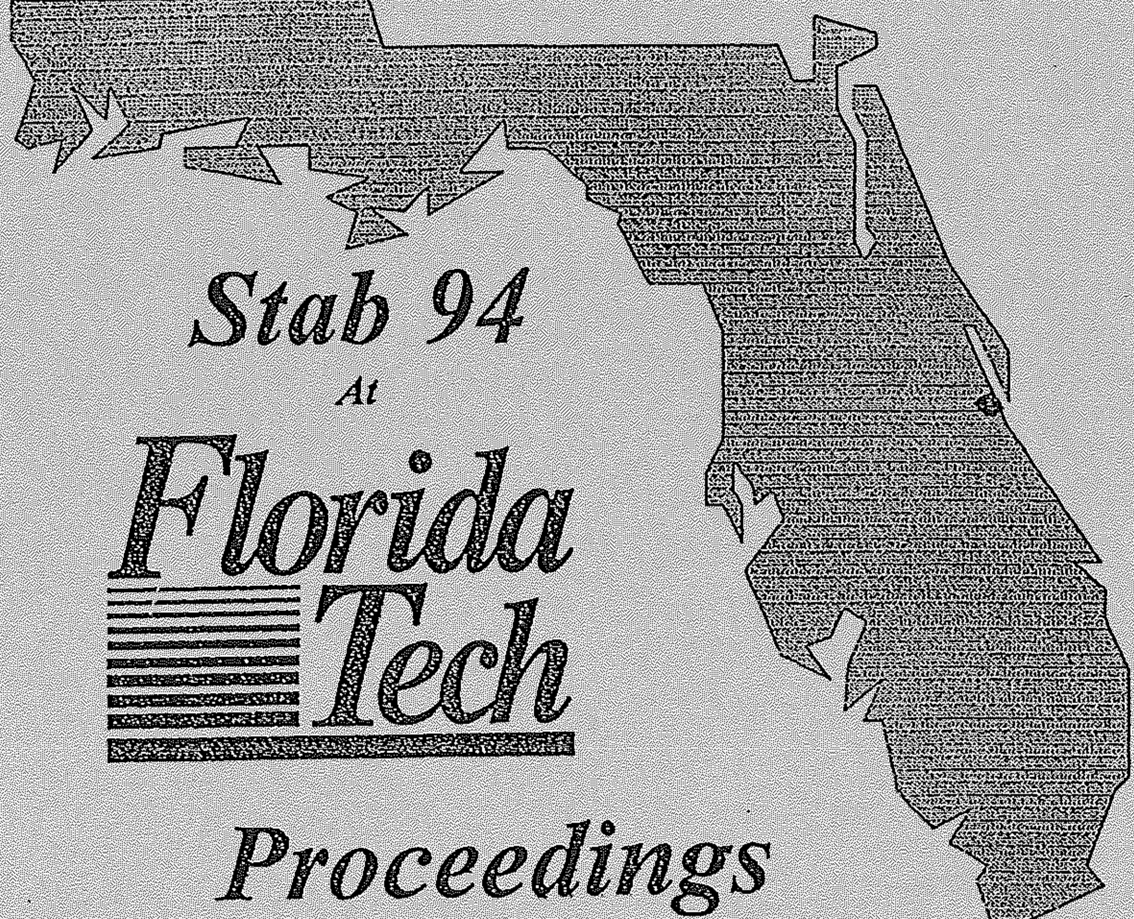
FIFTH INTERNATIONAL CONFERENCE ON STABILITY
OF
SHIPS AND OCEAN VEHICLES

NOVEMBER 7-11, 1994



Stab 94

At

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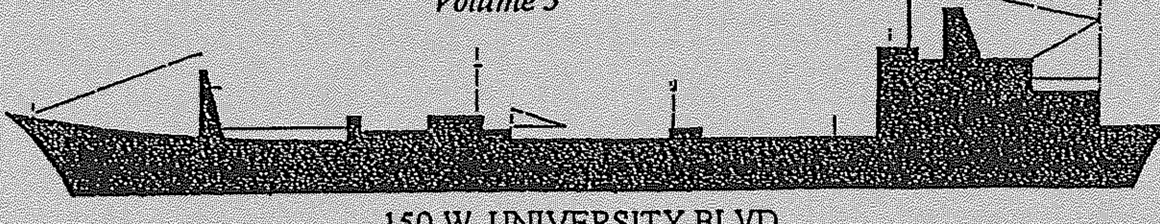
Proceedings

Volume 5



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PURPOSE OF STAB 94

STAB 94 had been offered to promote a full exchange of ideas and methodologies regarding STABILITY OF SHIPS AND OCEAN VEHICLES and to provide an opportunity to professional naval architects, capsize prevention researcher, regulatory agencies, inspection and certifying authorities, ship owners, consultants and ship operators to present, discuss and listen to improvements in capsize prevention for all types and sizes of ships.

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On the Relation between the Stability and the Roll of Ships in Waves

Chan Ik Shin*

ABSTRACT

If the heeling angle of a ship is within of the range of the stability in still water, a moment by coupled forces of weight and buoyancy acts in direction which the ship is restored to upright condition. If the heeling angle of the ship is larger than the angle of vanishing stability, the moment acts in direction which the ship is capsized. However, the ship does not necessarily capsize in waves, even if the rolling angle of the ship is larger than the angle of vanishing stability in the stability curve, according to the existing research results. Therefore, we can not judge the transverse stability of the ship by using the statical stability curve in waves, although we can judge with only that curve in still water.

This paper simulated behaviour which the ship restores or capsizes from an inclination in the vicinity of the angle of vanishing stability. And behaviour which the rolling angle exceeds the angle of vanishing stability in waves was simulated.

1. INTRODUCTION

Capsizing is the leading cause of death in marine accidents [1]. E.Aa.Dahle and T.Nedrelid [2] indicated as follows about the capsizing. 「"Capsize" implies that the vessel has been the subject of external forces which has turned the vessel over to a large angle, where the vessel remains stable.」 Storch [3] defines capsizing as "a loss or lack of sufficient transverse stability to remain upright". And Hayes [1] expresses that capsizing are caused by a loss of stability.

The transverse stability of a ship is the tendency which the ship has to return to the upright position when inclined away from that position due to external forces in natural environments. Therefore, it is said generally that a loss or lack of transverse stability induces the capsizing.

However, what kind of condition is to be a loss or lack of the transverse stability ?

In still water, it is known that when a ship heels over beyond the range of stability or the angle of vanishing stability, the ship becomes the condition of a loss or lack of the transverse stability. If the ship is in this condition, a moment by coupled forces of weight and buoyancy acts to capsize, rather than to right, the ship.

In waves, the ship does not necessarily capsize, even if the amplitute of the rolling motion of the ship is larger than the angle of vanishing stability, according to the existing research results [4,5].

The purpose of the present study is to simulate behaviour which the ship restores or capsizes from an inclination in the vicinity of the angle of vanishing stability and the amplitute of the rolling motion exceeds the angle of vanishing stability in waves.

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2. RESTORING AND CAPSIZING MOTIONS FROM THE VICINITY OF THE ANGLE OF VANISHING STABILITY

The curve of statical stability has a number of features which are significant in the analysis of the stability of the ship. In the stability curve, as shown in Fig.1, the range from upright to the angle at which the stability curve crosses the base line is called the range of positive stability. That crossed point, point E in Fig.1, is called the angle of vanishing stability. If the heeling angle of the ship is within of the range, the ship restores to upright condition. However, the heeling angle of the ship is slightly larger than the angle of vanishing stability, point E, the ship capsizes.

If the heeling moments due to the wind pressure or the shift of cargoes are calculated, these moments can be plotted on the same coordinates as the curve of statical stability, as illustrated in Fig.1. In this case, at points A and B in Fig.1, the heeling moment equals the righting moment and the ship is in equilibrium at two positions of points A and B. When the ship is in equilibrium at point A, a slight inclination in either direction will generate a moment tending to return the ship to original position A. Therefore, the point A is the position of the stable equilibrium. When the ship is in equilibrium at point B, if the ship is displaced slightly in either direction, the ship moves farther from position B, and the ship will either come to rest in position A or capsize. When the heeling moment exists, as in Fig.1, the range of positive stability is decreased by the effect of the heeling moment to point B and therefore the point B turn out a position of vanishing stability.

In this condition, if a periodic disturbance exist, as illustrated in Fig.1, the restoring or capsizing motion is different from above mentioned motions.

To simulate behaviour which the ship restores or capsizes from an inclination in the vicinity of the position of vanishing stability, assume that the curve of statical stability is divided into several straight lines, as illustrated in Fig.2.

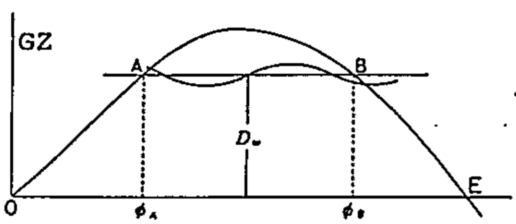

Fig.1 Stability Curve

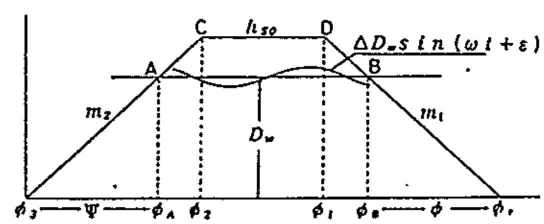

Fig.2 Approximate Stability Curve

2.1 MOTION IN NEGATIVE SLOPE OF CURVE OF STATICAL STABILITY

Assume that the curve of statical stability is divided into straight lines BD, DC and CA, as in Fig.2.

The roll equation of motion in negative slope of the curve of statical stability is expressed by

$$(I+\Delta I)\,\ddot{\phi}+N\dot{\phi}+Wm_1(\phi_r-\phi)=W\{D_w+\Delta D_w \sin(\omega t+\varepsilon)\}$$

where I is mass moment of inertia, ΔI added mass moment of inertia, N damping coefficient, W displacement of ship, WD_w heeling moment, ΔD_w amplitude of periodic disturbance and ε phase of periodic disturbance.

From $k^2=Wm/(I+\Delta I)$, where m is metacentric height in upright condition.

Hence

$$\ddot{\phi}+N_s\dot{\phi}+k^2\sigma(\psi_r-\phi) = k^2\sigma\psi\{1+\gamma\sin(\omega t+\varepsilon)\} \tag{1}$$

where k is the linear roll natural frequency, $\sigma=m_l/m$, $\psi=D_\psi/m_l$ and $\gamma=\Delta D_\psi/D_\psi$.

From $\phi_B=\phi_r-\psi$, Eq.(1) becomes

$$\ddot{\phi}+N_s\dot{\phi}-k^2\sigma\phi = -k^2\sigma\{\phi_B-\gamma\phi\sin(\omega t+\varepsilon)\} \tag{2}$$

Then the solution is

$$\phi = \phi_B+Ae^{\lambda_1 t}+Be^{-\lambda_2 t}-\frac{k^2\sigma\gamma\phi}{\sqrt{(k^2\sigma+\omega^2)^2+N_s^2\omega^2}}\sin(\omega t+\varepsilon+\delta)$$

$$\dot{\phi} = \lambda_1 Ae^{\lambda_1 t}-\lambda_2 Be^{-\lambda_2 t}-\frac{\omega k^2\sigma\gamma\phi}{\sqrt{(k^2\sigma+\omega^2)^2+N_s^2\omega^2}}\cos(\omega t+\varepsilon+\delta)$$

where $\lambda_1 = k\left(\sqrt{\sigma+(N_s/k)^2/4}-(N_s/k)/2\right) = \sqrt{k^2\sigma+N_s^2/4}-N_s/2$,

$\lambda_2 = k\left(\sqrt{\sigma+(N_s/k)^2/4}+(N_s/k)/2\right) = \sqrt{k^2\sigma+N_s^2/4}+N_s/2$,

$$\tan\delta = \frac{N_s\omega}{k^2\sigma+\omega^2}$$

For the initial conditions $\phi=\phi_0$, $\dot{\phi}=0$ at t=0, the solution of Eq.(2) is

$$A = -(\phi_B-\phi_0)\frac{\lambda_2}{\lambda_1+\lambda_2}+\frac{k^2\sigma\gamma\phi}{\sqrt{(k^2\sigma+\omega^2)^2+N_s^2\omega^2}}\,\frac{\lambda_2\sin(\varepsilon+\delta)+\omega\cos(\varepsilon+\delta)}{\lambda_1+\lambda_2}$$

$$B = -(\phi_B-\phi_0)\frac{\lambda_1}{\lambda_1+\lambda_2}+\frac{k^2\sigma\gamma\phi}{\sqrt{(k^2\sigma+\omega^2)^2+N_s^2\omega^2}}\,\frac{\lambda_1\sin(\varepsilon+\delta)-\omega\cos(\varepsilon+\delta)}{\lambda_1+\lambda_2}$$

$$\phi=\phi_B-(\phi_B-\phi_0)\frac{\lambda_2 e^{\lambda_1 t}+\lambda_1 e^{-\lambda_2 t}}{\lambda_1+\lambda_2}+\frac{k^2\sigma\gamma\phi}{\sqrt{(k^2\sigma+\omega^2)^2+N_s^2\omega^2}}\left\{\sin(\varepsilon+\delta)\frac{\lambda_2 e^{\lambda_1 t}+\lambda_1 e^{-\lambda_2 t}}{\lambda_1+\lambda_2}\right.$$
$$\left.+\cos(\varepsilon+\delta)\frac{\omega(e^{\lambda_1 t}-e^{-\lambda_2 t})}{\lambda_1+\lambda_2}-\sin(\omega t+\varepsilon+\delta)\right\} \tag{3}$$

$$\frac{\dot{\phi}}{k} = -(\phi_B-\phi_0)\frac{1}{k}\frac{\lambda_1\lambda_2}{\lambda_1+\lambda_2}(e^{\lambda_1 t}-e^{-\lambda_2 t})$$
$$+\frac{k^2\sigma\gamma\psi}{\sqrt{(k^2\sigma+\omega^2)^2+N_s^2\omega^2}}\left\{\sin(\varepsilon+\delta)\frac{1}{k}\frac{\lambda_1\lambda_2}{\lambda_1+\lambda_2}(e^{\lambda_1 t}-e^{-\lambda_2 t})\right.$$
$$\left.+\cos(\varepsilon+\delta)\frac{\omega}{k}\frac{\lambda_1 e^{\lambda_1 t}+\lambda_2 e^{-\lambda_2 t}}{\lambda_1+\lambda_2}-\frac{\omega}{k}\cos(\omega t+\varepsilon+\delta)\right\}$$

In these solutions, the terms including γ show an influence by periodic disturbance (or external wave force). As it is obvious from Eq.(3), a phase of the periodic disturbance ε exerts a great influence on the restoring motion of the ship. The ship restores early or late due to the phase of periodic disturbance. In the case that safety of the ship is examined, because the phase of periodic disturbance is optional, ε must takes the value which exerts the worst influence on the restoring motion of the ship. If the ship restores from a slightly small angle than ϕ_0 and reaches to ϕ_1 after time t_1, ε must takes the maximam value of the following expression.

$$F(\varepsilon,t) = sin(\varepsilon+\delta)\frac{\lambda_2 e^{\lambda_1 t_1}+\lambda_1 e^{-\lambda_2 t_1}}{\lambda_1+\lambda_2}+cos(\varepsilon+\delta)\frac{\omega(\lambda_2 e^{\lambda_1 t_1}-\lambda_1 e^{-\lambda_2 t_1})}{\lambda_1+\lambda_2}$$

$$-sin(\omega t_1+\varepsilon+\delta)$$

That is to say,

$$\frac{dF}{d\varepsilon} = cos(\varepsilon+\delta)\frac{\lambda_2 e^{\lambda_1 t_1}+\lambda_1 e^{-\lambda_2 t_1}}{\lambda_1+\lambda_2}-sin(\varepsilon+\delta)\frac{\omega(\lambda_2 e^{\lambda_1 t_1}+\lambda_1 e^{-\lambda_2 t_1})}{\lambda_1+\lambda_2}$$

$$-sin(\omega t_1+\varepsilon+\delta) = 0 \tag{4}$$

$$tan(\varepsilon+\delta) = \frac{\dfrac{\lambda_2 e^{\lambda_1 t_1}+\lambda_1 e^{-\lambda_2 t_1}}{\lambda_1+\lambda_2}-cos\omega t_1}{\dfrac{\omega(e^{\lambda_1 t_1}-e^{-\lambda_2 t_1})}{\lambda_1+\lambda_2}-sin\omega t_1}$$

In the case that the phase of periodic disturbance is given by Eq.(4), the stability of the ship becomes worst.

In the case of $\gamma=0$, the motion of the ship in the negative slope of the curve of statical stability is expressed by

$$\phi = \phi_B-(\phi_B-\phi_0)\frac{\lambda_2 e^{\lambda_1 t}+\lambda_1 e^{-\lambda_2 t}}{\lambda_1+\lambda_2} \tag{5}$$

Eq.(5) indicates that when an inclination of the ship is slightly smaller than ϕ_B, the ship restores. Because a position ϕ_B is an unstable, when the inclination of the ship is slightly larger than this position, the ship capsizes.

2.2 MOTION IN THE VICINITY OF ANGLE OF MAXIMUM STABILITY

Assume that the maximum righting arm is h_{so}. The roll equation of motion in the vicinity of angle of maximum stability is expressed by

$$(I+\Delta I)\ddot{\phi}+N\dot{\phi}+W\cdot h_{so} = W[D_w+\Delta D_w sin(\omega t+\varepsilon)]$$

and

$$(I+\Delta I)\ddot{\phi}+N\dot{\phi} = -Wm\frac{h_{so}-D_w[1+\gamma sin(\omega t+\varepsilon)]}{m} \tag{6}$$

where $f_m=(h_{so}-D_w)/m$.

The solution of Eq.(6) is

$$\phi = A_2 e^{-N_s t}+\frac{A_1}{N_s}-k^2\frac{f_m}{N_s}\left(t-\frac{1}{N_s}\right)-\frac{\gamma D_w}{m}\frac{k^2/\omega}{\sqrt{\omega^2+N_s^2}}sin(\omega t+\varepsilon+\delta_1)$$

$$\frac{\dot{\phi}}{k} = -\frac{N_s}{k}A_2 e^{-N_s t}-\frac{f_m}{N_s/k}-\frac{\gamma D_w}{m}\frac{k}{\sqrt{\omega^2+N_s^2}}cos(\omega t+\varepsilon+\delta_1)$$

where $tan\delta_1 = \dfrac{N_s}{\omega}$

When the restoring motion changes from the range of BD to the range of BC, the solution which is satisfied the condition of $\phi=\phi_1$, $\dot{\phi}=\dot{\phi}_1$ at $t=t_1$ is as follows.

$$A_2 = -\frac{k}{N_s}\left(\frac{\dot{\phi}_1}{k}+\frac{f_m}{N_s/k}\right)e^{N_s t_1}-\frac{\gamma D_w}{m}\frac{1}{N_s}\frac{k^2}{\sqrt{\omega^2+N_s^2}}e^{N_s t_1}\cos(\omega t_1+\varepsilon+\delta_1)$$

$$\frac{A_1}{N_s} = \phi_1+\frac{f_m}{N_s}k^2 t+\frac{\dot{\phi}_1}{N_s}+\frac{\gamma D_w}{m}\frac{k^2}{N_s\omega}\cos(\omega t+\varepsilon)$$

$$\phi = \phi_1-\frac{f_m}{N_s}k^2(t-t_1)+\frac{1}{N_s/k}\left(\frac{\dot{\phi}_1}{k}+\frac{f_m}{N_s/k}\right)\{1-e^{-N_s(t-t_1)}\}$$

$$+\frac{\gamma D_w}{m}\frac{k^2}{N_s\omega}\{\cos(\omega t_1+\varepsilon)-\cos\delta_1\cos(\omega t_1+\varepsilon+\delta_1)\,e^{-N_s(t-t_1)}$$

$$-\sin\delta_1\sin(\omega t+\varepsilon+\delta_1)\}$$

$$\frac{\dot{\phi}}{k} = -\frac{f_m}{N_s/k}+\left(\frac{\dot{\phi}_1}{k}+\frac{f_m}{N_s/k}\right)e^{-N_s(t-t_1)}$$

$$+\frac{\gamma D_w}{m}\frac{k}{\omega}\cos\delta_1\{\cos(\omega t_1+\varepsilon+\delta_1)\,e^{-N_s(t-t_1)}-\cos(\omega t+\varepsilon+\delta_1)\}$$

2.3 MOTION IN POSITIVE SLOPE OF CURVE OF STATICAL STABILITY

The roll equation of motion in the positive slope of the curve of statical stability is expressed by

$$(I+\Delta I)\ddot{\phi}+N\dot{\phi}+Wm_2(\phi-\phi_3) = W\{D_w+\Delta D_w\sin(\omega t+\varepsilon)\}$$

and

$$\ddot{\phi}+N_s\dot{\phi}+k^2\sigma_0\phi = k^2\sigma_0\phi_3+k^2\sigma_0\Psi\{1+\gamma\sin(\omega t+\varepsilon)\} \tag{7}$$

where $\sigma_0=m_2/m$ and $\Psi=D_w/m_2$.

