave height within 100 waves | $2.28\sqrt{R}$ |
| Maximum wave height within 200 waves | $2.43\sqrt{R}$ |
| Maximum wave height within 500 waves | $2.60\sqrt{R}$ |
| Maximum wave height within 1000 waves | $2.73\sqrt{R}$ |

## (4) Rolling of Ships amongst Irregular Waves

It is a matter of course that the rolling of ships amongst irregular waves has different aspects from that amongst regular waves. One of them is that, whilst the resonance curve in irregular waves has a steep crest at the synchronism, in irregular waves the crest of the curve at the synchronism becomes low, because the number of waves enough to cause the perfect synchronism do not come successively. Outside of the synchronism, on the contrary, there is a possibility, due to the irregularity of waves, that waves of the nearly synchronized period may occasionally come. Consequently the rolling curve tends to be as shown Fig. 13. The other one is that, since in irregular waves big and small rolling angles are mingled, the analyses on the rolling amplitude similar to those on the wave amplitude indicate that the relation between cumulative energy density and amplitude is the same as those given in Table 3 and Table 4 mentioned above.

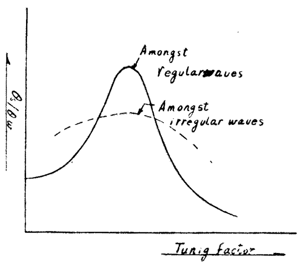
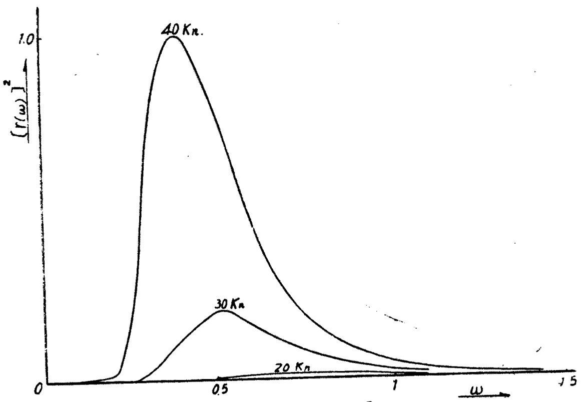


Fig. 13

With regard to the rolling of ships amongst irregular waves, M. St. Denis and W. J. Pierson [19] state on the theoretical solution. Now, the authors attempt to carry out the calculation in accordance with this method.



Neumann Spectrum of Wave Energy for Fully Arisen Sea

Fig. 14

Since the significant wave height of a series of waves having the spectrogram as shown in Fig. 14 is given by $1.416\sqrt{R}$ according to Table 3, this value coinsides with the wave height when such series of waves are represented by the regular wave. Now, let us assume that, amongst unit waves having such a height and frequency $\omega_1$, resonace curve of the ship is given by solid line in Fig. 15. Thence, the rolling angle amongst irregular waves distributed as shown in Fig. 14 can be derived from Table 3 and Table 4 as shown by dotted lines in Fig. 15 by computing the energy density of the rolling of ships. As shown in the figure, mean amplitude is far smaller than that in irregular waves and the significant amplitude is also smaller. The question to be considered, however, is big rollings occasionally occur. It is the matter of the probability that the maximum amplitude among what number of rolling should be taken. When the maximum rolling amplitude out of 20 to 50 rollings is considered taking into account the fact that its phase rarely coinsides with that of a gust, it becomes approximately 0.7 time the rolling amplitude amongst regular waves.