From $\Psi=\phi_A-\phi_3$, Eq.(7) becomes

$$\ddot{\phi}+N_s\dot{\phi}+k^2\sigma_0\phi = k^2\sigma_0\phi_A+k^2\sigma_0\gamma\Psi\sin(\omega t+\varepsilon) \tag{8}$$

The solution of Eq.(8) is

$$\phi = \phi_A+e^{-\frac{N_s}{2}t}(B_1\cos k_1 t+B_2\sin k_1 t)$$

$$+\frac{k^2\sigma_0\gamma\Psi}{\sqrt{(k^2\sigma_0-\omega^2)^2+N_s^2\omega^2}}\sin(\omega t+\varepsilon+\delta_2)$$

$$\dot{\phi} = e^{-\frac{N_s}{2}t}\left\{\left(k_1B_2-\frac{N_s}{2}B_1\right)\cos k_1 t-\left(k_1B_1+\frac{N_s}{2}B_2\right)\sin k_1 t\right\}$$

$$+\frac{\omega k^2\sigma_0\gamma\Psi}{\sqrt{(k^2\sigma_0-\omega^2)^2+N_s^2\omega^2}}\cos(\omega t+\varepsilon-\delta_2)$$

where $k_1^2 = k^2(\sigma_0-b_0^2/4)$ 、 $\tan\delta_2 = \dfrac{N_s\omega}{k^2\sigma_0-\omega^2}$

When the restoring motion changes from the range of DC to the range of CA, the solution which is satisfied the condition of $\phi=\phi_2$, $\dot{\phi}=\phi_2$ at $t=t_2$ is as follows.

$$B_1 = e^{\frac{N_s}{2}t_2}\left[(\phi_2-\phi_A)\cos k_1 t_2 - \frac{\frac{N_s}{2}(\phi_2-\phi_A)+\dot{\phi}_2}{k_1}\sin k_1 t_2 \right.$$

$$-\frac{k^2\sigma_0\gamma\Psi}{\sqrt{(k^2\sigma_0-\omega^2)^2+N_s^2\omega^2}}\left\{\left(\cos k_1 t_2 - \frac{N_s}{2k_1}\sin k_1 t_2\right)\sin(\omega t_2+\varepsilon-\delta_2)\right.$$

$$\left.\left.-\frac{\omega}{k_1}\sin k_1 t_2 \cos(\omega t_2+\varepsilon-\delta_2)\right\}\right]$$

$$B_2 = e^{\frac{N_s}{2}t_2}\left[(\phi_2-\phi_A)\sin k_1 t_2 + \frac{\frac{N_s}{2}(\phi_2-\phi_A)+\dot{\phi}_2}{k_1}\cos k_1 t_2 \right.$$

$$-\frac{k^2\sigma_0\gamma\Psi}{\sqrt{(k^2\sigma_0-\omega^2)^2+N_s^2\omega^2}}\left\{\left(\sin k_1 t_2 + \frac{N_s}{2k_1}\cos k_1 t_2\right)\sin(\omega t_2+\varepsilon-\delta_2)\right.$$

$$\left.\left.+\frac{\omega}{k_1}\cos k_1 t_2 \cos(\omega t_2+\varepsilon-\delta_2)\right\}\right]$$

$$\phi = \phi_A + e^{-\frac{N_s}{2}(t-t_2)}\left[(\phi_2-\phi_A)\left\{\cos k_1(t-t_2) + \frac{N_s}{2k_1}\sin k_1(t-t_2)\right\}\right.$$

$$+\frac{\dot{\phi}_2}{k_1}\sin k_1(t-t_2) - \frac{k^2\sigma_0\gamma\Psi}{\sqrt{(k^2\sigma_0-\omega^2)^2+N_s^2\omega^2}}\left\{\sin(\omega t_2+\varepsilon-\delta_2)\cos k_1(t-t_2)\right.$$

$$\left.\left.+\frac{\omega\cos(\omega t_2+\varepsilon-\delta_2)+\frac{N_s}{2}\sin(\omega t_2+\varepsilon-\delta_2)}{k_1}\sin k_1(t-t_2)\right\}\right]$$

$$+\frac{k^2\sigma_0\gamma\Psi}{\sqrt{(k^2\sigma_0-\omega^2)^2+N_s^2\omega^2}}\sin(\omega t+\varepsilon-\delta_2)$$

$$\frac{\dot{\phi}}{k} = e^{-\frac{N_s}{2}(t-t_2)}\left[-(\phi_2-\phi_A)\frac{k\sigma_0}{k_1}\sin k_1(t-t_2) + \frac{\dot{\phi}_2}{k}\left\{\cos k_1(t-t_2)\right.\right.$$

$$\left.-\frac{N_s}{2k_1}\sin k_1(t-t_2)\right\} + \frac{k^2\sigma_0\gamma\Psi}{\sqrt{(k^2\sigma_0-\omega^2)^2+N_s^2\omega^2}}\left\{\frac{k\sigma_0}{k_1}\sin(\omega t_2+\varepsilon\right.$$

$$-\delta_2)\sin k_1(t-t_2) - \frac{\omega}{k}\cos(\omega t_2+\varepsilon-\delta_2)\left[\cos k_1(t-t_2)\right.$$

$$\left.\left.\left.-\frac{N_s}{2k_1}\sin k_1(t-t_2)\right]\right\}\right] + \frac{k^2\sigma_0\gamma\Psi}{\sqrt{(k^2\sigma_0-\omega^2)^2+N_s^2\omega^2}}\frac{\omega}{k}\omega k\cos(\omega t+\varepsilon-\delta_2)$$

2.4 EFFECTS OF FREQUENCY OF PERIODIC DISTURBANCE

If $\omega \to \infty$, Eq.(5) becomes

$$\tan(\varepsilon+\delta) = 0$$

In Eq.(2),

$$\frac{k^2\sigma\gamma\phi}{\sqrt{(k^2\sigma+\omega^2)^2+N_s^2\omega^2}} = 0$$

Therefore, an influence of the periodic disterbance vanishes.

If $\omega \to 0$, the following expression is obtained.

$$\tan\delta = 0、\sin\omega t_1 = \omega t_1 、\cos\omega t_1 = 1$$

$$\tan(\varepsilon+\delta) = \frac{\dfrac{\lambda_2 e^{\lambda_1 t_1} + \lambda_1 e^{-\lambda_2 t_1}}{\lambda_1+\lambda_2} - 1}{\dfrac{\omega}{k}\left\{\dfrac{k\,(e^{\lambda_1 t_1} - e^{-\lambda_2 t_1})}{\lambda_1+\lambda_2} - k t_1\right\}}$$

For kt_1 which a denominator of above Eq. becomes to positive,

$$\tan(\varepsilon+\delta) \to \infty、\varepsilon+\delta = 90^\circ$$

Therefore, for $0<t<t_1$,

$$\sin(\varepsilon+\delta) = 1、\cos(\varepsilon+\delta) = 0、\sin(\omega t+\varepsilon+\delta) = 1$$

$$\frac{k^2\sigma\gamma\phi}{\sqrt{(k^2\sigma+\omega^2)^2+N_s^2\omega^2}} = \gamma\phi = \frac{\Delta D_w}{m_1} = \Delta\phi$$

$$\therefore\ \phi = \phi_B - (\phi_B-\phi_0)\frac{\lambda_2 e^{\lambda_1 t}+\lambda_1 e^{-\lambda_2 t}}{\lambda_1+\lambda_2} + \Delta\phi\left(\frac{\lambda_2 e^{\lambda_1 t}+\lambda_1 e^{-\lambda_2 t}}{\lambda_1+\lambda_2} - 1\right)$$

$$= \phi_B - \Delta\phi - (\phi_B-\Delta\phi-\phi_0)\frac{\lambda_2 e^{\lambda_1 t}+\lambda_1 e^{-\lambda_2 t}}{\lambda_1+\lambda_2}$$

In the case of $\omega \to 0$, the arm of heeling moment is able to regarded as $D_w+\Delta D_w$. Therefore, the range of postive stability is decreased.

2.5 NUMERICAL SIMULATIONS

Now $\phi_A=20^\circ$, $\phi_B=30^\circ$, $m=0.8$m, $m_1=0.41$m, $m_2=0.48$m, $h_{s0}=0.302$m, $D_w=0.3$m, $N_S=0.3k$, $\gamma=0$, 0.01, 0.02, 0.03, 0.04 and the time when a ship restores to ϕ_1 is supposed as kt=8. The bihaviour which a ship restores or capsizes from an inclination in the vicinity of the angle of vanishing stability is simulated by the above expressions.

The behaviour in the case of $\gamma=0$ is obtained by expression (5). As shown in Fig.3, the results of the numerical simulations indicate that the ship restores, when the heeling angle is slightly smaller than the angle of vanishing stability and the opposite motion.

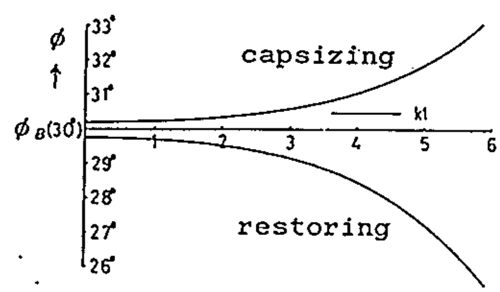

Fig.3 Restoring and Capsizing motions

When $\gamma=0$, 0.01, 0.02, 0.03, 0.04 respectinely for kt=8 and the most disadvantageous ε which is obtained by Eq.(4) is used to simulate the bihaviour from ϕ_B, the initial angle of inclination ϕ_0 and the behaviour which restores from ϕ_B to ϕ_1 are obtained by Eq.(3) as shown in Fig.4. This initial angle indicates the critical angle for the most disadvantageous ε. As shown in Fig.4, for $\gamma=0.02$, the initial angle which restores to ϕ_1 is $\phi_0=29.54^\circ$. However, when the ship is inclined at $\phi_0=29.6^\circ$ which is slightly larger than 29.54°, the ship capsizes.

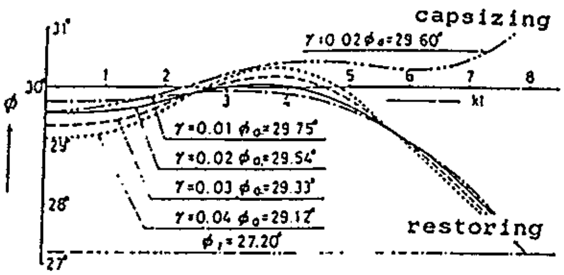

Fig.4 Restoring Motion for ε

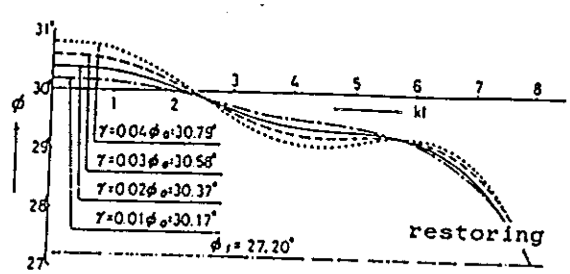

Fig.5 Restoring Motion for $\varepsilon+\pi$

In Eq.(4), $\tan(\varepsilon+\delta)$ is periodic function for π. Therefore, if it takes $(\varepsilon+\delta+\pi)$, the ship restores from large angle than ϕ_B, as shown in Fig.5.

3. ROLLING MOTION WHICH EXCEEDS ANGLE OF VANISHING STABILITY

3.1 EQUATION OF MOTION

In rough seas, small ships oscillate heavily with shipping water on deck. Deck wetness occurs on a ship when the magnitude of incident waves exceeds the critical value and the amount of the shipping water on deck depens on the excess of wave height over the critical wave height of deck wetness. In the worst case, the ship capsizes by the effects of the shipping water on deck.

Therefore, the equations of ship motions which describe the transient motions under the effect of the shipping water is necessary for this problem.

As shown in reference [5] and [6], the equations of motion with transient effects of the shipping water for the ship in regular beam seas,

$$\zeta = \zeta_a \cos(\omega t + Ky)$$

are expressed by

$$\begin{aligned} &M_{33}\ddot{z}+N_{33}\dot{z}+C_{33}z+A_{32}\ddot{y}+B_{32}\dot{y}+A_{34}\ddot{\phi}+B_{34}\dot{\phi}+C_{34}\phi = F_{za} \\ &M_{22}\ddot{y}+N_{22}\dot{y}+A_{23}\ddot{z}+B_{23}\dot{z}+A_{24}\ddot{\phi}+B_{24}\dot{\phi} = F_{ya} \\ &I_{44}\ddot{\phi}+N_{44}\dot{\phi}+WGZ(\phi)+A_{42}\ddot{y}+B_{42}\dot{y}+A_{43}\ddot{z}+B_{43}\dot{z}+C_{43}z = M_{\phi a}+m(w,t) \end{aligned} \tag{9}$$

In the equation (9), Hydrodynamic coefficients A_{IJ}, B_{IJ} and C_{IJ} are to be calculated on the sectional form immersed under the water and the frequency of motions is constant, the subscripts 2,3 and 4 denote sway, heave and roll motion respectively. M_{IJ} is the virtual mass, I_{44} virtual mass moment of inertia which including transient effects of the shipping water on deck. N_{IJ} is the damping coefficient including this effects.

The roll damping coefficient N_{44} through the transient is determined in the free rolling test of the models at the upright condition

In the equation (9), $GZ(\phi)$ is the value whose magnitude depends on every rolling angle ϕ. Using this $GZ(\phi)$, the behavoiur which the rolling angle exceeds the angle of vanishing stability can not be explained as it is, because ϕ is the absolute rolling angle. In this case, if the rolling angle exceeds the angle of vanishing stability, the ship capsizes, because the ship becomes the condition of a loss of the transverse stability from a static point of view.

However, experimental results [4], [5] teach us that the ship does not necessarily capsize, even if the angle of the rolling motion exceeds the angle of vanishing stability.

In this present work, to explain the experimental results, the inclination of the ship with respect to the surface of the wave was considerd.

When a ship rolls in waves, the angle of rolling motin of the ship with respect to the surface of the wave is not the angle of the ship from the vertical, as would be in still water, but $(\phi-\phi_w)$, where $(\phi-\phi_w)$ is the apparent roll angle and ϕ_w is the wave slope.

In such thouht, therefore, the equation of rolling motion becomes the same as equation (9) except that $(\phi-\phi_w)$ is substituted for ϕ in order to take account of the wave slope. However, in this present work, it was supposed that only the righting moment arm becomes $GZ(\phi-\phi_w)$ instead of $GZ(\phi)$ in Eq.(9).

3.2 NUMERICAL SIMULATIONS

The results of the simulations of the rolling motions with transient effects of the shipping water on deck are shown in Fig.6. Fig.6 indicates the time histories at a frequency very close to the natural rolling period for Model 1, as shown in reference [5]. As shown in Fig.6, the measured rolling angle exceeds the angle of vanishing stability, however the ship does not capsize. The numerical simulation by Eq.(9), as in Fig.6(a), describes qualitatively the experimental result well, but the angle of rolling motion of the numerical simulation does not exceed the

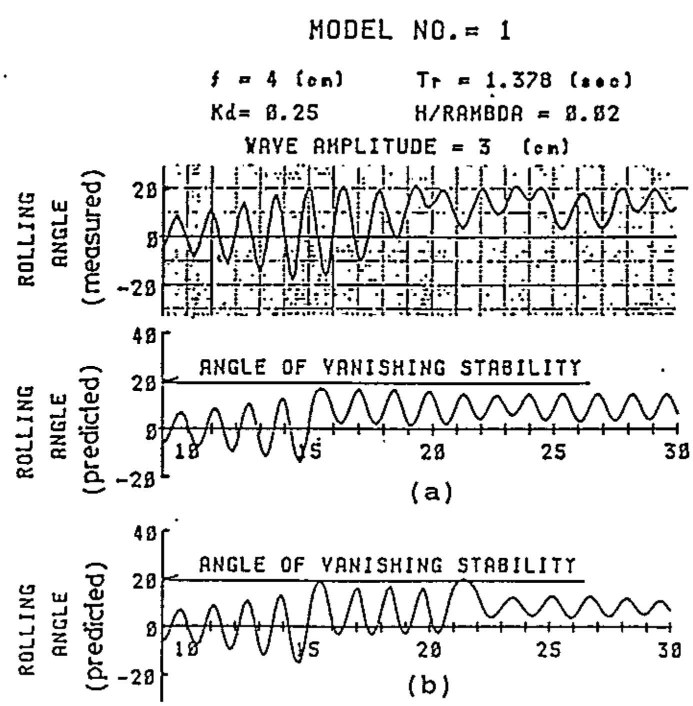

Fig.6 Rolling motion in the vicinity of the angle of vanishing stability

angle of vanishing stability. Therefore, it was not able to explain the experimental result in just as Eq.(9).

Result of a numerical simulation by the equation which takes $GZ(\phi-\phi_{s})$ instead of $GZ(\phi)$ is shown in Fig.6(b).

The numerical simulations by this equation describes an examples which the ship does not necessarily capsize, even if the angle of rolling motion is larger than the angle of vanishing stability.

This fact is showing that the angle of vanishing stability of the ship in waves differs from that in still water.

4. CONCLUDING REMARKS

In order to understand the relation between the stability and rolling motin of the ship, it is simulated that the ship restores or capsizes from an inclination in the vicinity of the angle of vanishing stability and the rolling angle exceeds the angle of vanishing stability in waves.

From the present study, the following conclusions are reached:

1) The stability of the ship which is heeling in the vicinity of vanishing stability depends on an influence of periodic disturbance. Therefore, the ship sometimes restores from larger angle than the angle of vanishing stability or capsizes from smaller angle than that by this influence.

2) Restoring or capsizing of the ship which is heeling in the vicinity of the angle of vanishing stability depends on an influence of a phase of the periodic disturbance which acts to the ship in waves.

3) Even if the rolling angle of the ship exceeds the angle of vanishing stability of the statical stability curve, a loss of stability which is the leading cause of capsizing does not necessarily occur in waves. Therefore, the ship sometimes restoring from large angle which exceeds the angle of vanishing stability in waves. The angle of vanishing stability of the ship in waves differs from that in still water.

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PIECE-WISE LINEAR METHODS FOR THE PROBABILISTIC STABILITY ASSESSMENT FOR SHIP IN A SEAWAY

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ABSTRACT

A probabilistic stability assessment that is generally described in a paper of Prof. N.Sevastianov needs some tools for calculating a probability of ship capsizing in a seaway during given time (value of such a probability taken for a unit of time also is called as "risk function"). Such tools should have a sufficient physical basis for being applicable to different kind of vessels and ocean vehicles, also they should give good results for relatively new types of ships, that have not enough operational and design statistics yet.

For creating such tools an exact knowledge of capsizing mechanic is necessary. This is quite complicate problem due to strong non-linearity of terms of ship motion equation, that can describe capsizing sufficiently. Proposed report is devoted to an attempt to avoid these obstacles by piece-wise linear methods.

Also a practical method of probability calculation is described. It is based on combination conventional non-linear rolling calculation with evaluation of probability of capsizing by piece-wise linear method on final part of GZ curve.

INTRODUCTION

There is a general algorithm of probabilistic estimation of vessels' stability, which was developed by N.Sevastianov[1]. For practical realization of such approach it is necessary to have corresponding method for capsizing risk function determination of ship in the given assumed situation with fixed loading conditions. This paper considers the single assumed situation, while ship is drifting in beam irregular seas and gusty wind.

Attempts to determine a probability of ship capsizing were made by many authors, who used different definition of capsizing phenomena. Capsizing as a loss of rolling motion stability in different variants were considered by W.Price [2], J.Wellicome [3], D.Kondrikov [4], V.Nekrasov [5], D.Ananyev [6], L.Zelenin [7] and others. I.Boroday [8] and J.Dudziak [9] used energetic approach to capsizing probability problem. Classical definition of stability for capsizing probability assessment was used by N.Sevastianov and Fam Ngock Hoeh [10] and N.Umeda [11].

This paper describes the author's attempt to solve this problem by piece-wise linear presentation GZ curve. This paper also summarizes previous author's results [12], [13], [14] with emphasis of practical calculation for real ships.

1. System of Ship Motion Equations

We shall use a following mathematical model of ship motion, which takes into account rolling, swaying and drift under action of irregular waves and gusty wind.

$$\begin{cases}(M+M_{22})\ddot{y}+R(\dot{y})=F_w(t)+F_a(t)\\(I_x+M_{44})\ddot{\phi}+\Lambda_{44}\dot{\phi}+M_R(\phi)+M_{24}\ddot{y}+M_{RD}(\dot{y})=M_w(t)+M_a(t)\end{cases}\quad(1)$$

Where: M - Ship mass; M_{22} - added mass 22; M_{24} - added mass 24; M_{44} - added mass 44; I_x - transversal inertia moment; R - horizontal damping force; M_{RD} - moment of horizontal damping force; Λ_{44} - angle damping coefficient; ϕ - relative roll angle; y - relative horizontal movement of ship's center of gravity;

$$\phi=\theta-\alpha \qquad y=\zeta_g-\zeta_w \quad(2)$$

θ - absolute roll angle; α - angle of wave slope; ζ_g - horizontal movement of ship center of gravity; ζ_w - horizontal movement of wave;

$M_R(\phi)$ - restoring moment; following [12] or [14] we shall use piece - wise linear approximation of the restoring moment (see fig. 1, taken from [14])

$$M_R^{*}(\phi)=\begin{cases}(I_x+M_{44})\cdot n_0^2\cdot k_{f0}\cdot\phi; & when\quad \phi\in[0;\phi_{m0}]\\(I_x+M_{44})\cdot n_0^2\cdot k_{f1}(\phi_v-\phi); & when\quad \phi\in]\phi_{m0};\phi_{m1}[\end{cases}\quad(3)$$

$F_w(t)$ and $M_w(t)$ are wave excitation force and moment. They should be presented by Furrier series with harmonic amplitudes obtained from corresponding spectra and with random initial phase angles, which have constant distribution.

$$F_w(t)=2\cdot D_w\cdot\sum_{l=1}^{N}\alpha_{0l}\kappa_\zeta(\sigma_l)\sin(\sigma_l t+\varphi_{0l})\quad(5)$$

$$M_w(t)=I_w\cdot\sum_{l=1}^{N}\alpha_{0l}\kappa_\theta(\sigma_l)\sigma_l^2\sin(\sigma_l t+\varphi_{0l})\quad(6)$$

α_{0l} - amplitude of wave slope angle of harmonic with frequency σ_l

$\kappa_\zeta(\sigma_l)$ - horizontal reduction coefficient

$\kappa_\theta(\sigma_l)$ - angle reduction coefficient

D_w - weight displacement

φ_{0l} - initial phase angle. It is random with constant distribution.

$F_a(t)$ and $M_a(t)$ are wind aerodynamic forces and moments. They also should be presented by Furrier series with the same set of harmonic frequencies, but with another set of initial phase angles - we assume that wind and waves are not correlated.

$F_a(t)$ and $M_a(t)$ are wind aerodynamic forces and moments. They also should be presented by Furrier series with the same set of harmonic frequencies:

$$F_a(t)=F_{a0}+\sum_{l=1}^{N}a_{yl}\sin(\sigma_l t+\psi_{0l})\quad(7)$$

$$M_a(t)=M_{a0}+\sum_{l=1}^{N}a_{ml}\sin(\sigma_l t+\psi_{0l})\quad(8)$$

ψ_{0l} - initial random phase angle for wind excitation. It is statistically independent on initial phase angle for wave excitation φ_{0l}.

From the other side, aerodynamic forces depend on wind velocity $c(t)$, presenting it as $c(t) = c_0 + c_t$, and neglecting c_t^2 as small value [16], we obtain:

$$F_a(t) = C_y \frac{\rho_a}{2} A_s (c_0^2 + 2c_0 c_t); \quad M_a(t) = C_m \frac{\rho_a}{2} A_s z_s (c_0^2 + 2c_0 c_t) \qquad (9)$$

Where: C_y, C_m - aerodynamic coefficients; ρ_a - air density; A_s - wind area; z_s - wind area center height;

A wind velocity random process has a normal distribution. Equation (9) allows to consider wind excitation forces and moments as normal random processes.

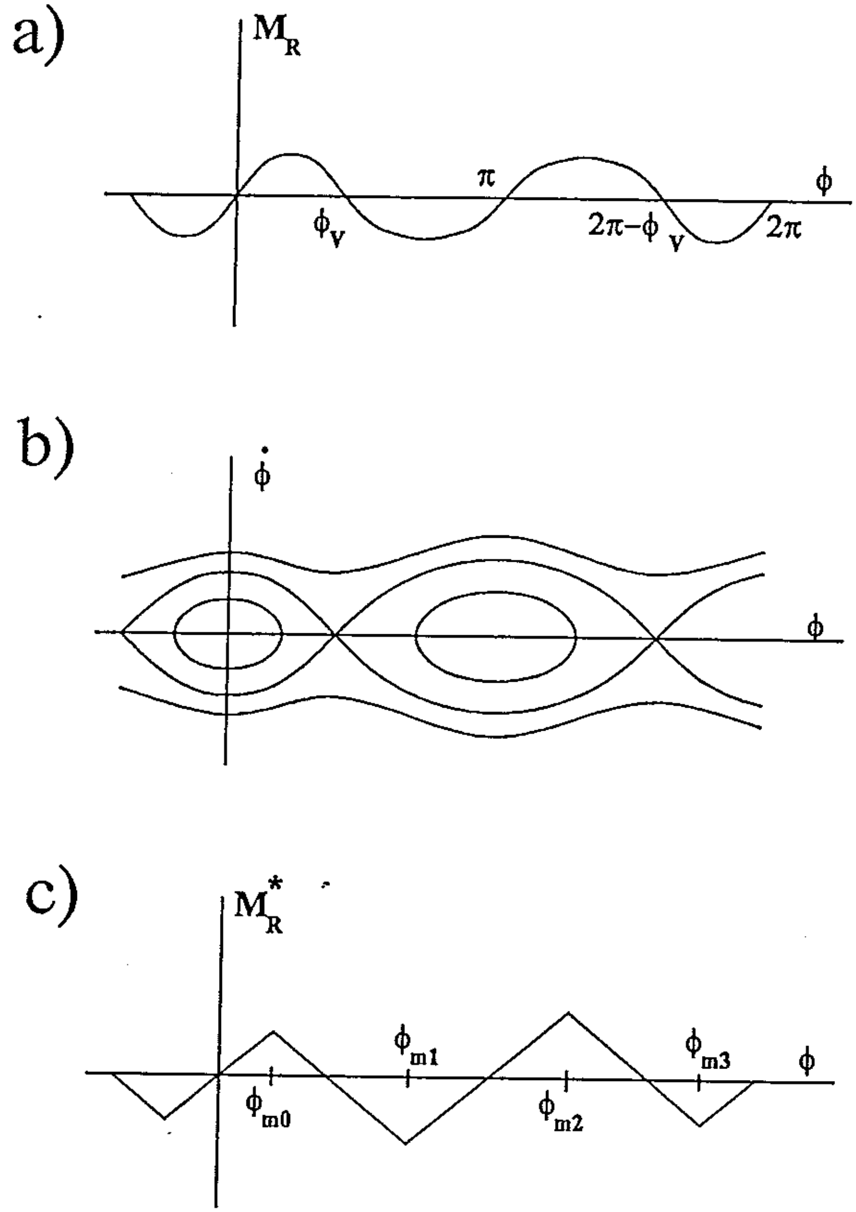

Figure 1. a. Restoring moment diagram
b. Phase plane
c. Piece-wise linear approximation of restoring moment

2. Swaying and Drift Motion

The equation of sway and drift motions is independent of rolling. This is ordinal non-linear differential equation with stochastic excitation. Following [17] we shall assume second power function for horizontal damping force:

$$R(\dot{y}) = K \cdot \dot{y}^2 \tag{10}$$

Where: K - is dimension coefficient of horizontal resistance.

$$K = \zeta_P \ \rho \ S_P / 2 \tag{11}$$

Where: ζ_P - dimensionless coefficient of horizontal resistance;
ρ - density of salt water;
S_P - area of diametrical projection of submersed part of ship hull.

The coefficient ζ_P can be obtained only from model serial experiment, like, for example, described in [18]. For the first expansion evaluation, the author can recommended the following linear regression formula, based on series test data [18]:

$$\zeta_P(\theta) = \zeta_{P0}(\theta) + \sum_{i=1}^{4} f_i(\theta) \cdot par_i \tag{12}$$

where: $\zeta_{P0}(\theta)$ - coefficient value for the basic model of series;
$f_i(\theta)$ - function of influence off geometric parameters;
par_i - influencing geometric parameter.

The following geometric characteristics can be used as influencing parameters (index *"0"* means that these characteristics belong to basic model of series):

$par_1 = (L/B) - (L/B)_0$ $\quad (L/B)_0 = 5.095$

$par_2 = (B/T) - (B/T)_0$ $\quad (B/T)_0 = 2.43$

$par_3 = (T/L) - (T/L)_0$ $\quad (T/L)_0 = 0.0808$

$par_4 = (C_b/C_m) - (C_b/C_m)_0$ $\quad (C_b/C_m)_0 = 0.665$

where: L - waterplane length; B - breadth; T - draught; C_b - block coefficient; C_m - midshipsection coefficient;

Coefficients for basic model and influence function can be found in tables 1 and 2 correspondingly.

Table 1

θ, degree	0	10	20	30	40	50
$\zeta_{P0}(\theta)$	0.832	0.948	0.874	0.997	0.971	1.113

Table 2

	0	10	20	30	40	50
f_1	0.6221	0.3251	0.7319	0.3929	0.2266	0.1603
f_2	-0.09453	-0.001378	0.1216	0.1419	0.2701	0.3026
f_3	0.5686	1.32	1.009	0.8789	0.9936	0.8698
f_4	-0.5608	-0.3085	-0.1047	0.8326	1.736	2.249

Further we shall interesting in stable drift only, because we are considering stable wind and wave excitation. We shall consider drift and swaying motion as a sum of a constant and time varying components.

$$\dot{y}(t) = \dot{y}_0 + \dot{y}_t(t) \tag{13}$$

We have to linearize horizontal motion equation, if we want to use the same theoretical background used by the author in [12], because it was assumed there that the system has only nonlinear restoring moment. So we assume here that the second power of the time varying component of horizontal motion could be truncated. It leads to the following equation of the horizontal motion

$$(M + M_{22})\ddot{y}_t + 2 \cdot K \cdot \dot{y}_0 \cdot \dot{y}_t + K \cdot \dot{y}_0^{\,2} = F_w(t) + F_a(t) \tag{14}$$

Equalizing time independent terms, constant horizontal velocity component $\dot{y}_0$ can be found.

$$\dot{y}_0 = \sqrt{F_{a0}/K} \tag{15}$$

As it was mentioned before we are interesting only in stable drift, so we can further consider only partial solution of the horizontal equation motion.

$$\dot{y}(t) = \dot{y}_0 + \sum_{l=1}^{N} b_l \sin(\sigma_l t + \gamma_l + \beta_l) \tag{16}$$

3. Rolling Motion

We begin consideration of rolling motion from M_{RD} - moment of horizontal damping force. It is well known that damping as physical phenomenon plays significant role in dynamic stability, but if the roll damping is widely investigated, the drift damping moment was considered in very few papers [18], [19], [20].

Physical nature of the moment M_{RD} as well as the horizontal damping force R, which leads to appearance of this moment, is quite complicate and now could not be adequately reflected by theory. All the papers devoted to this subject have model test background. The author used the method of calculation of M_{RD} taken from [19], [20]. This method is based mainly on the same series of model tests that paper [18] descries, but some tests of damaged ship model were added and more convenient coordinate system is used.

This method gives formula for the height of pseudo center of horizontal hydrodynamic pressure.

$$z_q(\theta) = T \cdot \sum_{l=1}^{5} f_l(\theta) \cdot par_l \tag{17}$$

where: $z_q(\theta)$ - coefficient value for the basic model of series;
$f_l(\theta)$ - coefficients of parameters (see table 3);
par_l - parameters:

$par_1 = 1 \qquad par_2 = B / T$
$par_3 = \theta_d \qquad par_4 = C_b / C_m$
$par_5 = L / B$

where : θ_d - angle of entrance of the upper deck to water when the ship is heeled (in degrees)

Table 3

	0	10	20	30	40	50
f_1	2.548	2.819	3.451	5.355	3.102	1.277
f_2	-0.027	-0.022	-0.103	-0.423	-0.424	-0.487
f_3	0.002	0.009	0.011	0.019	0.007	0.019
f_4	-2.414	-3.635	-6.590	-11.356	-14.111	-12.983
f_5	-0.046	0.037	0.267	0.525	1.198	1.256

Using of the term pseudo center means that the real point of drift resistance application is differ than point with height z_q. Real hydrodynamic as well as aerodynamic force have significant vertical component, that is neglected here, because we have mathematical model with two degrees of freedom. The authors of [19], [20] introduced this pseudo center to avoid a mistake in determination of drift resistance moment caused by hydrodynamic pressure. Horizontal force applied in this point yields the same moment that real hydrodynamic force.

Using equation (17) we can present M_{RD} as sum of time varying and constant components:

$$M_{RD} = M_{RC} + M_{RT}(t) \tag{18}$$

These components can be expressed as (fig. 2 taken from [19])

$$M_{RC} = K \cdot \dot{y}_0^2 \cdot (KG - z_q(\theta_0)) \cdot \cos\theta_0 \tag{19}$$

$$M_{RT}(t) = K \cdot \dot{y}_0 \cdot (KG - z_q(\theta_0)) \cdot \dot{y}_t \cdot \cos\theta_0 \tag{20}$$

Where: θ_0 - angle of pseudostatic heel, caused by constant components of aerodynamic and hydrodynamic pressures M_{RC} and M_{a0} (see fig 3).

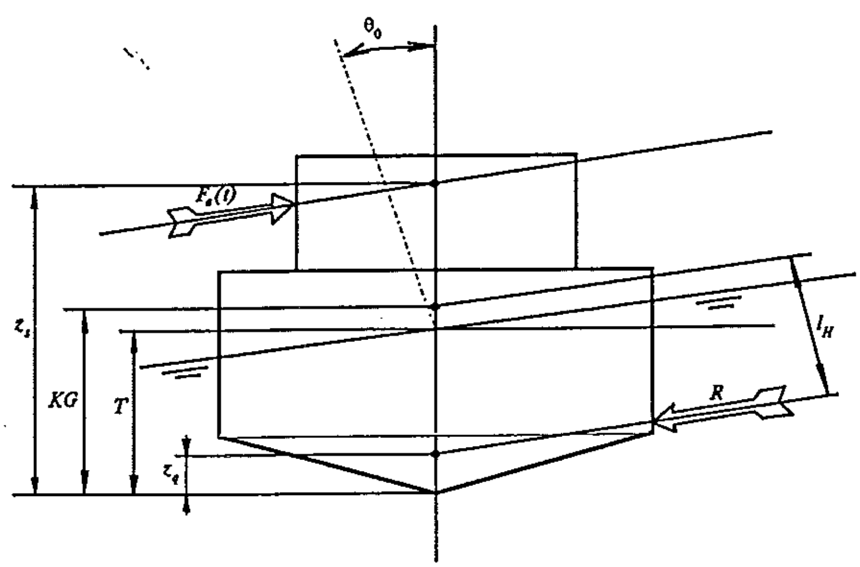

Fig. 2 Scheme of applying of the aerodynamic and hydrodynamic forces.

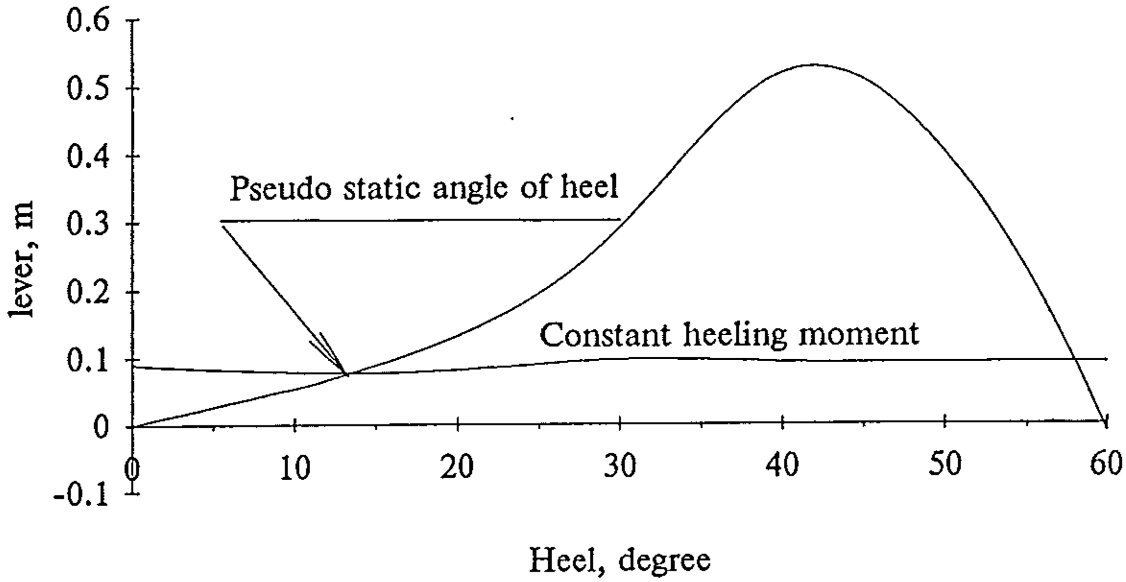

Fig. 3 Scheme of definition of pseudostatic angle of heel caused by constant components of wind excitation and horizontal damping in stable drift regime

Here we have to substitute real heel angle, which is depend on time by pseudostatic one, because of piecewise method that requires to keep linearity in all terms besides restoring moment.

Finally, we obtain rolling equation with single nonlinearity in restoring moment and complicated excitation, that allows to take into account horizontal motion.

$$(I_x + M_{44})\ddot{\phi} + \Lambda_{44}\dot{\phi} + M_R(\phi) = M_w(t) + M_a(t) - M_{24}\ddot{y} - M_{RC} - M_{RT}(t) \quad (21)$$

Substitution of (4), (6) and (8), as well as (16) and its derivative into a rolling motion equation (21) allows to solve it by following way. This equation is linear inside of every range. This allows to obtain general solution as a sum of natural and forced motions. Forced motion is generated by complex excitation, which contains hydro- and aerodynamic heeling moments and, also, inertial and dumping action of other degree of freedom - horizontal motion. Linkage between different ranges in piece-wise linear presentation of restoring moment is realized by initial conditions: corresponding angle of heel and angular velocity at the end of one range are initial conditions for motion on the another range.

For our purposes it will be enough to get the solution for the ranges No 0 and No 1 of piece-wise linear presentation:

For condition of $\phi \in [-\phi_{m0}; \phi_{m0}]$ range No 0

$$\phi(t) = \phi_a \exp(-\nu_\theta t)\sin(\omega_o t + \varepsilon_0) + q_0 + \sum_{l=1}^{N} q_l \sin(\sigma_l t + \delta_{ol} + \chi_l) \quad (22)$$

for condition of $\phi \in]\phi_{m0}; \phi_{m1}[$ range No 1 (positive angles)

$$\phi(t) = A\exp(\lambda_1 t) + B\exp(\lambda_2 t) + p_0 + \phi_v + \sum_{l=1}^{N} p_l \sin(\sigma_l t + \delta_{1l} + \chi_l) \qquad (23)$$

For condition of $\phi \in]-\phi_{m1}; -\phi_{m0}[$ range No 1 (negative angles) the structure will be the same as above.

The solution of rolling equation on range No O is quite ordinal: we shall have special interest of solution on range No 1. Values λ_1 and λ_2 are eigen values of the solution on the first range;

$$\lambda_{1,2} = -\nu_\theta \pm \sqrt{n_0^2 k_{f1} + \nu_\theta^2} \quad ; \qquad (24)$$

Values A and B are arbitrary constants of general solution for positive angles of heel;

$$A = \frac{(\dot\phi_1 - \dot p_B) - \lambda_2(\phi_1 - p_B - \phi_v)}{\lambda_1 - \lambda_2} \quad ; \qquad (25)$$

$$B = -\frac{(\dot\phi_1 - \dot p_B) - \lambda_1(\phi_1 - p_B - \phi_v)}{\lambda_1 - \lambda_2} \quad ; \qquad (26)$$

p_1 and $\dot p_B$ are initial values of particular solution and its derivative;

$$p_B = p_0 + p_e + \sum_{l=1}^{N} p_l \sin(\delta_{1l} + \chi_l) \quad ; \qquad (27)$$

$$\dot p_B = -\nu_\theta p_e + \sum_{l=1}^{N} p_l \sin(\delta_{1l} + \chi_l) \quad ; \qquad (28)$$

p_0 - mean value of particular solution on the range No 1;

$$p_0 = \frac{b_0}{n_0^2 k_{f1}} \ ; \qquad (29)$$

p_l - harmonic amplitude of particular solution on the range No 1;

$$p_l = \frac{u_l}{\sqrt{(n_0^2 k_{f1} + \sigma_l^2)^2 + 4\nu_\theta^2 \sigma_l^2}} \ ; \qquad (30)$$

δ_{1l} - harmonic initial phase angle of particular solution on the range No 1;

$$\delta_{1l} = \arctan\left(-\frac{2\nu_\theta \sigma_l}{n_0^2 k_{f1} + \sigma_l^2}\right) \qquad (31)$$

4. Probability of capsizing

A probability of capsizing during time T can be calculated for solution (22)-(23) as the probability of a random event, that the rolling process up-crosses the level ϕ_{m0} and arbitrary constant A is positive or the rolling process down crosses the level $-\phi_{m0}$ and arbitrary constant A^* is negative.

If arbitrary constant A is positive for positive heel angles, since exponential term with positive argument λ_1 in (23) will have a trend in positive infinity direction and will "lead" dynamic system (1) to capsizing in positive heel angle direction. If arbitrary constant A is negative for positive heel angles, since exponential term with positive argument in (23) will have a trend in negative infinity direction, it will "lead" dynamic system (1) to range No 0, where capsizing is impossible. Consequently, capsizing will not take place during this semi-period of the rolling oscillation. Analogously, if arbitrary constant A^* is negative for negative heel angles therefore capsizing will take place in negative heel angle direction.

$$P(T) = P_T(\phi > \phi_{m0})P(A > 0) + P_T(\phi < -\phi_{m0})P(A^* < 0) \tag{32}$$

here:

$P_T(\phi > \phi_{m0})$ - probability of capsizing of at least one up-crossing of ϕ_{m0} value level during time T with assumption of independence of rarely occurring of up-crossing events:

$$P_T(\phi > \phi_{m0}) = 1 - \exp(-\xi T) \tag{33}$$

ξ - intensity of up-crossings. Assuming normal law of distribution of rolling motion

$$\xi = \frac{1}{2\pi}\sqrt{\frac{V_{\dot\phi}}{V_\phi}}\exp\left(-\frac{(\phi_{m0} - m_{m0})^2}{2V_\phi}\right) \tag{34}$$

Where: $V_{\dot\phi}$ - variance of angular velocity. V_ϕ - variance of rolling motion. Here we shall assume rare occurring of up-crossings. It means that there is enough time between two neighboring crossings for natural oscillation to be damped. So the variances can be calculated as:

$$V_{\dot\phi} = \frac{1}{2}\sum_{l=1}^{N} q_l^2\sigma_l^2 \qquad V_\phi = \frac{1}{2}\sum_{l=1}^{N} q_l^2 \tag{35}$$

m_ϕ - mean value of rolling angles, with above mentioned assumption

$$m_\phi = q_0 \tag{36}$$

P(A>0) - probability of positivity of arbitrary constant A of particular solution on the range No 1, or the probability of capsizing after up-crossing event occurring. It is necessary to consider a law of distribution of the arbitrary constant A for this probability calculation. Arbitrary constant A can be considered as deterministic function of three random arguments (see formula (52)): angular velocity of up-crossing, values of forced oscillation and its derivative in the moment of up-crossing. It was shown in the author's previous papers, that the influence of excitation is very small during motion inside the first range of piece-wise presentation of stability diagram, and variances of corresponding forced oscillation and its derivative are very small too [12], [14]. The reason of this phenomena is absence of resonance in forced oscillation response curve in the first range. Therefore we can substitute random processes of $p(t)$ and $\dot p(t)$ by their mean values. Also corellation between forced oscillation in the ranges No 0 and No 1 can be neglected.

Then the distribution of the arbitrary constant A is required. To obtain it is not difficult, because arbitrary constant A is a linear function of the single argument: angular velocity of up-crossing. Rolling motion process has no correlation with the process of roll angular velocity. Therefore up-crossing is possible with any positive value of angular velocity. It means that we can consider angular velocity of up-crossing $\dot\phi_1$ as normal distributed value, and distribution of the arbitrary constant A also is normal (detail consideration of this question can be found in [13] or [12]).

Using above mentioned considerations, we can write:

$$P(A>0)=2\Phi\left(\frac{m_A}{\sqrt{V_A}}\right);\tag{37}$$

Φ - Laplas function:

$$\Phi(z)=\frac{1}{2\pi}\int_{-\infty}^{z}\exp\left[-\frac{x^2}{2}\right]dx\tag{38}$$

m_A- mean value of the arbitrary constant A :

$$m_A=-\frac{-\lambda_2(\phi_{m0}-\phi_v-p_o)}{\lambda_1-\lambda_2}\tag{39}$$

V_A- - variance of arbitrary constant the arbitrary constant A :

$$V_A=\frac{V_\phi}{(\lambda_1-\lambda_2)^2};\tag{40}$$

5. Capsizing Probability Computation for Given GZ Curve

A "triangle" diagram used above is good enough for theoretic investigation and understanding of physics of capsizing phenomena, but even for comparison assessments of real ship capsize probability the real stability diagram is required.

The distribution density of rolling process generally is differ from the normal law. This difference strongly depends on the form of the initial part of the GZ curve, because the most frequently met roll angles are situated in this range and their statistical weight has great influence on the result histogram.

Really, when the angle of heel is close to the maximum of diagram, then instant metacentric height as well as natural frequency are very small. Therefore all response curve is shifted to origin of coordinate system, where wave excitation is small. It means that dynamic system gets a very small quantity of energy from excitation, when angles of heel are close to maximum of the diagram, consequently such heel angles are relatively rare and could not change the character of the distribution. So, nonlinearity of the diagram caused by the maximum do not brake normal character of the distribution.

Contrary to, if the diagram has significant nonlinearity near zero heel angle, it changes character of the distribution dramatically, because variable stiffness takes place in the domain of often meeting angles of heel. More details on this subject can be found in [12].

Therefore a new method should be developed, which will be independent of the rolling distribution character. Such a method is can be based on following ideas [12]:

1. The border of the range No 0 (or non-linear range) is situated in the maximum of the stability diagram.

2. The other part of the diagram is substituted by multi-range broken line (See fig. 4).

3. Such initial angular velocity should be found, which promote satisfaction of the condition $A\approx 0$ in the beginning of the last range of the broken line. Such initial velocity will be called critical. All the initial angular velocities exceeding the critical will lead to capsizing. All the velocities less than the critical

one will not lead to capsizing due to small influence of the excitation on the motion on the decreasing part of the diagram.

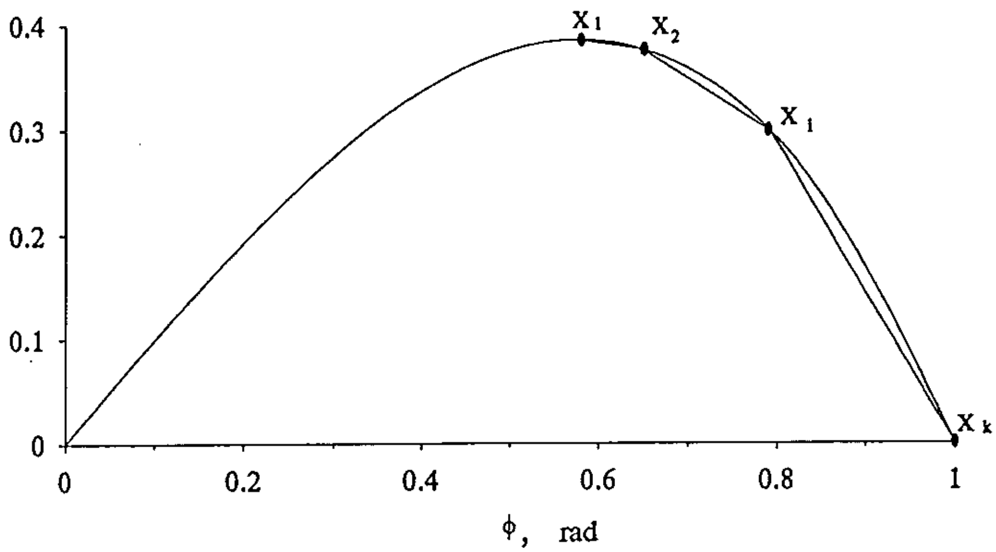

Fig. 4 Piece-wise presentation of decreasing part of stability diagram

4. Probability density of the processes of roll angles and angular velocities can be approximated using Tchebysheff-Ermitt polynoms up to the forth order according to recommendations [22].