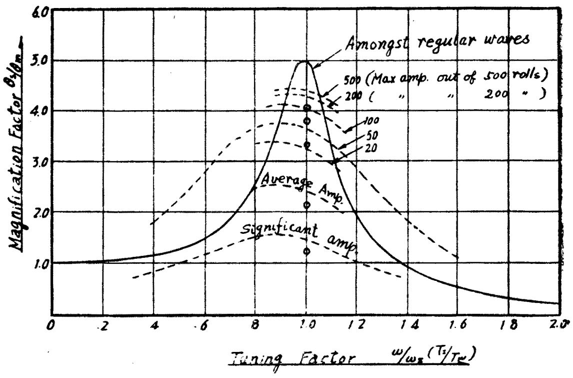



Fig. 15

On the other hand, the rolling angles, calculated by equation (8) according to the results of the experiments of NISSEI MARU [20] and HOKUTO MARU, amongst the synchronized waves possibly caused by the wind velocities at the time of experiments are as expressed by the solid lines in Figs. 16 and 17 respectively; whereas the rolling angles measured then are as plotted in the same figures. As these measured values indicate the heel angles including the effect of the wind rather than the rolling angles, they must be bigger than the rolling angles theoretically. However, both in Fig. 16 and 17, they are considerably smaller than the calculated values by equation (8).

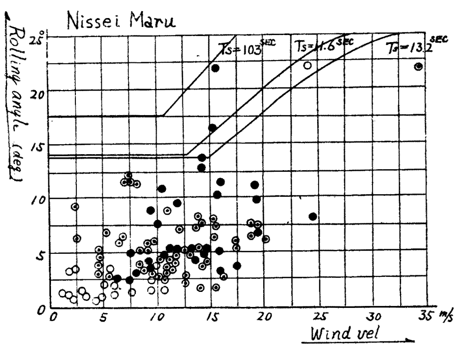



Fig. 16

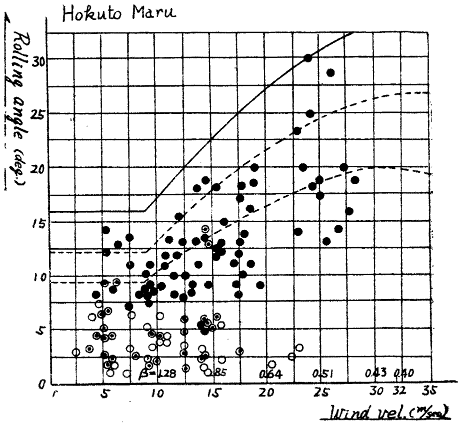



Fig. 17

Taking into account the afore-mentioned fact, the rolling angle of a ship is taken as 0.7 time the synchronized rolling angle amongst regular waves.

Accordingly, $\theta_0 = 0.7\,\theta_{syn}$

Therefore, from equation (8), we have

$$\theta_0 = \sqrt{138.5\,\gamma\delta/N} \quad \text{(degree)} \qquad (10)$$

From the above and from §4 and §5 wind, wave, rolling angle, etc. eventually become to be as given in Table 5.

Table 5.

| Ship | Cause of Winds | Standard Wind Velocity | Gustiness | $\theta_0/\theta_{syn}$ |
|---|---|---|---|---|
| Ocean-going | Typhoons | 26 m/sec | $\sqrt{1.5}$ | 0.7 |
| Coasting-I | Lows | 19 m/sec | $\sqrt{1.5}$ | 0.7 |
| Coasting-II | Fronts | 15 m/sec | $\sqrt{1.5}$ | 0.7 |

## § 7. Determination of Stability Criterions

### (1) Critical Value of C

Fig. 18 indicates the values of $C$ $(=b/a)$ calculated by equation (1) as to 57 conditions of 50 ships having available data, using equations (6), (7), (9), (10) and Fig. 11 and taking the velocity of steay wind within the range of 15 m/sec to 30 m/sec. The calculation has been made on the worst stability conditions that the ships may be subjected. In determining the critical value of $C$ from this figure, attention is to be paid to the following ships.

C-3 indicates the condition, at the time of casualty, of a sunken passenger ship (Coasting-II). C-19 and 20 are for passenger ships which have been given warning due to the insufficie ncy of the stability. For these ships it is rather $GZ_m$, which will be mentioned later, than $C$ that does not reach to the critical value. C-2, 6, 16, 18, 21, 22, 23, 24, 25 and 27 are for existing passenger ships (Coasting-II).