Tchebysheff-Ermitt polynoms can be defined as:

$$H_l(x) = (-1)^l \cdot \exp(x^2) \cdot \frac{d^l}{dx^l}\left[\exp(-x^2)\right]. \tag{41}$$

We shall search series in the following form:

$$f(x) = \exp(-x^2) \cdot \sum_{l=0}^{\infty} b_l \cdot H_l(x) \quad . \tag{42}$$

This series is usable if:

$$\int_{-\infty}^{\infty} f(x) \cdot \exp\left({(x-\bar{x})^2} \Big/ {4\sigma^2} \right) dx < \infty \tag{43}$$

and if $f(x)$ has finite number of gaps. So the series (42) is usable if probability density $f(x)$ decreases quick enough when argument x is growing up.

For obtaining of coefficients b_l it is enough to multiply both sides of equation (42) by $H_l(x)$ and to integrate them by x in infinite limits. This operation yields:

$$f(x) = \frac{1}{\sigma^2} \cdot \varphi\left({(x-\bar{x})} \Big/ {\sigma} \right) + \frac{1}{\sigma} \cdot \sum_{l=3}^{\infty} a_l \cdot \frac{1}{\sigma^l} \varphi^{(l)}\left({(x-\bar{x})} \Big/ {\sigma} \right) \tag{44}$$

where:

$$\varphi(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \tag{45}$$

$\varphi^{(l)}(x)$ is the derivative of $\varphi(x)$ of the l-th order

a_l are the coefficients, which can be defined as:

$$a_l = \sum_{j=0}^{\mathrm{int}(l/2)} \frac{(-1)^{j+l} \cdot \sigma^{2j} \cdot M_{l-2j}}{(l-2j)! \cdot j! \cdot 2j!} \qquad (l = 3, 4, \ldots) \tag{46}$$

where: M_l - the third central moment of the distribution;

Proceeding up to the forth order of derivative, it possible to obtain [22]:

$$f(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \exp\left(-\frac{z^2}{2}\right) \cdot \left(1 - \frac{Sk}{3!}(3z - z^3) + \frac{Ex}{4!}(z^4 - 6z^2 + 3)\right) \tag{47}$$

where: $z = {(x - \bar{x})}/{\sigma}$;

Ex - excession of the distribution, Sk - symmetry of the distribution

$$Ex = \frac{M_4}{\sigma^4} - 3 \qquad Sk = \frac{M_3}{\sigma^3} \tag{48}$$

σ - standard deviation;

M_3 - the third central moment of the distribution;

M_4 - the forth central moment of the distribution;

Example of such approximation in comparison with simulation results is presented on fig. 6 and fig. 7.

The moments of the distribution of both processes can be calculated by moment method as it is recommended in [5].

5. Probability of exceeding of the critical angular velocity should be found by the given law of rolling angular velocity distribution, in other words: a probability of capsizing after up-crossing of the maximum diagram level ϕ_{max} should be calculated:

$$P_T(\phi > \phi_{\max}) = 1 - \exp(-\xi T), \tag{49}$$

where intensity of up-crossings ξ can be calculated as [22] (with assumption of independence of rolling and rolling angular velocities processes: they are not normal now, since absence of correlation do not warrantee statistical independence):

$$\xi = \int_0^{\infty} \dot{\phi} \cdot f(\phi = \phi_{\max}) d\dot{\phi} \tag{50}$$

6. Simulation example

In order to illustrate possibilities of approximation of the distributions some simulation of rolling coupling with stable drift and swaying were made.

The simulative model took into account two degrees of freedom as it was proposed above(see equation 1) and only one non-linearity on restoring moment. All other non-linearities mentioned in equation (1) was linearized as it was proposed above. Input data on the ship taken for the simulation are given in a table 4 and data on hydro-aerodynamic coefficients are given in table 5.

The following spectra were used for wave and wind excitation description. A wave spectrum was taken in well known from of Barling Spectrum:

$$S_W(\sigma) = 9.43\frac{V_W}{\sigma_{wm}}\left(\frac{\sigma_{w\max}}{\sigma}\right)^6 \exp\left[-1.5\left(\frac{\sigma_{w\max}}{\sigma}\right)^4\right] \tag{51}$$

where: $\sigma_{w\max}$ - frequency of spectrum maximum; σ_{wm} - mean wave frequency; V_W - variance of waves.

Table 4

Waterplane length L, m	136.1
Breadth molded B,m	20.05
Draught T, m	6.8
Block coefficient C_B	0.714
Waterplane coefficient C_W	0.907
Midshipsection coefficient C_M	0.977
Mass displacement M, ton	13590
Transverse inertia moment I_X, ton m²	669300
Height of buoyancy center CB, m	3.74
Beam metacentric radius BM, m	7.99
Gravity center height KG, m	11.42
Wind area A_S , m²	2048
Height of wind area center z_S, m	8.24

Table 5

Horizontal added mass M_{22} , ton	13830
Added moment of inertia M_{44}, ton m²	167300
Horizontal damping coeff. K, ton/m	758
Dimensionless drift coeff. ζ_P	1.64
Constant aerodynamic force F_{a0}, kN	1032
Const. aerodynamic moment M_{a0}, kNm	3632
Const hydrodynamic moment M_{RC}, kNm	8670
Horizontal aerodynamic coefficient C_Y	1.3
Moment aerodynamic coefficient C_M	1.3
Natural frequency n_0 , 1/s	0.2444
Roll damping ν_θ , 1/s	0.0083969
Linearized horizontal damping ν_η , 1/s	0.06447
Cross coefficient of added mass μ_{24}, 1/m	0.05106
Cross damping coefficient ν_{24}, 1/(m s)	0.01775
Stable drift velocity $\dot{y}_0$, m/s	1.168
Stable drift heel angle θ_0 , degree	14.12

A wind spectrum was taken from [5]:

$$S_a(\sigma) = \frac{1}{4}C_S(\varepsilon c_0)^{2/3}\sigma^{-5/3} \tag{52}$$

where: c_0 - mean wind velocity; C_S - empirical coefficient, here taken 1.9 in accordance with recommendation of [5]; ε - turbulence coefficient, can be obtained if variance of wind fluctuation is given.

The variance of wind fluctuation was taken using recommendations [15]:

$$V_C = 0.0206\, c_0^2 \tag{53}$$

The simulations were carried out in a form of consequent realizations, which are differ one from another by unlike sets of initial phase angles φ_i and ψ_i, which are supposed to be random values with constant density distribution. Simulation parameters well as excitation data are give in table 6.

Table 6

Number of realizations	84
Number of point in each realization	5000
Time step, s	1
Number of frequencies	49
Frequency step, 1/s	0.02
Maximum frequency, 1/s	0.978
Significant height of waves h_s, m	6.39
Mean period of waves T_{wm}, s	9.58
Mean wind velocity c_0, m/s	24.52

The resulting histograms of roll angles and angular velocities with comparison with approximations of probability density in accordance with equation (47) are given in figures 5 and 6

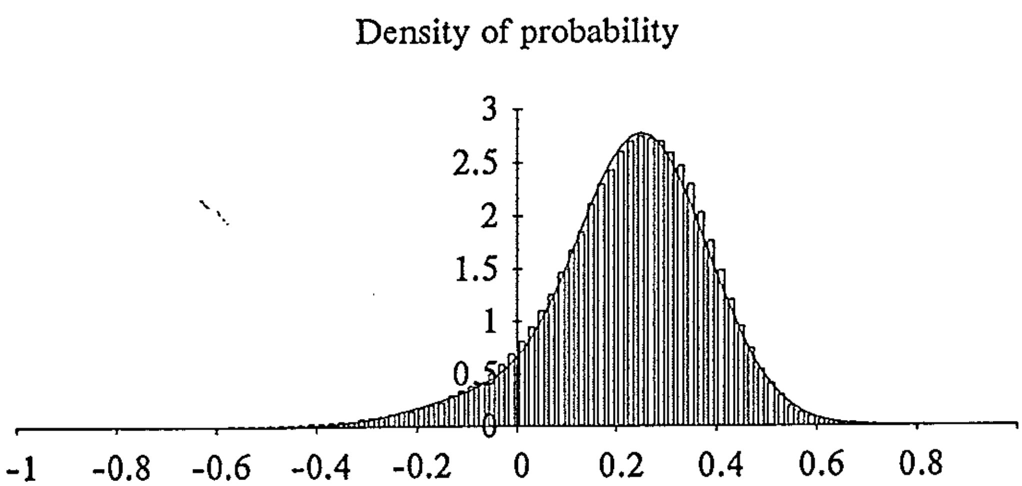

fig. 5. Empirical (bars) and theoretical (line) distribution of rolling

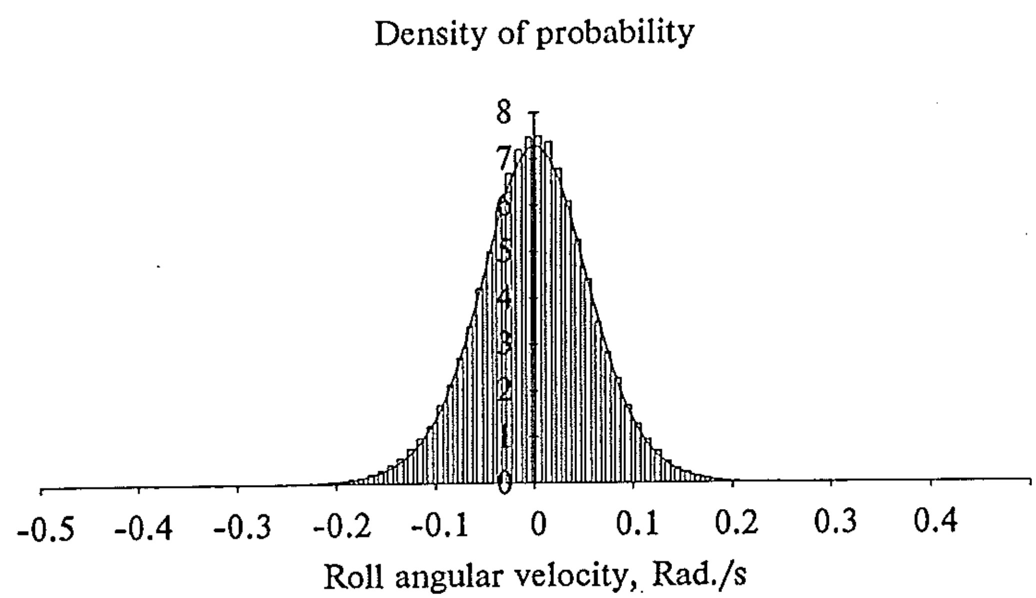

fig. 6. Empirical (bars) and theoretical (line) distribution of roll angular velocities

7. Algorithm of the calculation of critical angular velocities

Let us consider algorithm of critical velocity calculation more detail. Let decreasing part of the stability diagram is presented by broken line with ranges with angular coefficients a_i and free terms b_i. Calculation of critical velocity can be realized by any iteration method, which is suitable for transcendental equation solution. An auxiliary function $A^{**}(\dot{\phi})$ is built for this purpose

$$A^{**}(\dot{\phi}) = \begin{cases} A_{k-1} & \text{if process reaches } x_{k-1} \\ -1 & \text{if process do not reach } x_{k-1} \end{cases} \tag{54}$$

where x_{k-1} is the point of the last range beginning

Procedure of calculation of this function is described here.

1. A range No i is considered, where i is changing from 0 to k-1. Initial angular velocity is $\dot{\phi}_i$ in the beginning of the range No i.

2. Reach the rolling process the end of range No i or not? For answering of this question let us calculate a time, which is necessary for angular velocity $\dot{\phi}(t)$ to reach zero. This can be done by following transcendental equation solution:

$$\lambda_{1i} A_i \exp(\lambda_{1i} t) + \lambda_{2i} B_i \exp(\lambda_{2i} t) = 0 \tag{55}$$

Here: A_i and B_i are arbitrary constants, depending on initial conditions.

$$A_i = \frac{\dot{\phi}_i - \lambda_{2i} x_i + \lambda_{2i}(p_i + b_i / a_i)}{\lambda_{1i} - \lambda_{2i}} \tag{56}$$

$$B_i = -\frac{\dot{\phi}_i - \lambda_{1i} x_i + \lambda_{1i}(p_i + b_i / a_i)}{\lambda_{1i} - \lambda_{2i}} \tag{57}$$

λ_1 and λ_2 are eigen values:

$$\lambda_{1i,2i} = -\nu_\theta \pm \sqrt{a_i + \nu_\theta^2} \tag{58}$$

p_i mean value of forced motion:

$$p_i = -\frac{m_{a0} - f_{a0}\nu_{24} / \nu_\eta}{a_i} \qquad (59)$$

Here m_{a0} and f_{a0} are relative mean values of aerodynamic horizontal and angular excitation.

The equation (55) can be solved by any iteration method, for any negative A_i and positive $\dot{\phi}_i$. If A_i is positive, described above examination have no sense, because angular velocity will increase without any limits and never will reach zero. It means that rolling process will reach the end of the range No i in any case.

If A_i is negative, and above mentioned time $t(\dot{\phi}_i = 0)$ has been founded, it is necessary to test following condition:

$$\phi(t_{\dot{\phi}_i=0}) > x_{i+1} \qquad (60)$$

If this condition can be satisfied, therefore rolling process will reach the end of the range No i.

If this condition cannot be satisfied, therefore rolling process never will reach the end of the range No i and capsizing is impossible. In this situation

$$A^{**}(\dot{\phi}_1) = -1$$

3. Let us calculate a time, which is necessary for rolling process to reach the end of range No i.

$$\phi(t) = x_{i+1} \qquad (61)$$

Where

$$\phi(t) = A_i \exp(\lambda_{1i}t) + B_i \exp(\lambda_{2i}t) + p_i + b_i / a_i \qquad (62)$$

The equation (62) can be solved by any iteration method.

4. Let us calculate the angular velocity of up-crossing the border between ranges No i and No $i+1$.

$$\dot{\phi}_{i+1} = \dot{\phi}(t_{\phi=x_{i+1}}) \qquad (63)$$

Further calculations should be repeated with $i=i+1$ until i will reach value $k-1$.

5. When i will reach value $k-1$, only value of arbitrary constant A_{k-1} should be calculated. Calculation of auxiliary function $A^{**}(\dot{\phi})$ is being finished here.

A initial angular velocity of rolling, which yields zero value of auxiliary function is our goal - critical initial value of angular velocity.

Conclusions and Final Comments

A main purpose of this paper was to develop a method for calculation of capsizing risk function for ship in beam irregular seas and gusty wind.

This purpose can be reached by using piece-wise linear presentation of righting arm diagram. It is enough to use two range presentation for understanding of nature of investigated phenomena.

Multi range piece-wise presentation can be use for comparison calculation of capsizing probability. The main advantage of such the method is, that it can be used for any given distribution of rolling process.

Distribution of rolling process is depend on the form of the stability diagram near of the origin of the coordinate system. Non-linearity caused by existence of maximum of the diagram has relatively small influence on the distribution character.

The distribution density function can be presented by expansion in series by Tchebyshev - Ermitt orthogonal polynoms, but problem of accuracy of such presentation should be considered in future.

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Computer Simulations on the Dynamic Tensions of the Emergency Towing Lines of Tankers in the Seas

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Abstract

This study concentrate on the dynamic tensions on the towlines during the towing operations of tankers by tug boats. Emphasis is given at the emergency towing arrangements onboard tanker referred in SOLAS Chapter V. The necessity of designing the towing gear on the tanker is surfaced to facilitate salvage and emergency towing to reduce risk of pollution. Followed up on these requirements, a simulation study centred on the dynamics of tanker-tug tow system is taken up. Three tankers with each of 20000 dwt, 100000 dwt, and 200000 dwt were considered. Two tugs of different pulling capacity of 100 kN and 400 kN respectively were considered for towing operation. The important towing parameters like line length, tow speed are mainly decided based on the sea conditions.

Motion response of tug and tanker connected by towline is determined through numerical simulation. The excitations of the tanker and tug are considered treating the towline as a spring. As the tanker is large in size compared to the size of the tug, the excitations of the tug is dominant. Using the determined tension values for various sea states defined by Beaufort scales, typical cases of stability of tug during the tow operation are calculated. Both low and high frequency motions of the surface vessels are accommodated in the computer simulation, but the inertia force of towline is neglected. The wave exciting forces, drag of towed vessels and the line tensions govern the system dynamics. Towline tensions in irregular sea are determined as well.

1 Introduction

Towing marine structure to the required site in the sea, towing a tanker in salvage operation etc. are indispensable in ocean engineering. Both dynamic stability and directional stability of the towing tug are essential qualities for the successful completion of the mission requirement. In calm sea conditions propulsive force is responsible for the motion of the tow system against the tow rope pull and external forces. However, the towing operations become critical with the presence of wind, waves and current. In ship dynamics, calculation for actual ships are difficult to carry out because there is a shortage of numerical data and research work. Investigations on these problems are badly in need to alleviate such critical situations.

In a previous paper by Inoue et al(1994), the authors considered the inertial effect of towline in water and proposed the safety range of towing conditions for various harmonic motions of towline ends which are assumed to be the same as sea motion corresponding to various sea

states. In the present paper the inertia force of towline is neglected and the motion response of the surface vessels are taken in to account. In direct towing the towed body does not always directionally follow the towing tug boat or ship. Surface towing is complicated due to the presence of wind, wave and current and hence the fluctuating towline tension.
Bishop(1981) enquired whether it is possible to connect directional stability and righting stability. Vassalos(1985) stated that under low frequency of encounter condition, the dynamic forces will be relatively unimportant compared to the hydrostatic effects. Handy et al(1994) proposed stability criteria for tugs.
The tug boat during the operation can be capsized in so many ways. The effects of towline tension on the stability is discussed in this paper and the tension components may be suitably fitted in to the recently reported mathematical models so as to critically rewiew the stability characteristics of a particular vessel.
The draft guide lines for emergency towing arrangements on tankers insists on the strength requirement of the towing components. The strength should be sufficient for all relevant angles of towline. The towing pennant should have a length of at least twice the freeboard at the fairlead plus 50 m. However, in this study the parameters of towlines are adopted as required for tankers by the classification societies and these parameters are applied for the normal direct towing.

2 The motion response of the tug and the tanker

In this paper the motion response of the tug and tanker in seaway is determined by neglecting inertia effects of towline and the excitation of the line is assumed as the forced oscillation of the tug and tanker respectively. The springing of the towline connected in between the tug and tanker contributes to the dynamic forces in a towing operation. The details of the parameters of the towline used onboard three typical tankers are given in the Table 1. These parameters were determined referring to the equipment number recommended by Nippon Kaiji Kyokai(1978). The towline parameters used for emergency purpose on board tanker varies according to the equipment number. The principal particulars of two typical tugs for the computer simulations are shown in Table 2.

2.1 Motion simulation

The motion history of tug boat influences the tension variation on the towline. Fig. 1 shows towing configuration in horizontal plane with external force. Two dimensional strip method can be applied to determine the hydrodynamic forces of the tug boat. Let m_1 be the mass of the tug, m_x and m_y be the added mass in x_1 and y_1 direction respectively, then the equations of surface motion of the tug can be formed. For a tug with a velocity $\dot{x}_1$ in x_1 direction , $\dot{y}_1$ in y_1 direction and $\dot{\psi}_1$ the angular velocity. The relevant equations of motion in horizontal plane are as follows.

$$(m_1 + m_x)\ddot{x}_1 + (m_1 + m_y)\dot{y}_1\dot{\psi}_1 = -(m_y - m_x)v_c\dot{\psi}_1 \sin\psi_1 + F_{x_1} + T_{x_1} \qquad (1)$$

$$(m_1+m_y)\ddot{y}_1+(m_1+m_x)\dot{x}_1\dot{\psi}_1=(m_y-m_x)v_c\dot{\psi}_1\cos\psi_1+F_{y_1}+T_{y_1} \quad (2)$$

$$(I_{zz}+J_{zz})\ddot{\psi}_1=M_{z_1}+aT_{y_1} \quad (3)$$

Where v_c is the current velocity, F_{x_1} is the environmental force in x_1-direction, F_{y_1} is the environmental force in y_1-direction , M_{z_1} is the moment about the z_1-axis, T_{x_1} is the tension force in x_1 direction and T_{y_1} is that in the y_1 direction. The environmental forces and moments include wave exciting force, current force and wind force. To get motion history, the tension force is treated as spring force without mass. And a, the distance of the connecting end of towline from the longitudinal centre of gravity of tug boat, I_{zz} and J_{zz} are the mass moment of inertia and added mass moment of inertia respectively. For the above equations the tension of the towline is a function of the horizontal distance of the towline and this is non-linear. The equations of motions for the tanker are similar to those of the tug.

2.2 The static and dynamic analyses of towline as a spring

Static and dynamic tension of towline are non-linear. The towline hangs in a catenary-like curve. As the towline is extended statically, the curve becomes shallower with only a small increase in tension. With more extension, more force is required per unit increase in the extension. When the tension is large enough to make the catenary shape shallow or nearly a straight line, further increases in extension can be accommodated only by wire stretching, and for stiff materials this requires large tension increases.

The tug and tanker are assumed to be exciting at a certain frequencies and the towline is assumed as spring. The dynamic tension is calculated by excitation of both the ends of the line connecting the tanker and the tug. Towlines are usually composite systems. Wire rope, a synthetic stretching fiber rope in line with a wire rope and synthetic fiber rope are used as towlines. However, wire ropes are considered in this study as it is recommended by classification societies.

3 Results and Discussion

Type A tug and type B tug are considered and their principal particulars are provided in the Table 2. The principal particulars of the Tankers already mentioned in Table 1.

The calculating conditions of sea states are shown in Table 3. Motion and tension responses when the Tanker A is towed by Tug A(pull force 100 kN) under the sea condition of Beaufort scale 3 is shown in Fig.2. A 500m long line with a dia. of 58 mm was used for this simulation because of towline dia. of 44 mm for Tanker A is too weak to tow in this sea condition. ISSC spectrum is relied upon for this simulation.

Fig.3 shows (the maximum dynamic tension of towline)/(the mean pull of tug)($= T_d/T_s$) taken from the tension response similar to Fig.2 for various conditions. The dynamic tensions on the 58 mm dia. towline with length varying from 500 m to 1000 m are shown in this figure for various Beaufort scales. The dynamic tension is lesser than that in the case of previous study by Inoue et al(1994). In the previous study, the motion response of the tug and tanker in the sea was assumed to be the same as the motion of the sea wave for the Tug and negligibly small for the Tanker. Similar results are achieved when Tanker B is pulled by the same vessel, Tug A. This shows the the influence of the tanker size in the tension apmlification of the towline. For bigger Tanker C as shown in the Fig.5 higher tension values than in the case of Tankers B and A. The inertial load due to the movement of the surface vessels is responsible for the dynamic tension on the towline. Due to a higher mean pull of 400 kN by Tug B the dynamic tension is increased and is shown in Fig.6 and compared to Fig.3 the dynamic tension values are more. When the same Tug B(pull force 400 kN) pulls the Tanker B or the Tanker C no much difference is seen in the dynamic tension as shown in Fig.7 and 8.

The stability creterion of the Tug A and Tug B for a Beaufort scale of 5 is determined using the tension values. The extreme case of towing perpendicular to the centerline of the tug is considered. The wind is also taken in to account and assumed to be in the same direction as towing under the condition of wind speed 18 kt. However, the wind loads are very small compared to the towing mean pull of 100 kN for Tug A and 400 kN for Tug B respectively. This is due to the smaller lateral projected area of the tug. For Tug A the determined stability criterion is shown in Fig. 9 and for the same Beaufort scale the righting lever for Tug B is shown in Fig. 10. This stability requirement conditions is in agreement with the criterion mentionaed by Hendy et al(1994). The moment due to the tension is opposed by the righting moment in both the cases. The determination of this moment is done on a rough estimate. The area A_2 is greater then 1.4 times the area A_1 in both the cases. Although this is safe, a worse condition can occur when the Beaufort scale is higher and/or dynamic tension of towline act on the tug in lateral direction periodically.

Directional stability of the tug and tanker is also important in towing. The course stability of the tanker is seen to be stable in case of 500 m length of towline and is shown in Fig.11. If the course stability of the tanker is poor in case of short length of towline, the dynamic tension due to tanker is increased much more as shown in Fig.3 to 8. The course stability of the tug is shown in Fig.12. This figure shows the influences of tension of towline on the course stability of the tug.

From these detailed numerical results it may be appropriate to brief the physics of the towing problem. The hydrodynamic forces on the surface vessels can have large influence on the relationship between the tension and end point motion.

Conclusion

Numerical simulations were carried out to check the critical situations of ocean towing of tankers in various conditions. Simulations considering the motion response of the tug and the tanker in irregular sea were carried out to get the maximum tensions during the tow. The tension response determined as non-linear spring force depends on the motions of the tug and the tanker. From these simulations the dynamic tension increases when, the order of sea state is increased, the mean pull is increased and the length of the towline is decreased. An optimised length-pulling force can be chosen from the chart of the study for a successful operation. The dynamic tension obtained from the motion simulation were used to determine the stability criterion of the tug boats. The authors wish to give a suggestion on the emergency towing arrangements onboard tanker as such a requirement is raised in the draft guideline of SOLAS Chapter V. Using the tension values obtained by simulations, the stability criteria in dynamic condition is also discussed in this paper. For this the angle of tow line with respect to the towing ships centre line may be assumed conveniently for rough estimation of righting moment for dynamic stability. The course stability of the tug and tanker are determined through the numerical simulation. Both the Tanker A and Tug A were seen to be stable under the sea condition of Beaufort Scale of 5.

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List of Figures

Table 1. Principal particulars of tanker and the line parameters

tanker	dead weight (tf)	LBPxBxd (in meter)	equipment no.	towline			
				length (m)	dia. (mm)	breaking load (tf)	unit weight (kg/m)
A	20,000	135.0x 21.3x 8.6	1570	220	44	96	7
B	100,000	224.0x 35.9x 13.7	3210	280	58	150	11
C	200,000	293.0x 47.0x 17.3	5500	300	58	150	11

Table 2. Principal particulars of Tugs

tugs	LBP (m)	breadth (m)	draft (m)	displacement (tf)	pull (kN)
A	16.0	6.1	3.0	180	100
B	27.0	10.0	4.0	900	400

Table 3. Calculating conditions of sea state

Beaufort Scale	significant wave		wind speed
	height (m)	frequency (rad/sec)	(knots)
3	0.6	1.21	8
4	1.0	1.05	12
5	2.0	0.88	18
6	3.0	0.80	24
7	4.0	0.75	30
8	5.5	0.71	36

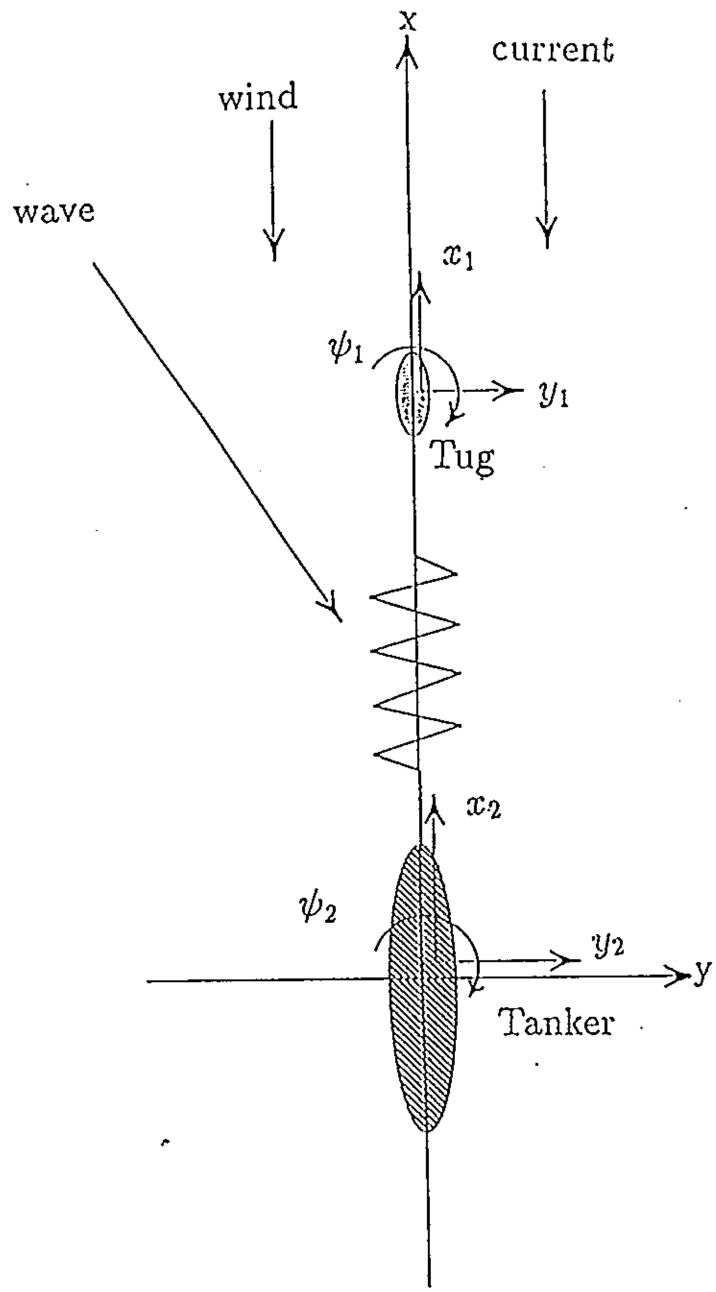

Fig.1 System coordinates

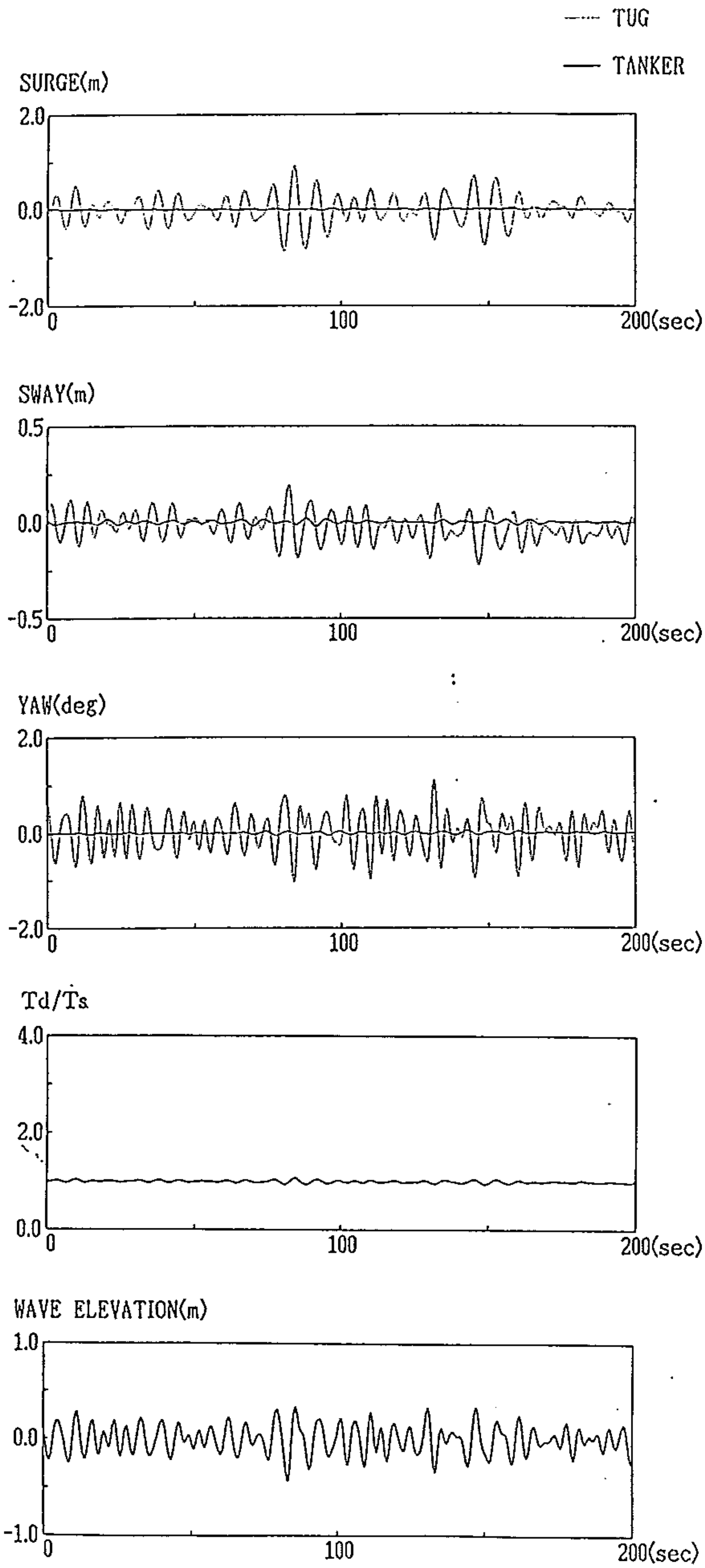

Fig.2 Motion and tension response of

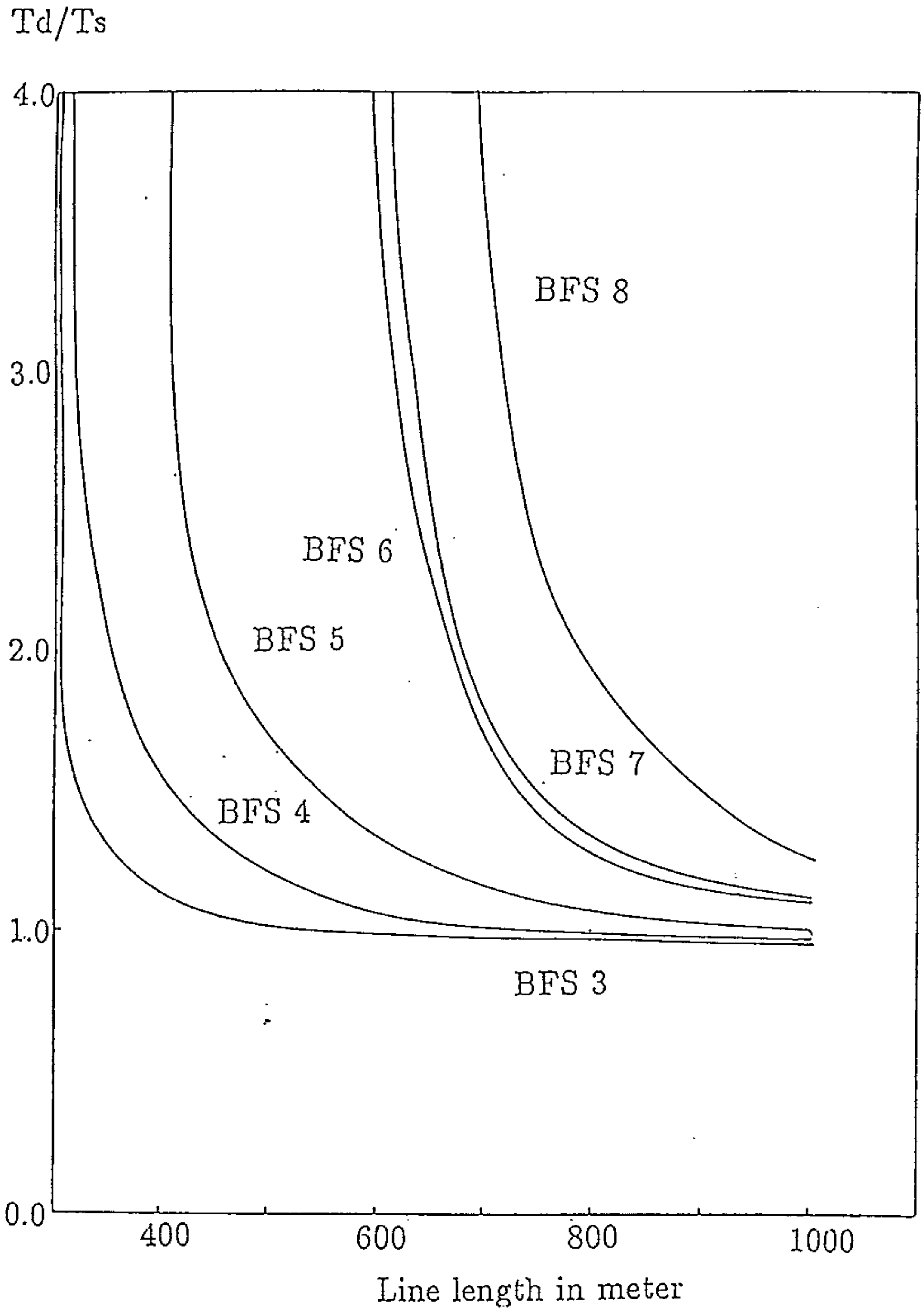

Fig.3 Dynamic tension for Tanker A and Tug A
(mean pull 100 kN, 58 mm dia. towline)

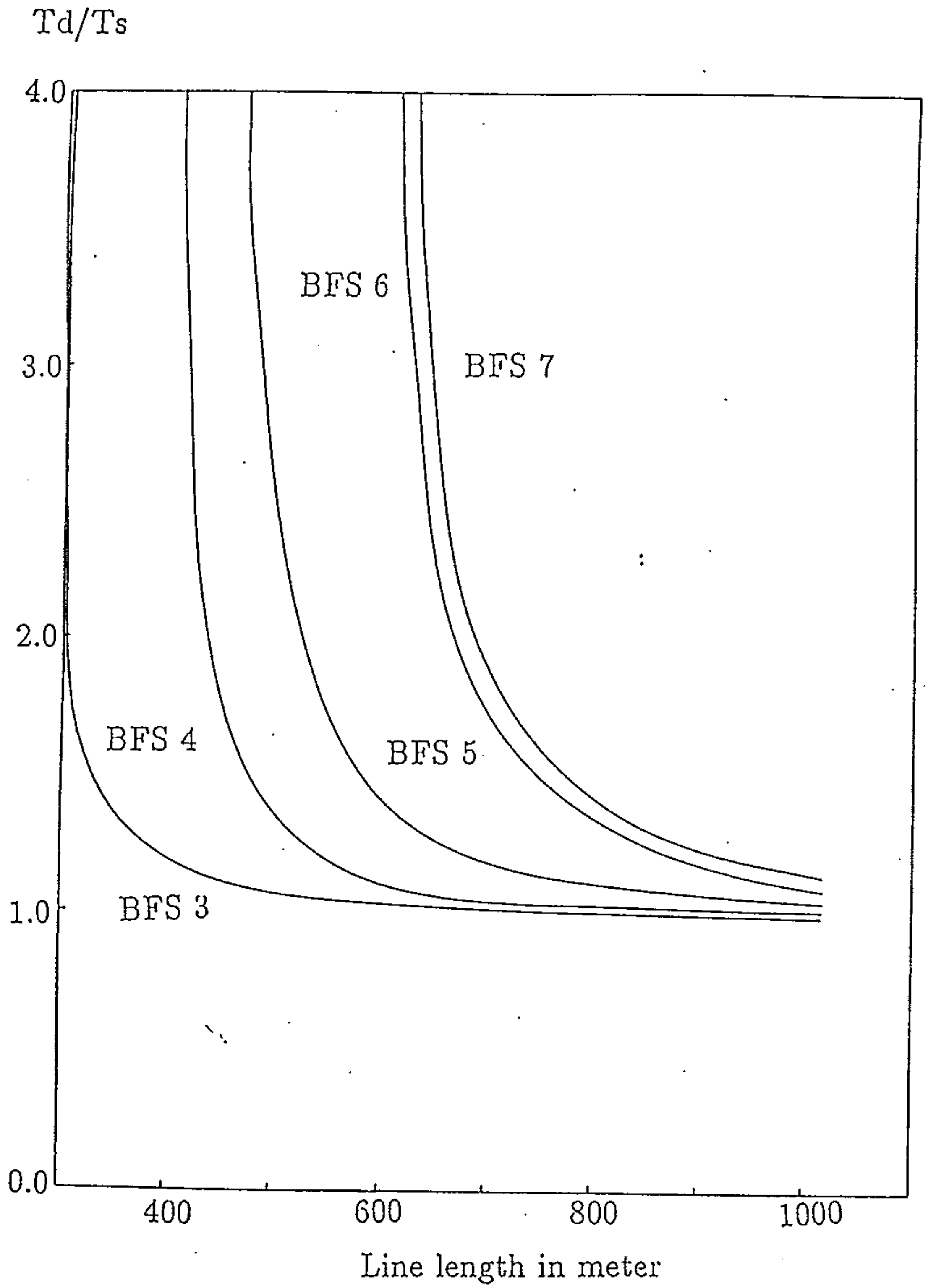

Fig.4 Dynamic tension for Tanker B and Tug A (mean pull 100 kN, 58 mm dia. towline)

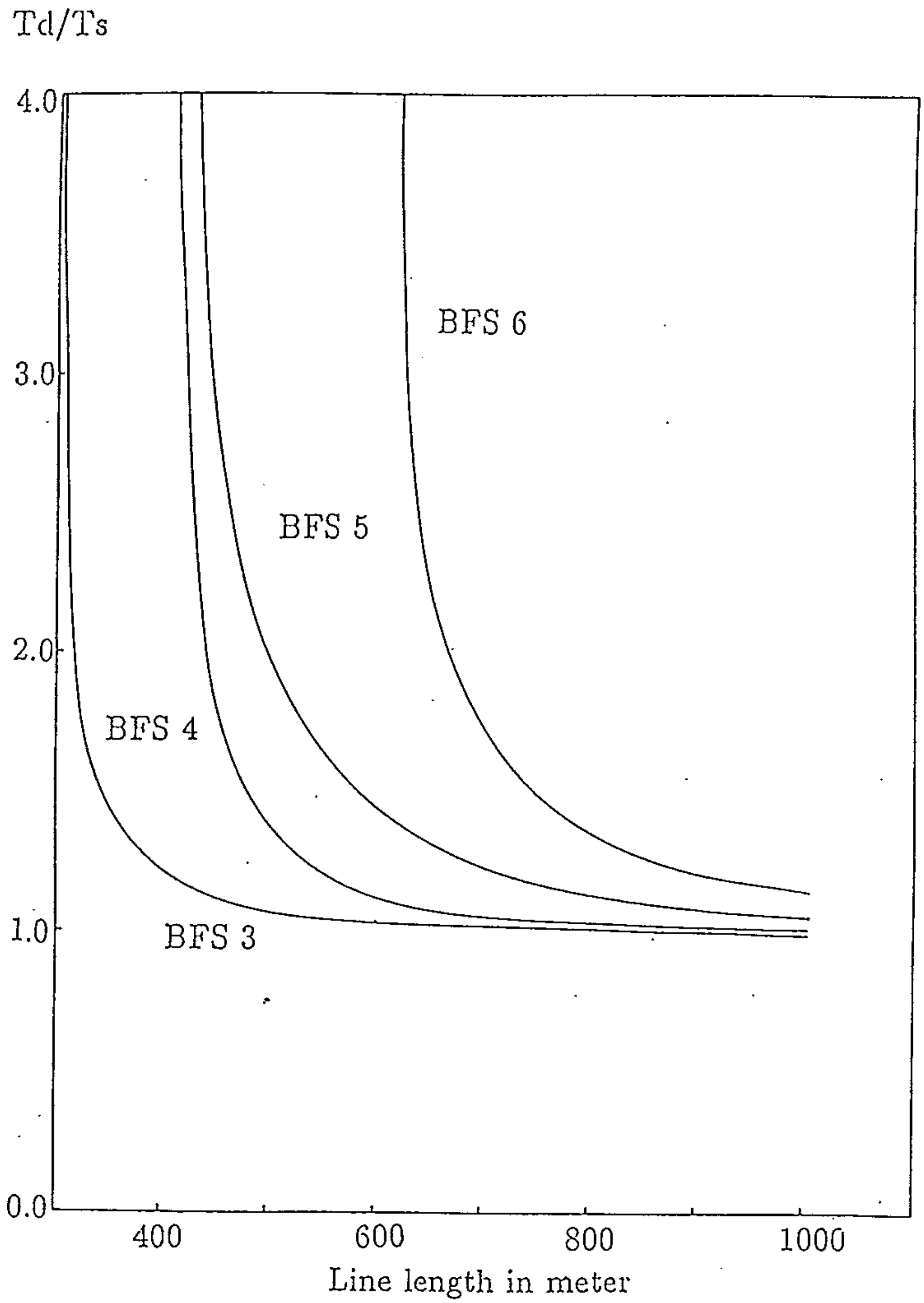

Fig.5 Dynamic tension for Tanker C and Tug A
(mean pull 100 kN, 58 mm dia. towline)