C-7 is for a passenger ship (Coasting-I) which has been found safe after rolling to about 25 degrees under the wind of 17 m/sec velocity. C-8-I represents the condition, at the time of casualty, of a sunken passenger ship (Coasting-I) ; C-8-II the full loaded condition in which the stability was considered insufficient, and C-8-III the condition after the renovation in which the stability was adequate. C-9 is for an existing passenger ship (Coasting-I) in which the angle of flooding is about 24 degrees due to the opened stairway located at the ship's side of the upper deck. If this opening is effectively closed, $C$ will increase considerably. C-13-I represent the condition, at the time of casualty, of a sunken passenger ship (Coasting-I), and C-13-II the full loaded condition of the same ship. C-28 to 37 are for ferry boats between Aomori and Hakodate (Coasting-I), Although some values of $C$, for instance C-34-I, represent the condition, at the time of casualty, of the sunken ship, the critical value of $C$ for Coasting-I can not be determined from these data, because the weather condition at sea then was considered abnormal as for this coasting area. C-35-I and 37-I represent the condition of the ships which stood against the stormy weather at that time. C-1, 4, 5, 10, 11, 12, 14, 15, 17 and 26 are for existing passenger ships (Coasting-I).

O-1 and 2 are for cargo ships (Ocean-going) which were deemed to have insufficient stability. For these ships $GZ_m$ is under critical value, mentioned later, rather than the value of $C$. O-3, 7 and 9 are for existing passenger ships (Ocean-going). As the structures above the upper deck were excluded from the effective buoyancy for these ships, actual value of $C$ may increase due to the effect of superstructures. O-8 to 11 are for large passenger ships (Ocean-going) which have ample stability. O-12-I represents the the condition, at the time of casualty, of a sunken torpedo boat (Ocean-going), and C-12-II the condition after the renovation in which the stability has been made ample. O-13 represents the condition, at the time of causalty, of a sunken destroyer (Ocean-going). O-4, 5 and 6 are for existing passenger ships (Ocean-going).

From the above data, it is considered advisable to take the critical value of $C$ as 1.0 for standard wind velocities of 26 m/sec, 19 m/sec. and 15 m/sec according as Ocean-going, Coasting-I and Coasting-II respectively.

Next, in order to compare the above critical value of $C$ $(C=1.0)$ with the critical value of

$C_1$ ($C_1$=0.8) described in the paper [4], calculations have been made according to both methods, whereupon it has been ascertained that $C_1$ (Coasting)=0.8 corresponds to $C$=1.0 when the standard wind velocity to be used for Fig. 2 is taken as 18 to 20 m/sec, and that $C_1$ (Greater Coasting and Ocean-going)=0.8 corrosponds to $C$=1.0 when taken as 25 to 27 m/sec. Accordingly the judgement that the critical value of $C$ is taken as 1.0 in association with the standard wind velocity of 26 m/sec and 19 m/sec for Ocean-going and Coasting-I respectively has approximately the same severity as that presented by the paper [4].