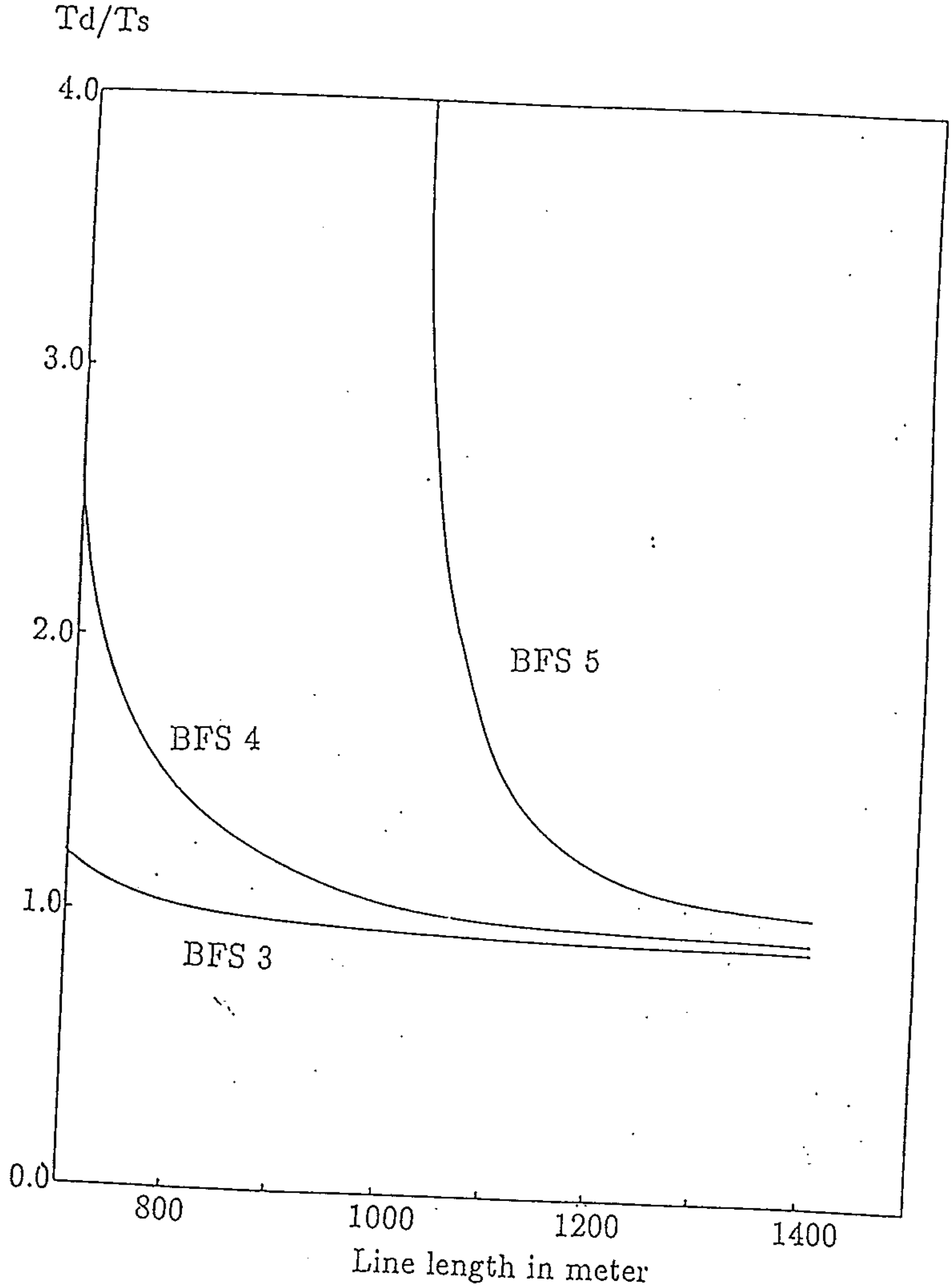

Fig.6 Dynamic tension for Tanker A and Tug B (mean pull 400 kN, 58 mm dia. towline)

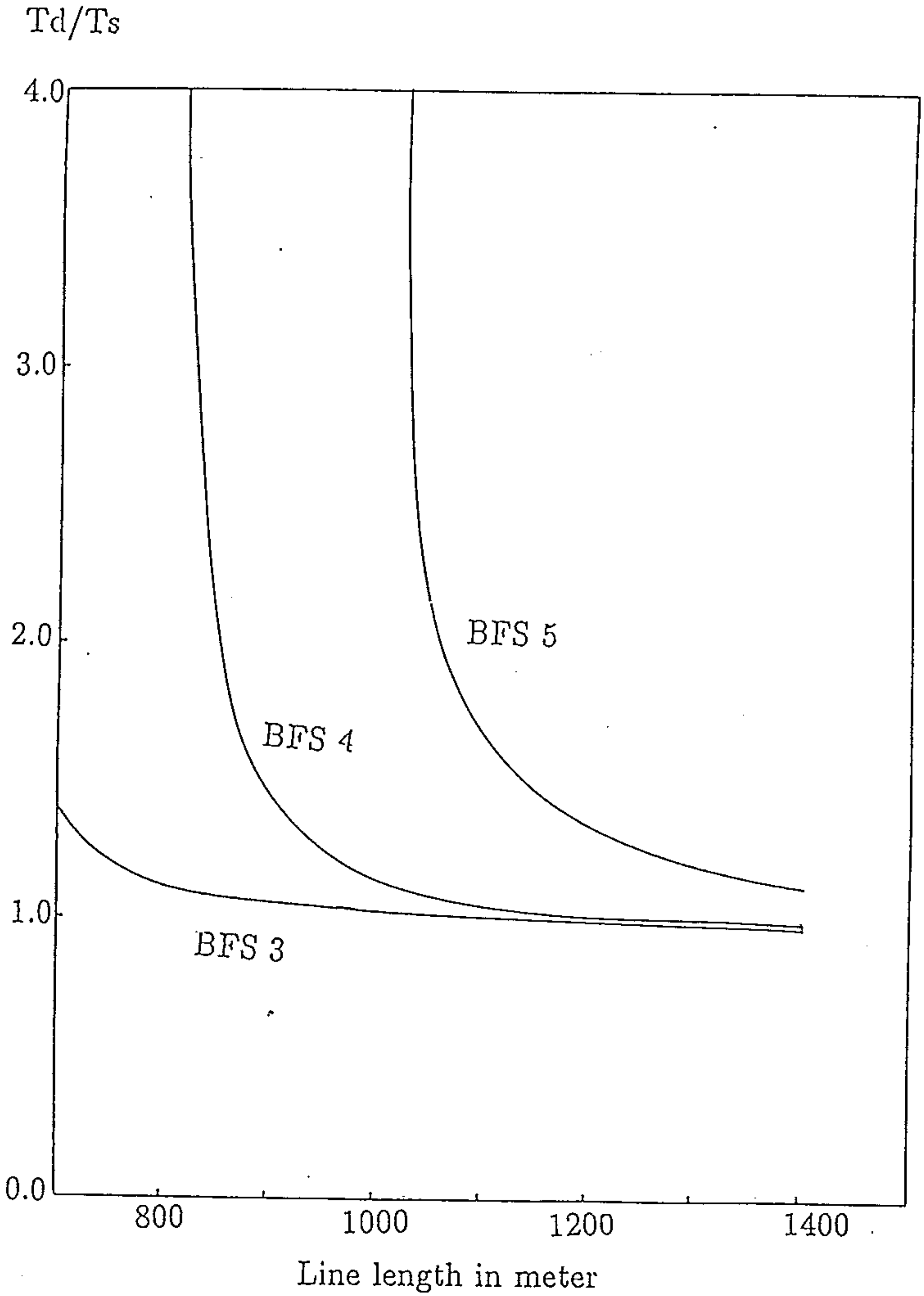

Fig.7 Dynamic tension for Tanker B and Tug B
(mean pull 400 kN, 58 mm dia. towline)

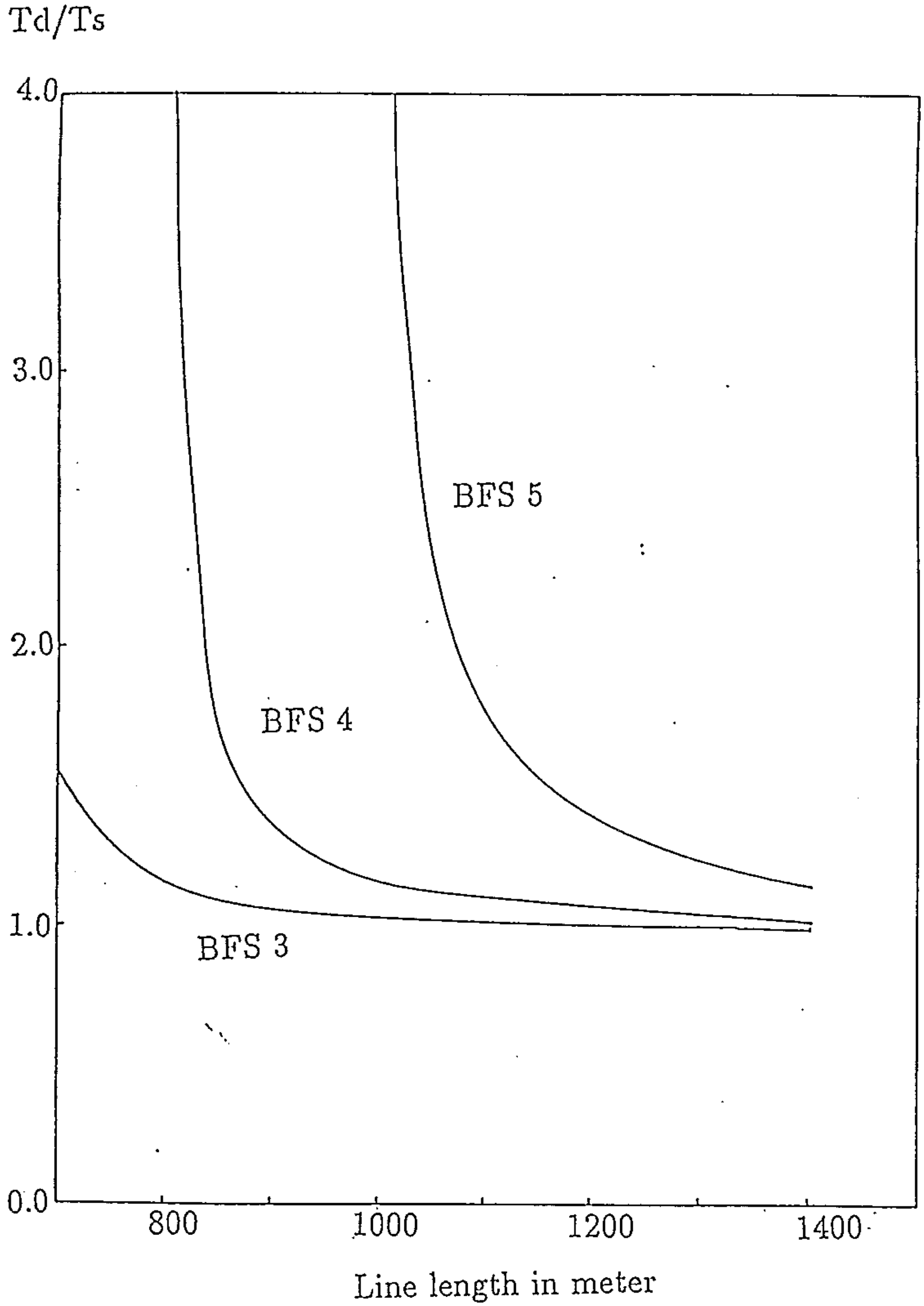

Fig.8 Dynamic tension for Tug B and Tanker C
(mean pull 400kN, 58 mm dia. towline)

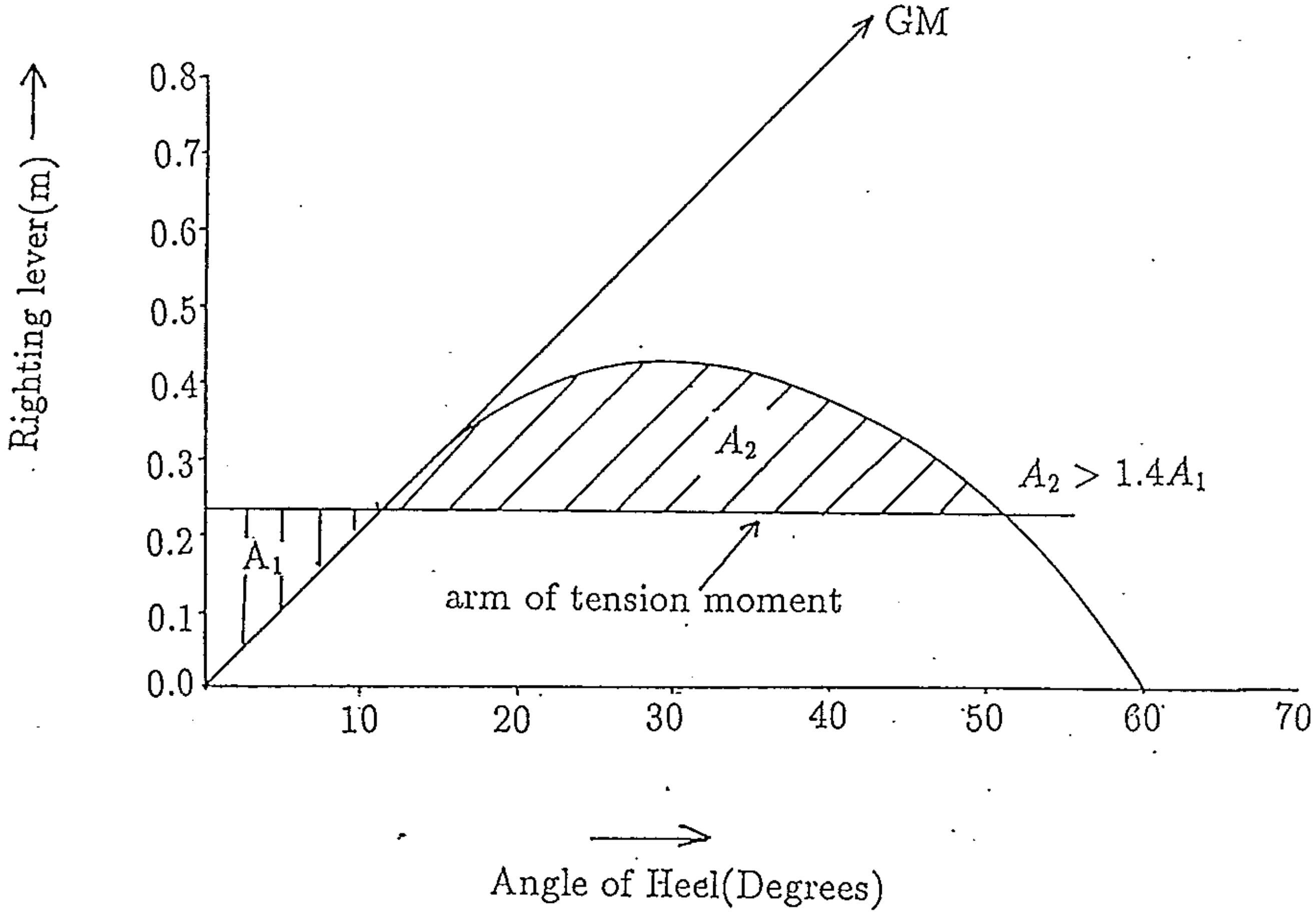

Fig.9 Stability of Tug A

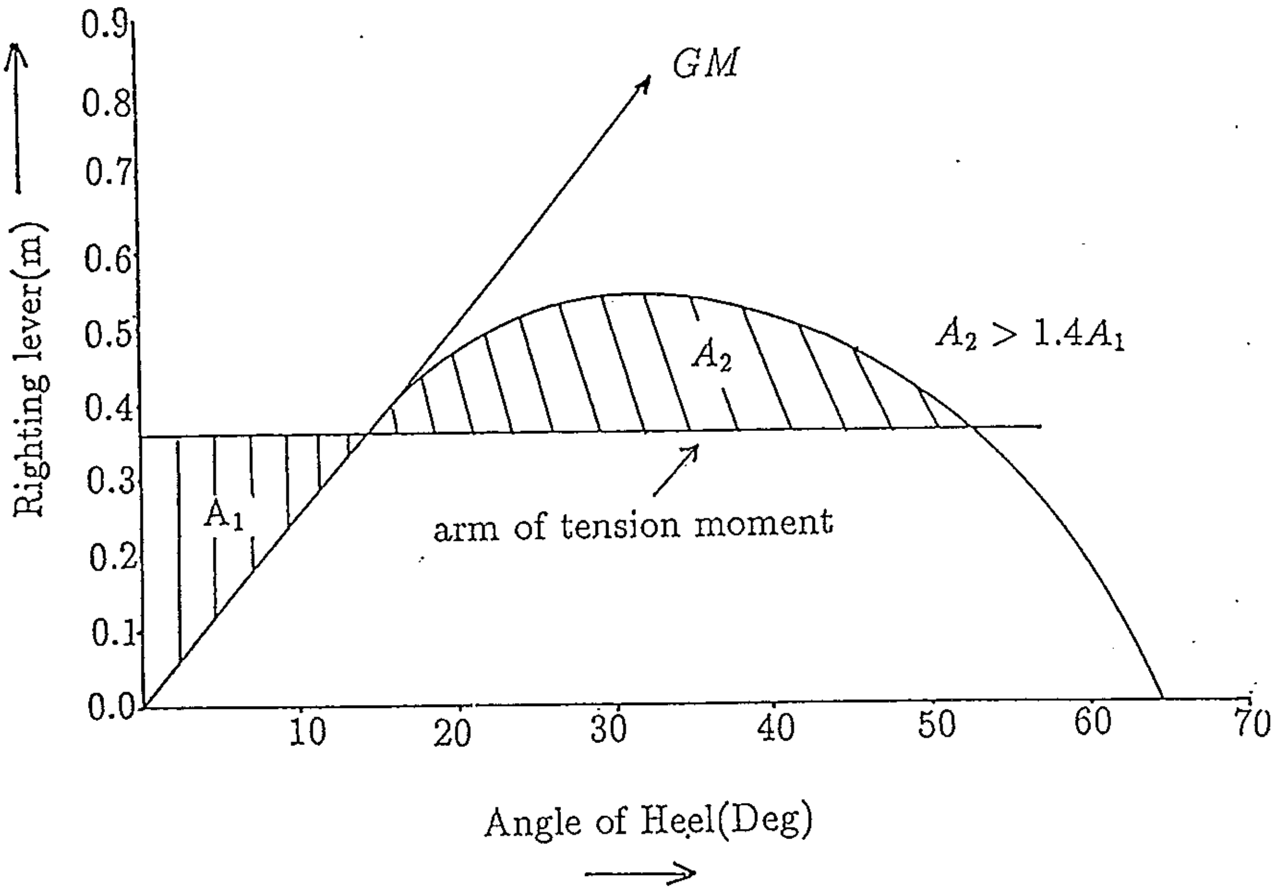

Fig.10 Stability of Tug B

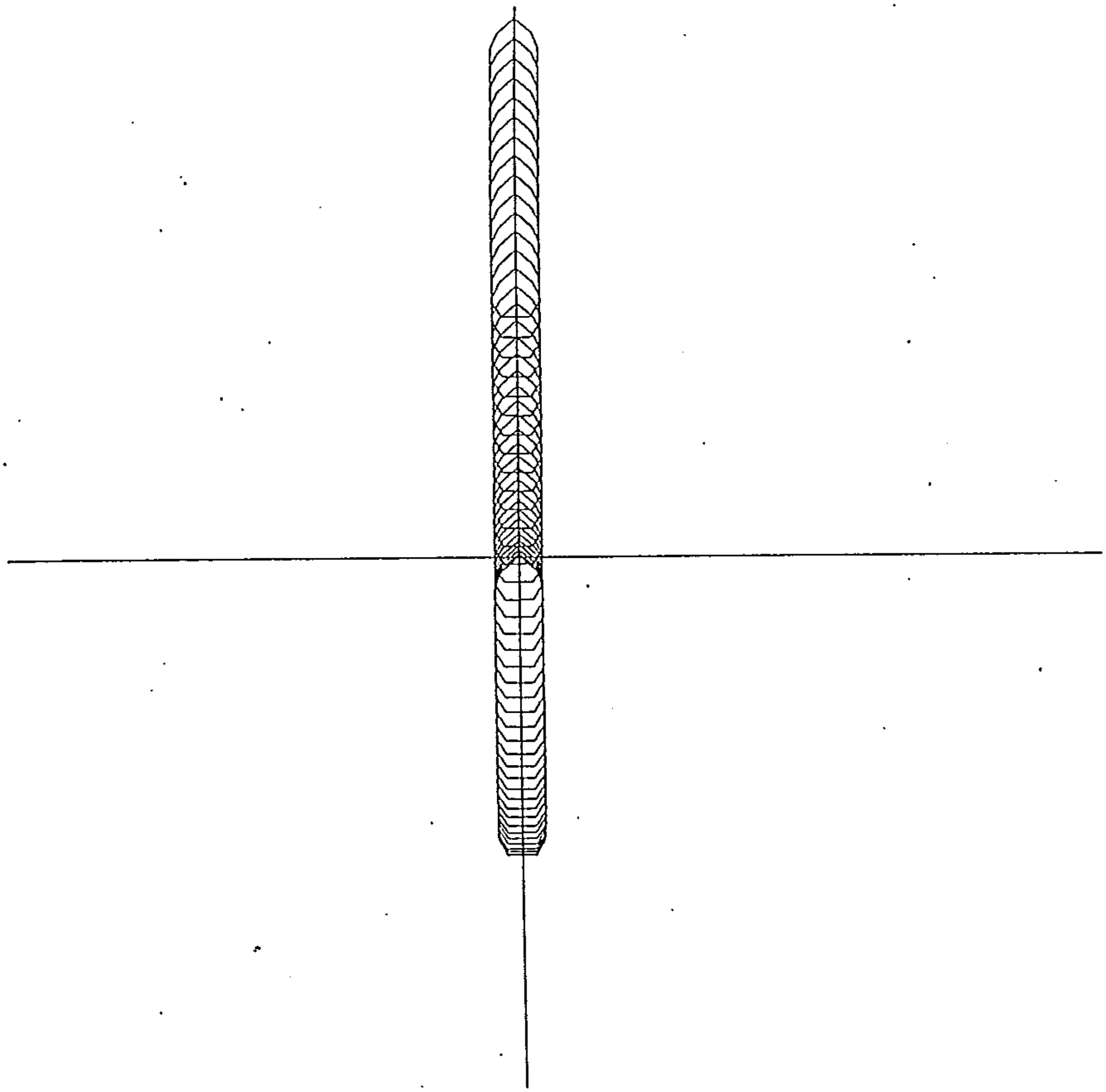

Fig.11 Course stability of Tanker A

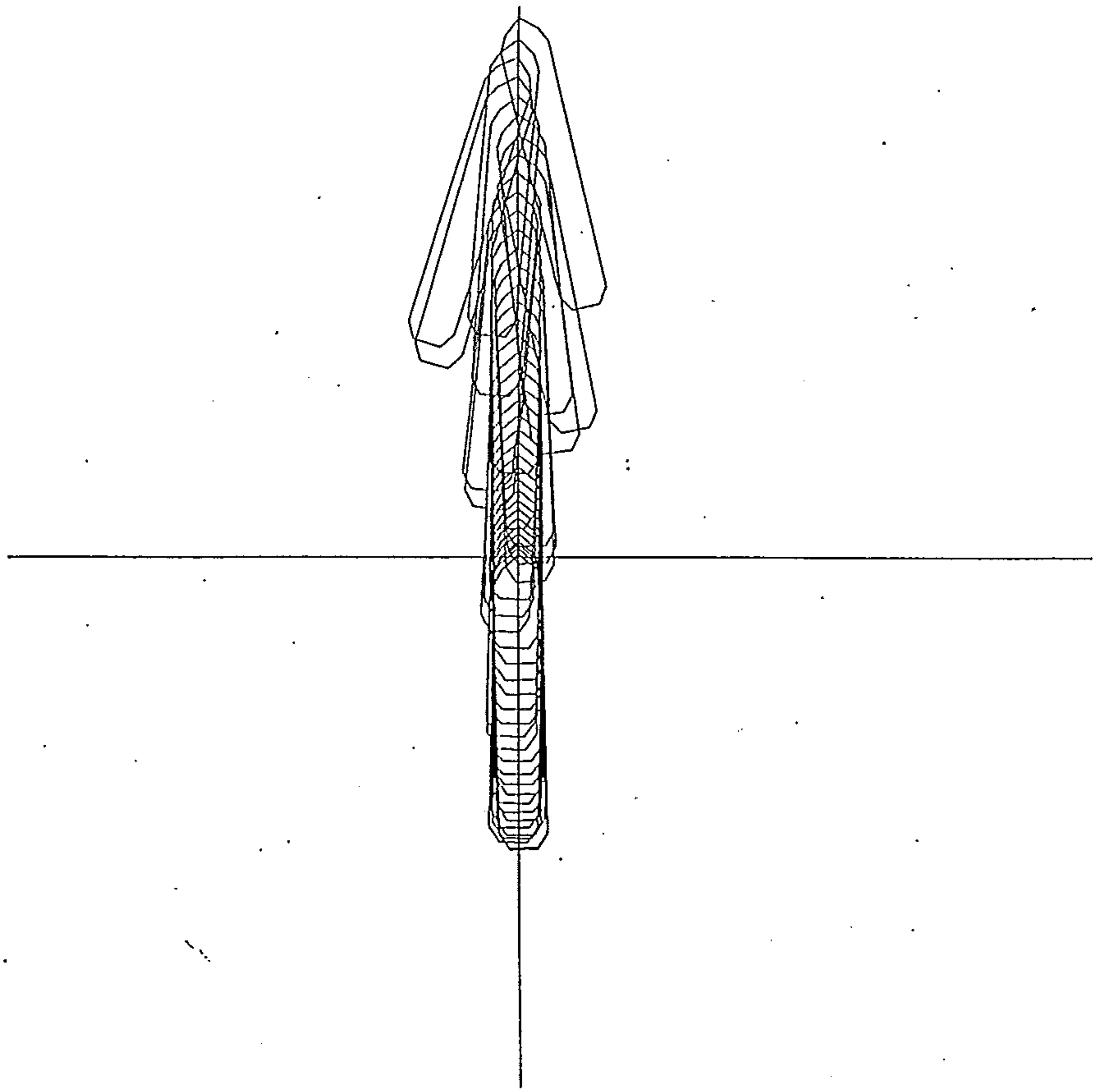

Fig.12 Course stability of Tug A

VESSEL'S HEELING AND STABILITY IN THE REGIME OF MANEUVERING AND BROACHING IN FOLLOWING SEAS

by
Prof., Dr. Sc. D.M.Ananiev, Head of Naval Architecture Department and
Ms. L.Loseva, researcher of the same Department
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ABSTRACT

The mathematical model of broaching and heeling of the vessel and capsizing caused by them is considered here. The excitation transverse force and the excitation moment of yawing cause the broaching, they are being determined with the consideration of approximate influence of viscosity. The results of the mathematical modeling made possible to conclude, that it is practically impossible to avoid capsizing in broaching regime by the increasing of the stability reserve.