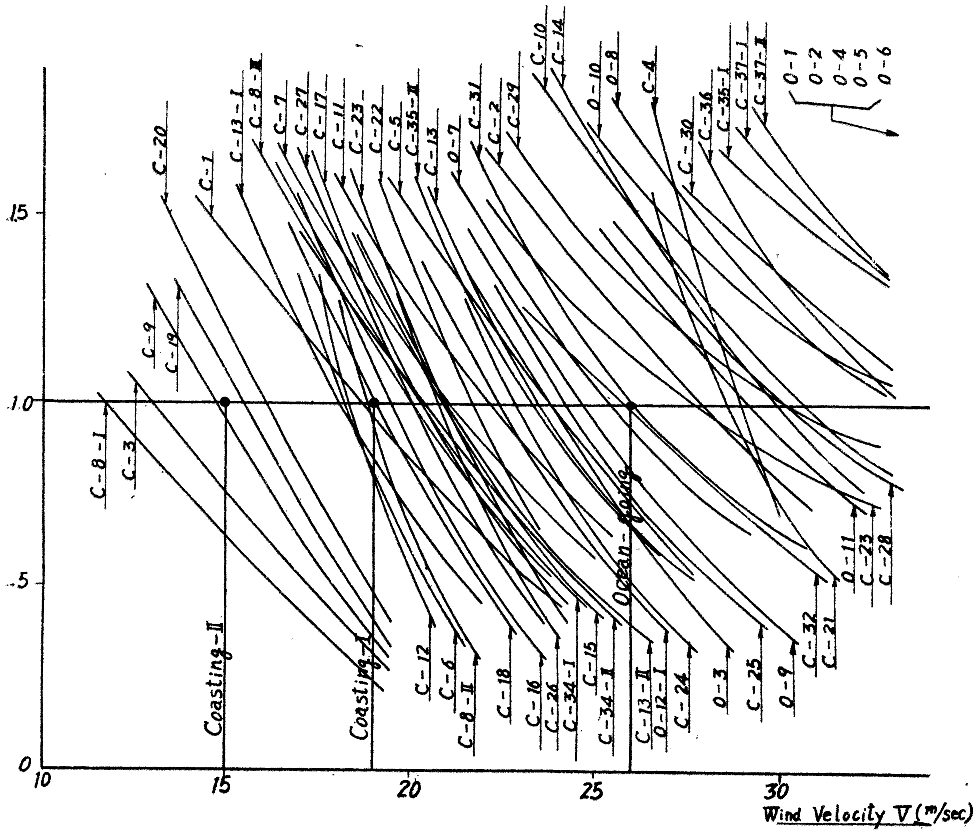



Fig. 18

(2) **Critical Value of $GZ_m$**

In Fig. 19 $GZ_m$ are plottd against $B$, according to the idea of equation (5), as to 117 ships having available data.

From this figure it is considered advisable to take the critical value of $GZ_m$ as 0.0215 $B$ and 0.275 m, taking into account the fact that, among sunken ships or ships having insufficient stability, values $C$ for C-8-II, 12-II and 13 do not reach to 1.0 for standard wind velocity although their $GZ_m$ are not small, and that C-28 to 30 are for ships which were sunken under abnormal stormy weather as for Coasting-I area.

(3) **Critical Value of GM**

As a a critical value of GM, the standard for ships engaged in Smooth Water Area [1] is adopted.

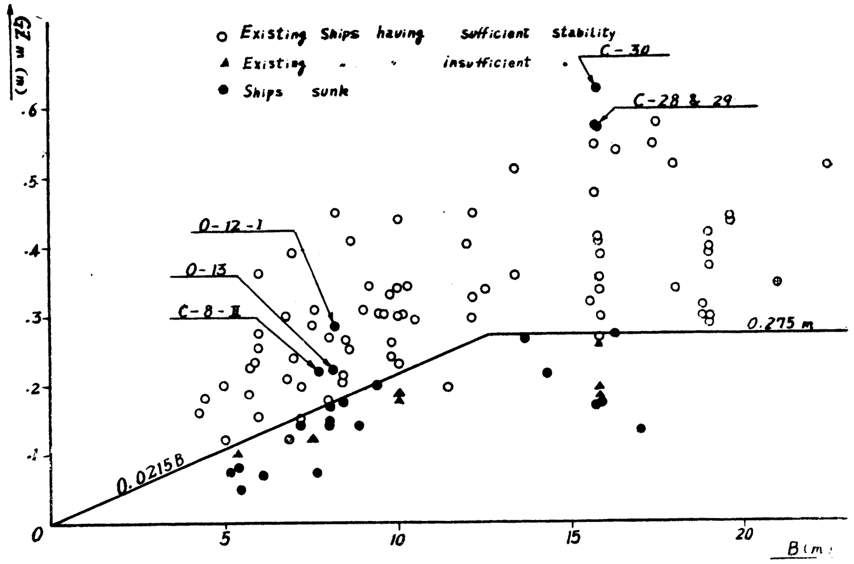



Fig. 19

## § 8. Standard of Stability

### (1) Criterion of $C$

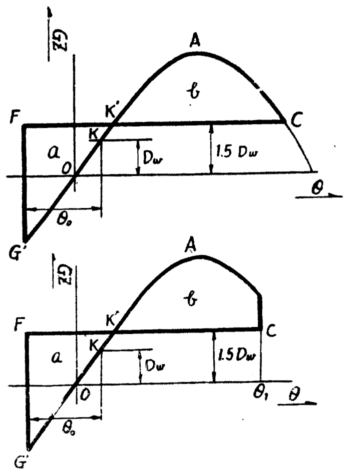



Fig. 20

In Fig. 20, draw moment lever $D_w$ parallel to the base line, take rolling angle $\theta_0$ to the windward (left side) from $K$, the intersection of $D_w$ with the stability curve, and then draw moment lever due to gust, 1.5 $D_w$, parallel to the base line. When the areas K′FG′ and AK′C are denoted as "$a$" and "$b$" respectively, then