The maneuverability of the ship on a seaway depends from the longitudinal and lateral wave forces (X_W,Y_W) and yawing moment M_{ZW}. These forces include the part connected with the wave pressure and diffraction component. The wave pressure is assumed and calculated for a wave, which is not affected by the ship presence. The first component of the longitudinal force X_W is considered in the paper [1], the corresponding components of the lateral force and yawing moment, are being calculated in the same assumptions as X_W:

$$Y_{W_1} = -\rho g \alpha_0 A_0(\varepsilon) \sin\varepsilon \sin q, \qquad M_{ZW} = \rho g \alpha_0 B_1(\varepsilon) \sin\varepsilon \cos q; \tag{1}$$

$$A_0(\varepsilon) = \kappa_A \int_{-L/2}^{L/2} \omega \cos k_1 x dx, \qquad B_1(\varepsilon) = \kappa_B \int_{-L/2}^{L/2} \omega x \sin k_1 x dx, \tag{2}$$

where κ_A,κ_B are the reduction coefficients due to the finiteness of the transverse dimensions of ship in relation to the wave length. Diffraction part of X_W has small value and is ignored. For determination of the corresponding components Y_W and M_{ZW} the strip theory was used. Their values at an arbitrary moment were taken the same as at the movement with constant speed, without drift and rotation. For this aim the lateral diffraction load was determined and integrated along the ship length. If the limits of integrating are from -L/2 to L/2, then the diffraction force and moment may be calculated for ideal fluid. Such a method was proposed by Korvin-Kroukowsky [2].

However, experiments with ship model and rectangle plate (all wave forces on such a plate are of diffraction nature) show essential divergence with theory. It could be explained by influence of viscosity. To take into account the effect of viscosity one may suppose that vortices have separated at the cross section with abscissa x_0 (Fig.1). For this reason the domain of integration is limited by this cross-section. This method was used by G.V.Sobolev to receive the values for a wing of very low-aspect-ratio, which moves in still water with constant drift and constant angular speed. These values coincided with the values which were calculated according to the vortex theory [3]. It is possible to consider the section coinciding with abscissa x_0 of lifting of keel line on sternpost or with the edge of the deadwood. Let us assume that this section is a place of vortices separation. In this case (see Appendix) the diffraction force and the moment should be expressed by the formulas:

$$Y_W = -\rho g \alpha_0 \sin\varepsilon[\kappa_V A_0'(\varepsilon)\sin q - \frac{\mu_{20}}{\rho k}\bar{v}\cos\beta\cos(q - k_1 x_0)],$$
$$M_{ZW} = -\rho g \alpha_0 \sin\varepsilon[\kappa_V B_0'(\varepsilon)\cos q + \frac{x_0\mu_{20}}{\rho k}\bar{v}\cos\beta\cos(q - k_1 x_0)], \tag{3}$$

$$A_0'(\varepsilon) = \frac{1}{\rho}\int_{-L/2}^{L/2}\mu_2(x)\cos k_1 x dx,$$
$$B_0'(\varepsilon) = \frac{1}{\rho}\int_{-L/2}^{L/2}x\mu_2(x)\sin k_1 x dx, \tag{4}$$

$\mu_2(x)$ is an added mass of a section;

$$\mu_{20} = \mu_2(x_0), \qquad \bar{v} = \frac{v}{c}; \tag{5}$$

c is the phase velocity of waves, v is the ship gravity center velocity;

$$\kappa_v = 1 - \bar{v}\cos(\varepsilon - \beta). \tag{6}$$

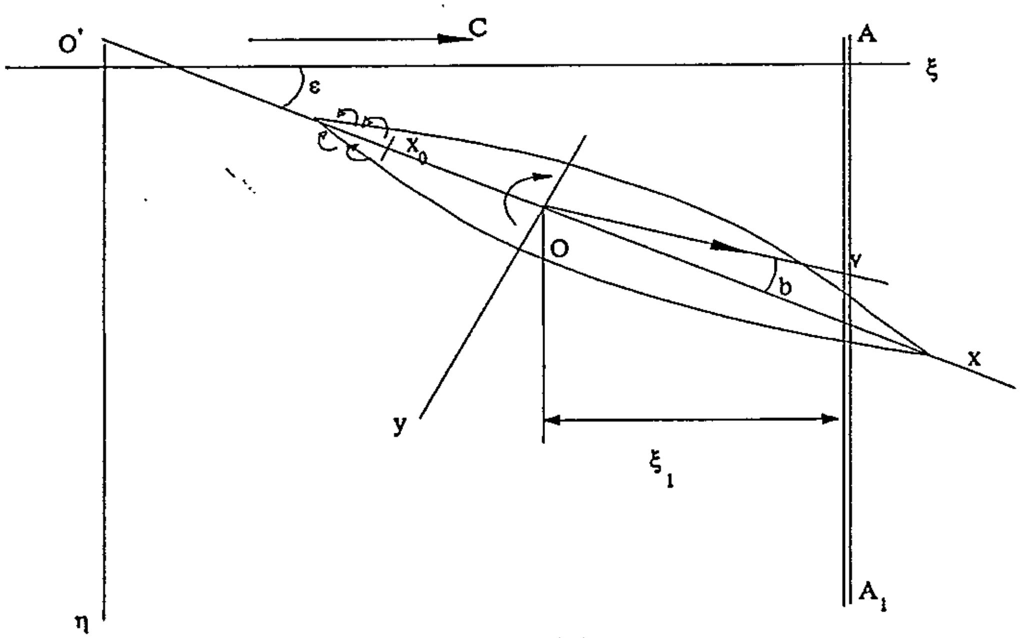


Figure 1.
Coordinate system

Comparison of experimental and theoretical results allows to take viscosity into account (see Appendix). It is suitable to express the equations of ship's movement in horizontal plane in dimensionless form [4]. They may be written as follows:

$$\begin{aligned}
&\frac{d\bar{v}}{ds} = \bar{v}tg\beta\frac{d\beta}{ds} + \frac{\bar{v}}{\overline{m}_{11}\cos\beta}\left(C_X - \overline{m}_{22}\bar{r}\sin\beta\right)\\
&\frac{d\beta}{ds} = \left(\frac{\overline{m}_{11}}{\overline{m}_{22}}\cos^2\beta + \frac{\overline{m}_{22}}{\overline{m}_{11}}\sin^2\beta\right)\bar{r} - \frac{C_Y\cos\beta}{\overline{m}_{22}} - \frac{C_X\sin\beta}{\overline{m}_{11}};\\
&\frac{d\bar{r}}{ds} = \frac{m_Z}{\overline{m}_{22}} - \frac{\bar{r}d\bar{v}}{\bar{v}ds};\\
&\frac{dq}{ds} = \frac{2\pi L}{\lambda}\left(\frac{1}{\bar{v}} - \cos(\varepsilon-\beta)\right)\\
&\frac{d\varepsilon}{ds} = \bar{r}
\end{aligned} \tag{7}$$

Here:

$$ds = \frac{v}{L}dt, \tag{8}$$

$$\bar{r} = \frac{rL}{v}, \tag{9}$$

$$\overline{m}_{11} = \frac{2(m+m_{11})}{\rho A_L L}, \quad \overline{m}_{22} = \frac{2(m+m_{22})}{\rho A_L L}, \quad \overline{m}_{66} = \frac{2(I_Z+m_{66})}{\rho A_L L^3} \tag{10}$$

m_{11}, m_{22}, m_{66} are the added masses, A_L is the area of the lateral projection of vessel's underwater part, r is an angular velocity relatively to the vertical axis.

The equations include coefficients of forces and yawing moment acting to the hull of a ship in still water caused by viscosity, ship's waves, propeller and rudder forces, aerodynamic forces and, finally, forces and moments due to the influence of a seaway:

$$\begin{aligned}
&C_x = C_{xh}(\bar{v},\beta,r) + C_{xp} + C_{xa} + \frac{C_{xw}}{\bar{v}^2}\sin q\\
&C_y = C_{yh}(\beta,\bar{r}) + C_{yp} + C_{yr} + C_{ya} - \frac{1}{\bar{v}^2}\left(C_{yw}\sin q - \Delta C_{yw}\cos(q-k_1x_0)\right),\\
&m_z = m_{zh}(\beta,\bar{r}) + m_{zp} + m_{zr} + m_{za} + \frac{1}{\bar{v}^2}\left(m_{xw}\cos q + \frac{x_0}{L}\Delta C_{yw}\cos(q-k_1x_0)\right).
\end{aligned} \tag{11}$$

In formulas (11) forces are related to $\frac{1}{2}\rho A_L v^2$, and moment to $\frac{1}{2}\rho A_L L v^2$

$$C_{xw} = \frac{2g\alpha_0\varepsilon\cos\varepsilon}{A_L c^2}, \tag{12}$$

$$C_{yw} = \frac{2g\alpha_0[A_0(\varepsilon) + \kappa_v A_0'(\varepsilon)]\sin\varepsilon}{A_L c^2}, \tag{13}$$

$$m_{zw} = \frac{2g\alpha_0[B_1(\varepsilon) + \kappa_v B_1'(\varepsilon)]\sin\varepsilon}{A_L L c^2}, \tag{14}$$

$$\Delta C_{yw} = \frac{2\alpha_0 \mu_{20} \bar{v} \cos\beta \cos\varepsilon}{\rho A_L}, \tag{15}$$

Two evaluations are regarded in the following and quartering waves:

1. broaching, the rudder has no deflection in the regime of surf-riding;
2. movement, the rudder has a momentary deflection by the constant angle in the surf-riding regime or in surging.

Since the navigator endeavors to keep ship exactly along the following stormy wave, it is reasonable to admit the initial condition $\varepsilon(0) = 0$. For surf-riding regime we take $\bar{v}(0) = 1$, the phase q is being found from the correlation

$$q(0) = \arcsin \frac{R_C - X_{PC}}{\rho g \alpha_0 A_o}, \tag{16}$$

after the information that the ship really moves in surf-riding regime [1]. If maneuvering is considered at regime of surging, we can assume without big mistake that the initial speed of a ship equals to it's speed in still water $(\bar{v}(0) = v_0/c)$, and the phase q may be chosen arbitrary.

Ship enters into to the directional instability under the influence of excitations, which are small in usual conditions. We had show theoretically and confirmed by the mathematical modeling, that in the course time the kinematical parameters at different (but small) initial excitations are practically coinciding. Therefore imitating lateral impulse, we can choose arbitrary small $\beta(0)$ and $\bar{r}(0)$. In the case of modeling controlled maneuver $\beta(0)=\bar{r}(0)=0$.

For calculating of heeling process it is necessary to add corresponding equation of the movement:

$$\frac{d^2\vartheta}{ds^2} + \left(\frac{d\bar{v}}{\bar{v}ds} + W\left|\frac{d\vartheta}{ds}\right|\right)\frac{d\vartheta}{ds} + \frac{b_0}{\bar{v}^2}\bar{l}_\theta(\vartheta) = -b_1\left(\frac{d^2 a_m}{ds^2} + \frac{d\bar{v}}{ds}\frac{da_m}{ds}\right) + b_2 C_{yh} + b_3 C_{ya} \tag{17}$$

The function, which we shall find, is the conditional relative angle of heel measured in the origin of coordinates:

$$\vartheta = \theta - a_m \tag{18}$$

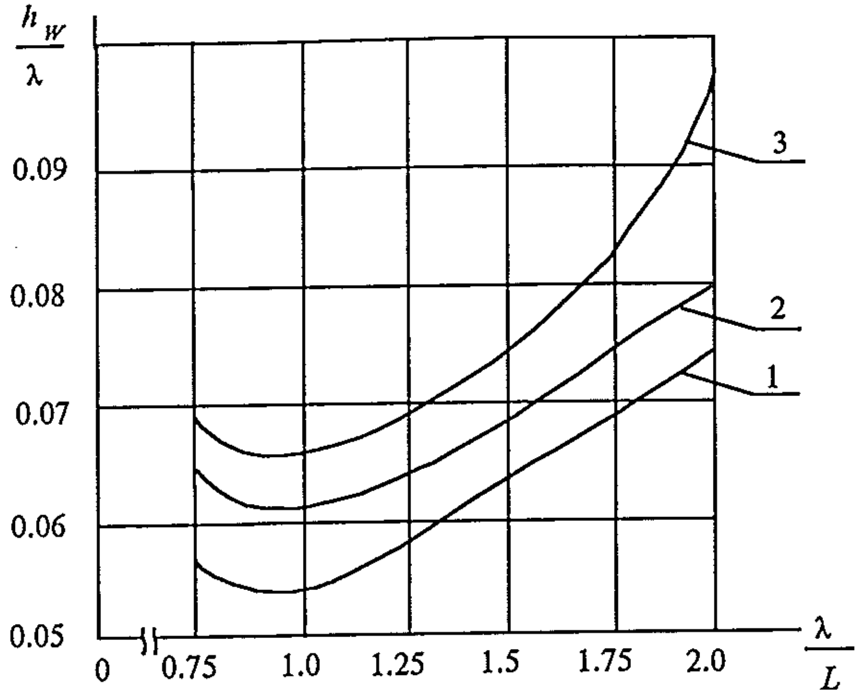
Here θ is an angle of heel in absolute coordinate system;

$$\alpha_m = \kappa_\theta(\varepsilon)\alpha_0 \sin q \tag{19}$$

Reduction coefficient κ_θ is to be derived for small heeling from the moment of buoyancy. Such an approach was used in the model of non-linear rolling oscillations at $\varepsilon=90^0$ [5] and it brought the satisfactory results. We use the same way for the angle of course.

Then $\kappa_\theta = \kappa_T \kappa_B \kappa_\varepsilon$ (20)

where we take into account finiteness of the draught and the beam of the ship, and is a reduction coefficient of the course angle.



1 — GM=0.646 m (IMO)
2 — GM=0.55 m (USSR Register)
3 — GM=0.67 m

Figure 6. Boundaries of capsizing for different values of *GM*

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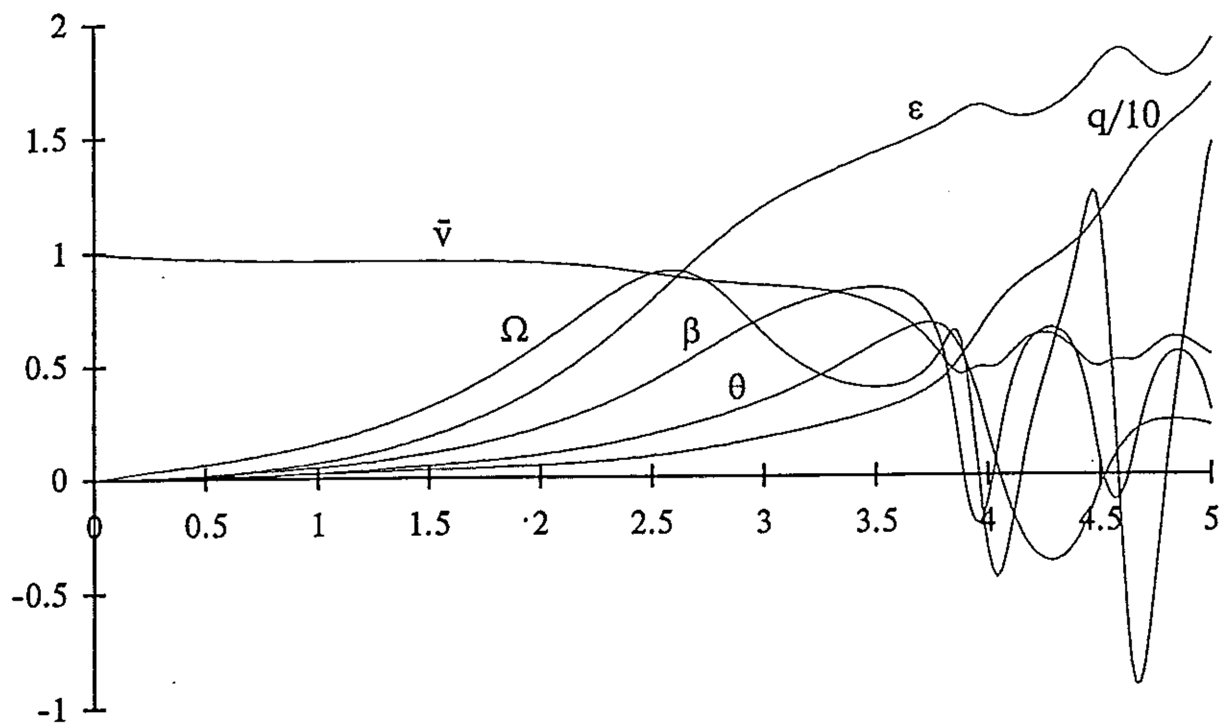

Figure 5.
Diagram of the maneuver $\lambda= L$, h_w/λ=0.05, v_0=10 knots, δ=25^0, GM=0.67 m.

In the calculations done for little trawler the coefficients of transverse force and of the moment of yawing were taken by Mastushkin method [9] and they were equal to

$$C_{yh} = 0,425\beta + 0,61\beta|\beta| + 0,0762\bar{r},$$
$$m_{zh} = 0,1094\beta - 0,0927\bar{r} - 0,50\beta^2\bar{r}.$$

The coefficient c_{xh} was taken by the removing resistance on a still water without taking into account the influence of β and $\bar{r}$.

Mathematical modelling of little trawler movement, as far as different ships, allows us to come to conclusion; that the influence of the wind of the force approximately equal to the seaway force and removing the rudder on the vessels removing and heeling is little.

There boundaries of capsizing were build in coordinates (λ/L, h_W/λ) for the little trawler in broaching regime for the three values of GM:

1. GM=0,464 m - minimal GM value by the recommendations of IMO,
2. GM=0,55 m - minimal GM value by the norms of the Register of USSR
3. GM=0,67 m - by its factual value (Fig. 6).

So if it is possible to expect the packages of waves with the stipness h_W/λ to 0,1 and the attempt to avoid capsizing in broaching regime is not in perspective. To avoid such a dangerous situation the choosing of such a speed should be done in which the wave does not capture the vessel.

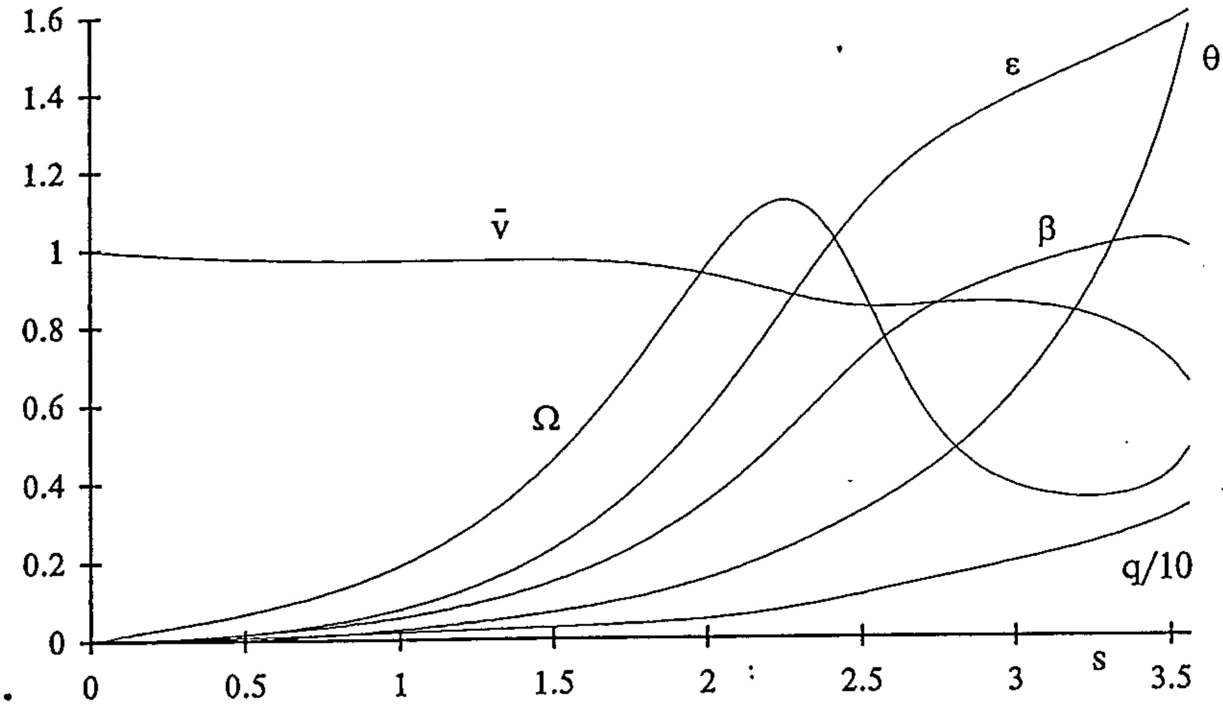

Figure 3.
Diagram of the maneuver $\lambda = L$, $h_w/\lambda=0.075$, $v_0=10$ knots, $\delta=25^0$, $GM=0.67$ m.