$$C = b/a > 1$$

In this case stability curve is limited to the angle of flooding $\theta_1$ as shown in Fig. 20.

Since the standard wind velocities are taken as 26 m/sec, 19 m/sec and 15 m/sec for Ocean-going, Coasting-I and Coasting-II respectively, $D_w$ can be obtained as follows by introducing these values into equation (6) :

$$D_w = K_1 Ah/\Delta \quad \text{(m)}$$

Where, $K_1 = 0.0514$ : Ocean-going
$= 0.0274$ : Coasting-I
$= 0.0171$ : Coasting-II

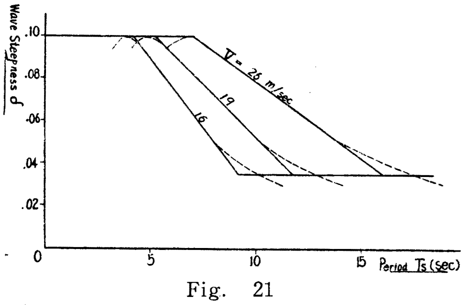



Fig. 21

$\theta_0$ can be obtained from equation (10), that is,

$$\theta_0 = \sqrt{138.5\,\gamma\delta/N}$$

$\gamma$ can also be obtained from equation (9), that is,

$$\gamma = 0.73 + 0.60\frac{\mathrm{OG}}{d}$$

$\delta$ can be determined by drawing Fig. 11 curves as to the standard wind velocity, which is as shown in Fig. 21. From this figure, we obtain

$$\left.\begin{array}{l}\delta = K_2 - K_3 T_s \\ 0.100 \geqq \delta \geqq 0.035\end{array}\right\}$$

Where, $K_1 = 0.151$ $K_2 = 0.0072$ : Ccean-going
0.153 0.0100 : Coasting-I
0.155 0.0130 : Coasting-II

$N$ is taken as 0.02 for ordinary ships having bilge keel.

(2) **Criterion of $GZ_m$**

$GZ_m$ must satisfy either of the following formulæ.

$$\left.\begin{array}{l}GZ_m \geqq 0.0215\,B \\ GZ_m \geqq 0.275\ \mathrm{m}\end{array}\right\}$$

In this case, $GZ_m$ is taken as the maximum value of GZ within the angle of flooding $\theta_1$, as shown in Fig. 22.

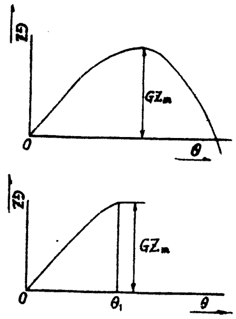


Fig. 22

(3) **Criterion of GM**

As the criterion of GM is the same as that for ships engaged in Smooth Water Area [1], only it's result is described below.

$$\left.\begin{array}{l}GM \geqq (1.1\,Ah + \sum kn\bar{B})\,B/100f\Delta \\ f \leqq B/5.5\end{array}\right\}$$

Where, $n$ = Number of passengers in each accommodation space
$\bar{B}$ = Average athwart ship distance, within which the passengers are free to move, in each accommodation space (m)
$f$ = Freeboard (m)
$k = 0.134\,(7 - n/a)$
$a$ = Floor area in each accommodation space ($m^2$)

## §9. Application of the Standard of Stability

(1) **Standard of Stability and Condition of Ships**

Since, in applying the standard of stability, calculations as to all service conditions of a ship are difficult and complicated, the conditions listed in Table 1 have been adopted as mentioned in §2 (2). In actual service, however, there are other various conditions of the ship than those given in Table 1, and therefore even if a ship has been found to comply with the standard of stability in all conditions given in Table 1, the ship can not always be regarded as having sufficient stability. On the contrary, even if there are some conditions in which a ship has failed to comply with the standard, the ship may not always be considered unsatisfactory so long as such unsatisfactory conditions can be avoided by means of ballasting or by other suitable measures. In other words, the ship may be considered satisfactory if her conditions are restricted to those in which she can comply with the standard. Accordingly it is considered more advisable to adopt the following method than to make calculations of the criterions as to conditions given in Table 1.

As the factors necessary for the calculation of the criterions are classified as shown in Table 6, the criterions can be calculated when the draft of the ship $d$ and the position of the center of gravity of the ship KG (GM) are given.

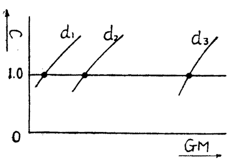


Fig. 23

Assuming that the drafts of the ship are $d_1, d_2, d_3, \cdots$ taken at equal intervals within the range of minimum and maximum drafts and that GM corresponding to respective assumed drafts are at equal intervals, value of $C$ for each combination of $d$ and GM can be derived as shown in Fig. 23. As the relation between $d$ and GM to make $C=1$ is obtained from this figure, (i)-curve in Fig. 24 can be

Table 6.

| Factor | | | Constant | Dependent upon $d$ | Dependent upon $d$ and KG (GM) |
|---|---|---|---|---|---|
| Criterion of $C$ | Stability curve | | —— | —— | Stability curve |
| | Angle of flooding, $\theta_1$ | | —— | $\theta_1$ | —— |
| | $D_w = K_1 A h / \Delta$ | | $K_1$ | $A,\ h,\ \Delta$ | —— |
| | $\theta_0$ | $\gamma = 0.73 + 0.60\ \mathrm{OG}/d$ | —— | $d$ | OG |
| | | $\delta = K_2 - K_3 T_s$ | $K_2,\ K_3$ | —— | $T_s$ |
| | | $N$ | 0.02(Ordinary ships) | —— | $N$ (Extraordinary ships) |
| Criterion of $GZ_m$ | Angle of flooding, $\theta_1$ | | —— | $\theta_1$ | —— |
| | $GZ_m \geqq 0.0215\,B$ or 0.275 m | | $B$ | —— | $GZ_m$ |
| Criterion of GM | | | $k,\ n,\ \bar{B},\ B$ | $A,\ h,\ f,\ \Delta$ | —— |

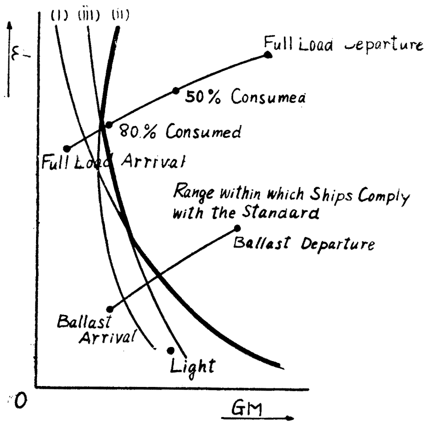



Fig. 24

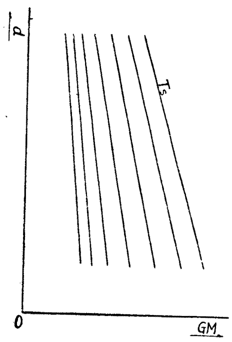



Fig. 25

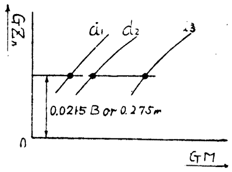



Fig. 26

drawn. With regard to $T_s$ in the calculation of $C$, the curve drawn on the basis of $d$ and GM as shown in Fig. 25 (which is an example when H. Kato's presumption method [16] is used) may facilitate the calculation.

In the calculation of $GZ_m$, the relation between $d$ and GM to satisfy Fig. 26 and to make $GZ_m = 0.0215\,B$ or 0.275 m can be obtained as shown by (ii)-curve in Fig. 24 in the similar manner as in the case of the calculation of $C$. The criterion of GM can also be obtained as shown by (iii)-curve in Fig. 24 when required GM for the above-mentioned $d_1$, $d_2$, $d_3$, ⋯ are calculated.

From these curves, the relation between $d$ and GM that the ship comply with the standard can be determined as illustrated in Fig. 24.

Therefore whether the ship complies with the standard in the condition given in Table 1 can easily be judged by plotting $d$ and GM in these condition on Fig. 24, and moreover the conditions of the ship can be restricted form this figure so that she can comply with standard.

This calculation method by assuming $d$ and GM is advantageous compared with the direct calculation method as to certain chosen conditions.

( i ) When the lines of a ship are given, the range within which the ship complies with the standard can be obtained as shown in Fig. 24 before the execution of the inclining test.

After the inclining test, it can be judged only by plotting GM against $d$ in each condition whether the ship complies with the standard. Even where the center of gravity of the ship estimated at the stage of initial design has been found different from that obtained by the inclining test, it is not necessary to calculate the standard again, but sufficient to correct the plots of GM in Fig. 24.

(ii) Standard of $C$, $GZ_m$ and GM can be expressed only on the basis of $d$ and GM as shown in Fig. 24.

(iii) The value of GM computed by the operator of a ship can be checked from the value of $T_s$ by adding Fig. 25 to the data previously supplied to the operator for the purpose of computing GM. Moreover, by furnishing Fig. 24 to the operator, he can easily judge by only GM value whether the ship complies with the standard.

(iv) Passenger ships engaged in international voyage are subjected to Ship Subdivision Regulations and are required to maintain the specified stability (GM) in non-damaged condition in order to insure safety at the time of damage. Since both standards of stability, proposed in this paper and required above, can be expressed on the basis of $d$ and GM, whether these ships comply with these both standards can readily be judged by plotting the latter on Fig. 24.

(2) **Disposition for Exceptional Ships**

In applying the standard, there are some ships, for instance those described below, to which direct application of the standard is not considered appropriate. In such cases the stability is judged in each particular case by making investigations on each ship.

(i) Ships having extraordinary flare, tumble home, bulge, etc. to which the application of the standard of GM is not appropriate.

(ii) Ships of special form or having bilge keels of special form or size in which it is not applicable to take $N$ as 0.02.

(iii) Ships in which an excessive amount of sea water is liable to be shipped and contained on upper deck due to the special feature of the structural arrangement on the upper deck.

(iv) Ships of specially high speed which are excessively heeled due to steering,

## §10. Conclusions

In the forgoing, the authors have attemped to describe the particulars and process in preparing the standard of stability for passenger ships engaged in Ocean-going and Coasting Services, which may be summarized as follows :

(1) The standard of stability for passenger ships has been developed, and is in the process of legislation as the first Govermental Regulations respecting stability in Japan.

(2) Previous to other countries, effect of waves has been introduced in the standard adopted by the Goverment.

(3) Investigations have been made on various elements affecting stability, such as wind (steady wind and gust), wave, shipping of sea water, shift of weights aboard, steering, as well as the effect of external force, metacentric height, dynamical stability, maximum righting arm, etc. ; whereupon the method of comprehensive judgement of the stability has been developed.

(4) Stability of ships to be complied with the standard could be indicated by the draft and the corresponding metacentric height, which has enabled operators to judge the stability from the metacentric height alone. Accordingly the stability of a ship specified by Ship Subdivision Regulations, which was dealt with separately in the past, can be judged simultaneously by the same elements (draft and metacentric height) as dealt with in this paper.

It would be needless to emphasize the importance of the stability here. Number of countries which legislate the stability standard would be increased, and in countries which have already established the regulations investigations would be progressed in view of revising them. In future, moreover, it would be conceivable that the standard of stability be adopted in the International Convention.

The standard developed by the authors can not be declared to be a complete one, containing many provisions to be revised. It is strongly hoped, therefore, that further investigations be made, the standard be always maintained in modernized condition and eventually a perfect standard would be developed.

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