On the lesser stipness $h_w/\lambda=0.05$ the vessel is heeled strongly, but it is not capsizing (fig. 4 and fig. 5).

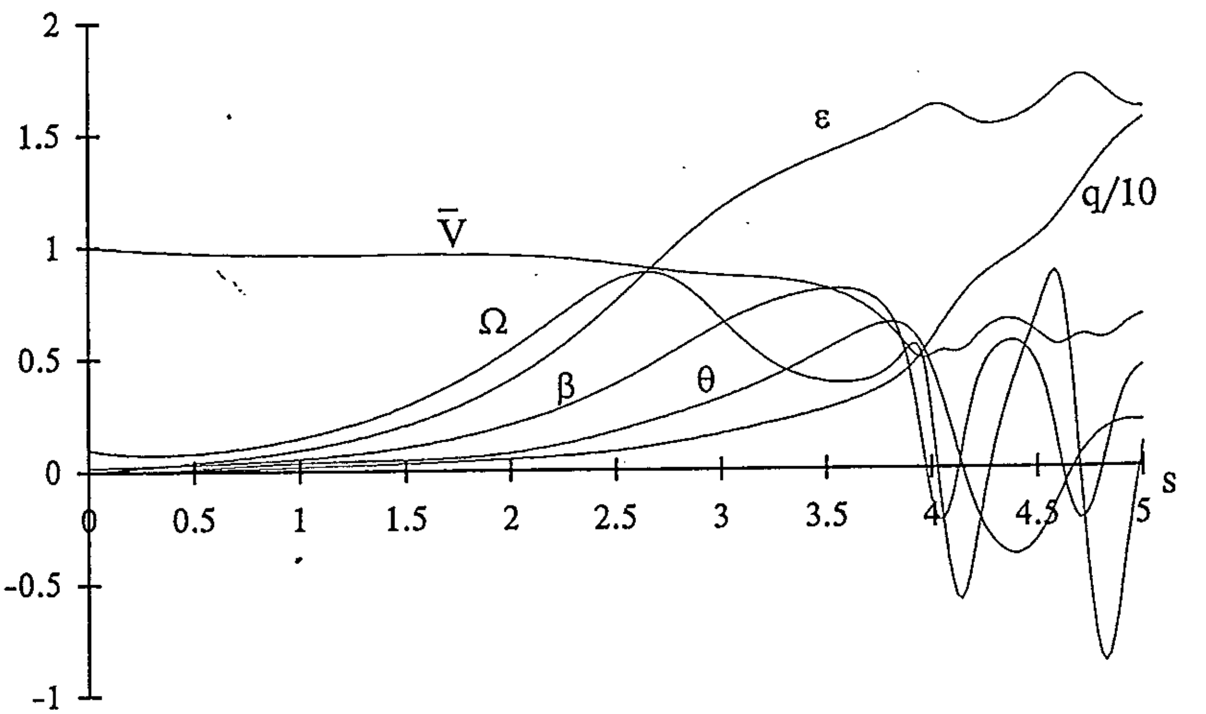

Figure 4.
Diagram of the broaching: $\lambda = L$, $h_w/\lambda=0.05$, $v_0=10$ knots, $GM=0.67$ m.

Their numerical values were taken according to [6], where κ_ε had bean denoted x_β.

Other notations:

$$b_0 = \frac{mgL^2 \nu GM}{(I_x + \mu_{44})c^2}; \quad b_1 = \frac{I_x}{I_x + \mu_{44}};$$
$$b_2 = \frac{\rho L^2 A_L l_h}{2(I_x + \mu_{44})}; \quad b_3 = \frac{\rho L^2 A_L l_a}{2(I_x + \mu_{44})}; \qquad (21)$$

Here I_x and μ_{44} are the moment of ship's inertia and added inertial moment. W is dimensionless coefficient of square-law damping,

l_θ is an arm of statical stability, $\bar{l}_\theta = \frac{l_\theta}{GM}$,

GM is the metacentric height,

l_h, l_a are the arms of hull's and aerodynamic forces.

As an example the results of mathematical modeling of the small trawlers movement in broaching (fig. 2) and surf-riding regime with momentary deflection of rudder at 25° (fig.3) is given. The main ship dimensions were: $L \times B \times T = 22 \times 6{,}8 \times 2{,}38$ m. Speed at still water was 10 knots, GM=0,67 m, wave length equaled to the ship's length, wave steepness was h_W/λ=0.075, (h_W=2r$_0$), the wind was ignored. In both cases the vessel capsized.

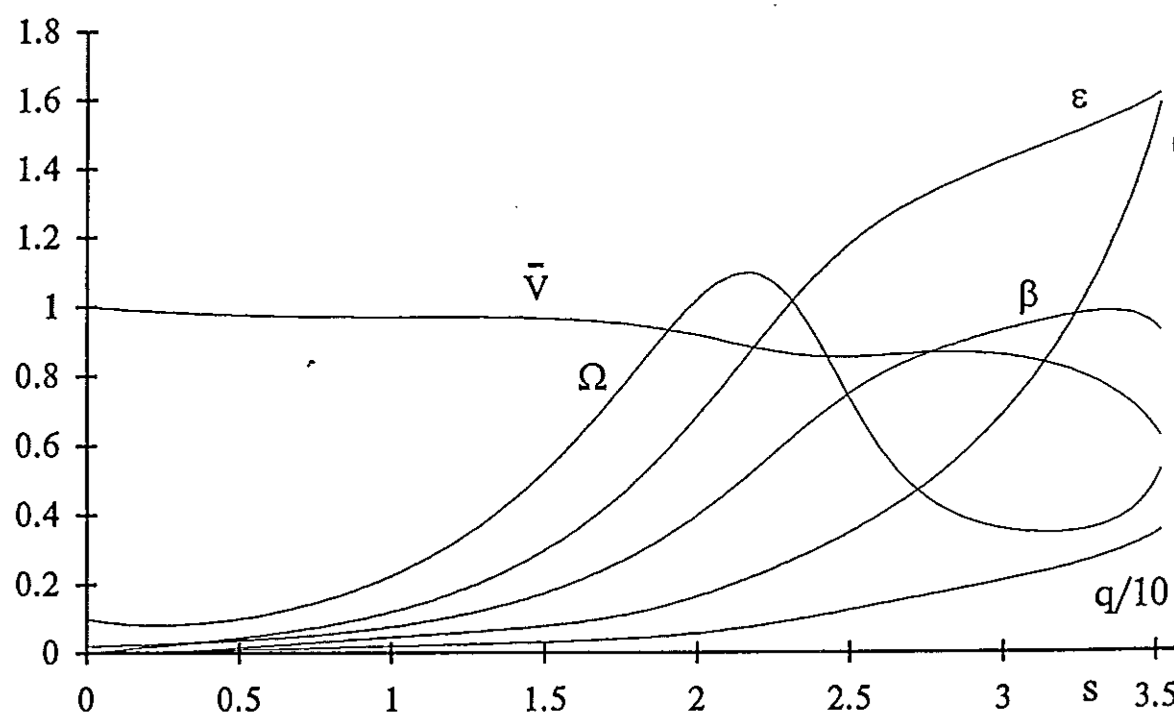

Figure 2.
Diagram of the broaching: $\lambda = L$, h_w/λ=0.075, v_0=10 knots, GM=0.67 m.

APPENDIX: THE DIFFRACTION TRANSVERSE FORCE AND YAWING MOMENT.

Let the vessel moves straightly without acceleration with the speed u without drift angle, under the angle ε to the seaway. The profile of seaway could be expressed by the formula

$$Z_W = -r_0 \exp[i(\sigma_e t - k_1 x + k_2 y)], \tag{A1}$$

where the frequency of encounter with wave is equal to

$$\sigma_e = \sigma - ku\cos\varepsilon,\ i = \sqrt{-1}, \tag{A2}$$

The strip theory was used for determination of transverse diffraction load. Let the fluid to be ideal. The diffraction momentum of fluid layer which has thickness dx, equals to:

$$\Delta Q_y = c_2(x) v_y dx \tag{A3}$$

where v_y is the transverse velocity of this ship section related to fluid which is equal to orbital velocity of fluid particles with opposite sign, when $y=z=0$. (The ratios of ship's transverse dimensions to the wave length are small).

$$v_y = -r_0 \sigma \sin\varepsilon \exp[i(\sigma_e t - k_1 x)] \tag{A4}$$

The function

$$c_2(x) = \mu_2^o(x) - \frac{i\lambda_2^o(x)}{\sigma} \tag{A5}$$

is complex hydrodynamic coefficient containing diffraction added mass $\mu_2^0(x)$ and damp coefficient $\lambda_2^0(x)$. The coefficient $c_2(x)$ was determinated from the solution of plane task for movement of infinite cylinder in waves [7].

The transverse diffraction force upon ship element with length dx according to momentum law equals to:

$$dY_{W_2} = -\frac{d\Delta Q_y}{dt}, \tag{A6}$$

where differentiation is to be made in stationary coordinate system. In that case the transverse load is:

$$\gamma(x,t) = \frac{dY_{W_2}}{dx} = -\frac{d}{dt}(c_2 v_y). \tag{A7}$$

The way from finding the derivative in non-movable coordinate system to finding the derivative in a coordinate system connected with the vessel is shown down.

$$\frac{d}{dt} = \frac{\partial}{\partial t} - u\frac{\partial}{\partial x}$$

Integrating the load over all ship's length we get the transverse force Y due to movement in ideal fluid. This force is linked with force $Y_{W_2}^o$ at u=0 by ratio:

$$Y_{W_2}^{Id} = \int_{-L/2}^{L/2} \gamma(x,t)dx = Y_{W_2}^o\left(1 - \frac{u}{c}\cos\varepsilon\right) \tag{A8}$$

Analogously the yawing moment is to be defined by formula:

$$M^{id}_{ZW_2} = \int\limits_{-L/2}^{L/2} x\gamma(x,t)dx = M^{o}_{ZW_2}(1-\frac{u}{c}\cos\varepsilon) - \frac{iu}{\sigma}Y^{o}_{W_2}. \qquad \text{(A9)}$$

Here $M^{o}_{ZW_2}$ is a moment at u=0.

In resulting forms for a force and for a moment only the real part of complex functions should be kept. Taking into account the viscosity we remove the load $\gamma(x,t)$ abaft the section x_0, where the vortices are assumed to be separated (fig.1). Then the new part are to be added to force and moment (A8) and (A9):

$$\Delta Y_{W_2} = -\int\limits_{-L/2}^{x_0} \lambda(x,t)dx; \quad \Delta M_{w_2} = -\int\limits_{-L/2}^{x_0} x\gamma(x,t)dx \qquad \text{(A10)}$$

The derivative $dc_2(x)/dx$ plays the main role in this corrections since the function $c_2(x)$ quickly changes from 0 to $c_2(x_0)$ along the part $\left(-\frac{L}{2},x\right)$.

Figure 7 shows the results of experiments and calculations for the rectangle plate with aspect-ratio $2T/L$=0.175, which moves without drift but with ε=24 in a regular seaway.

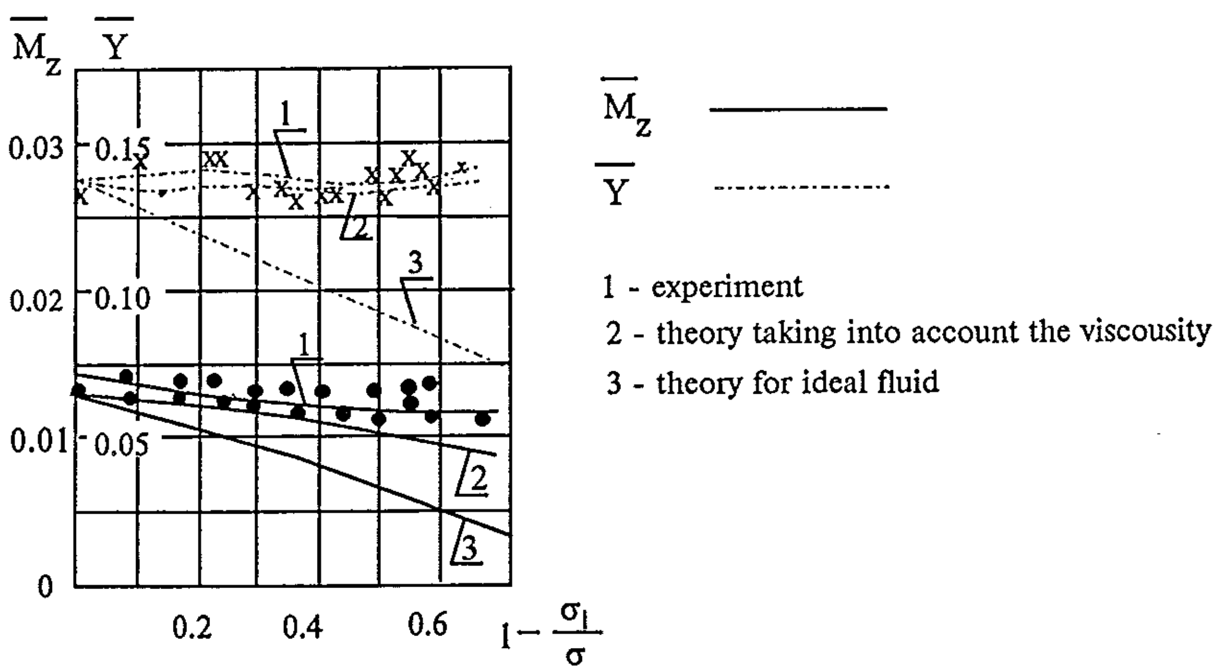

Figure 7.
Dimensionless amplitudes of lateral force and yawing moment acting on rectangular plate

The amplitudes of a force and a moment were expressed in dimensionless form:

$$\overline{Y} = \frac{2Y_{WA}}{\rho g \alpha_0 L^2 T}; \qquad \overline{M}_Z = \frac{2M_{ZWA}}{\rho g \alpha_0 L^3 T} \tag{A12}$$

Coefficient $c_2(x)$ was calculated in accordance with [8]. Comparison of the results shows, that the theory which takes into account the viscosity (curves 2) shows satisfactory coincidence with experiment, meanwhile the neglect of the viscosity to effect (curves 3) the essential mistakes. The same conclusion may be done relatively to angles . Using the hypothesis of stationary and replacing in formulas (A8) and (A9) $u\cos\varepsilon$ to ship speed projection $v\cos(\varepsilon\text{-}\beta)$ onto direction of waves propagation, and also u in form (A9) to $v\cos\beta$, and also replacing $c_2(x)$ to added mass $\mu_2(x)$ and taking of members due to asymmetry relatively to the mid section, we shall have forms (3) of basic text of the paper.

DETERMINATION THE BOUNDARIES OF SURF-RIDING DOMAIN ANALYZING SURGING STABILITY

by
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ABSTRACT

The method of determination of vessel's surf-riding regime domain is presented here. The method is based on the investigation of surging and it's directional stability using the Liapunov theory. This method allows to receive necessary results without difficult calculations of phase trajectories of ship motion.

There are two regimes of ship movement in following waves:

1 - movement with constant average speed accompanied by surging,

2 - surf-riding regime when the ship is "captured" by the following wave, ship's position relatively to the wave profile is being invariable.

Surf-riding regime is, as a rule, unstable. Therefore ship enters into the broaching regime she has large heel angle and even capsizing is possible. Our investigation shows that it is practically impossible to provide such a ship stability reserve for the small ship, that would be enough for staying out of capsizing. The most practical procedure that helps to avoid the broaching regime is to reduce the speed of the ship before the ship capture by the following waves. First of all, let us consider the longitudinal forces acting on ship in a following seaway. We are assuming that the resistance force R and the traction of propellers X_p are constant as in still water.

We will find the force of the longitudinal wave X_p from the Krylov's hypothesis, ignoring it's diffraction part and wave damping force, because of small significance of it. Let the waves to be regular, water depth is infinity.

The wave profile in the non-movable coordinate system Oξηζ (fig.1)

$$\zeta_W = -r_0 \cos(\sigma t - k\xi) \qquad (1)$$

the dynamic part of the wave pressure

$$\Delta P = -\rho g r_0 e^{k\zeta} \cos(\sigma t - k\xi) \qquad (2)$$

The ship position relatively to the waves is characterized by the distance ξ_1 between the foot of the wave, which coincides with an axis Oη at the moment t=0, and the angle of course ε.

Then the same but only in the ship fixed coordinate system:

$$z_W = -r_0 \cos(q - k_1 x + k_2 y) \qquad (3)$$

$$\Delta p = -\rho g r_0 e^{kz} \cos(q - k_1 x + k_2 y) \qquad (4)$$

where k_1=kcosε, k_2=kcosε (5)

$$q = k\xi_1 \qquad (6)$$

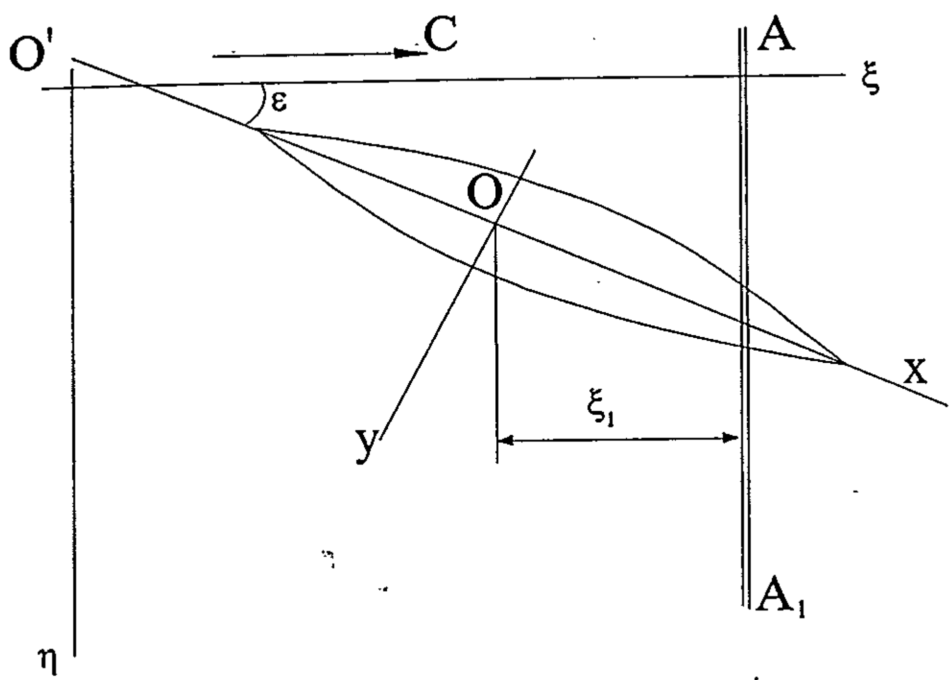

Figure 1. Coordinate system

X_W is calculated by integrating the pressure p on surface of the ship:

$$X_w = \rho g a_0 \cos\varepsilon (A \sin q - B_0 \cos q) \tag{7}$$

where a_0 is the amplitude of the wave slope angle,

$$\begin{aligned} A_0(\varepsilon) &= \iiint_V e^{kz} \cos(k_1 x - k_2 y) dV \\ B_0(\varepsilon) &= \iiint_V e^{kz} \sin(k_1 x - k_2 y) dV \end{aligned} \tag{8}$$

Transverse dimensions of the vessel are assumed small in comparison to the wave length. Besides B_0, which is connected with asymmetry of a ship relating mid ship section, is ignored. Then integrates (8) can be performed in a simple form:

$$X_w = \rho g a_0 A_0 \cos\varepsilon \sin q \tag{9}$$

$$A_0 = \kappa_A \int_{-L/2}^{L/2} \omega \cos(k_1 x) dx \tag{10}$$

where κ_A is the reducing coefficient due to the finiteness of the transverse dimensions of ship in comparison to the wave length. Surging will be investigated on following waves (ε=0). Although it is not difficult to expand the solution on the quartering seas. In this case when ship is moving with an average speed v_A, which is a little higher than the speed of the vessel on a still water and it has surging oscillations, the surging displacement is being designated ξ_S.

Then $\quad \xi_1 = (c - v_a)t - \xi_S \qquad (11)$

where $c = \sqrt{\frac{\lambda g}{2\pi}}$ is the phase velocity of the waves;

$$X_w = \rho g \alpha_0 A_0 \sin(\sigma_e t - q_S) \tag{12}$$

where $\sigma_C = \sigma - kv_a$ is the encounter frequency;

$$q_S = -k\xi_S \tag{13}$$

The equation of movement

$$(m_{11} + m)\ddot{\xi}_S = X_p - R + X_w \tag{14}$$

can be performed in dimensionless form

$$\frac{d^2 q_S}{d\tau^2} + H\frac{dq_S}{d\tau} + Q\sin(\tau + q_S) = Hp \tag{15}$$

where $\tau = \sigma_e t$ (16)

$$Q = \frac{\rho\alpha_0 A_0}{(m + m_{11})u_a^2} \tag{17}$$

$$u_a = 1 - \frac{v_a}{c},\ p = \frac{v_a - v_0}{cu^2} \tag{18}$$

$$H = \frac{\lambda_{11} c}{(m + m_{11})g|u_a|} \tag{19}$$

Here v_0 is the ship's speed on the still water; λ_{11} plays a role of the damping coefficient and it equals to:

$$\lambda_{11} = \left[\frac{d(R - X_p)}{dv}\right]_{v=v_0} \tag{20}$$

λ_{11}, H_P are results of decomposition $(R\text{-}X_p)$ into Taylor's series in point v_0, when only the first term of series is being kept.

The solutions of the movement equation were received in form of expansion into a power series of Q [1].

$$q_S = \sum_{n=0}^{\infty} q_n Q^n,\ p = \sum_{n=0}^{\infty} p_n Q^n \tag{21}$$

The method of solving of the movement equation is presented in the Appendix. The Liapunov method was used to estimate surging stability. If the equation of ship motion is in form:

$$\ddot{x} + F_1(\dot{x}, t) + F_2(x, t) = const \tag{22}$$

then by the first Liapunov's method the equation in variations is being created:

$$\Delta\ddot{x} + \frac{\partial F_1}{\partial \dot{x}}\Delta\dot{x} + \frac{\partial F_2}{\partial x}\Delta x = 0 \tag{23}$$

It lead to a linear differential equation with periodic coefficient

$$\frac{d^2\Delta q}{d\tau^2} + H\frac{d\Delta q}{d\tau} + \Delta q Q\cos(\tau + q_S) = 0 \tag{24}$$

The solution of that equation is:

$$\Delta q = e^{\nu_1\tau}\Phi_1(t) + e^{\nu_2\tau}\Phi_2(\tau) \tag{25}$$

where $\Phi_i(W)$ are the periodic functions,

$$\mathrm{Real}\,\nu_{1,2} = -\frac{H}{2} \pm \rho \tag{26}$$

Boundary of stability takes place when ρ_0=H/2 and it has the universal character, since sizes of wave and qualities of ship are generalized by parameters *Q* and *H.*

The universal diagram of stability of the surging is drawn on the basis of Floquet's theory and solution for q_S. It is shown in fig.2.

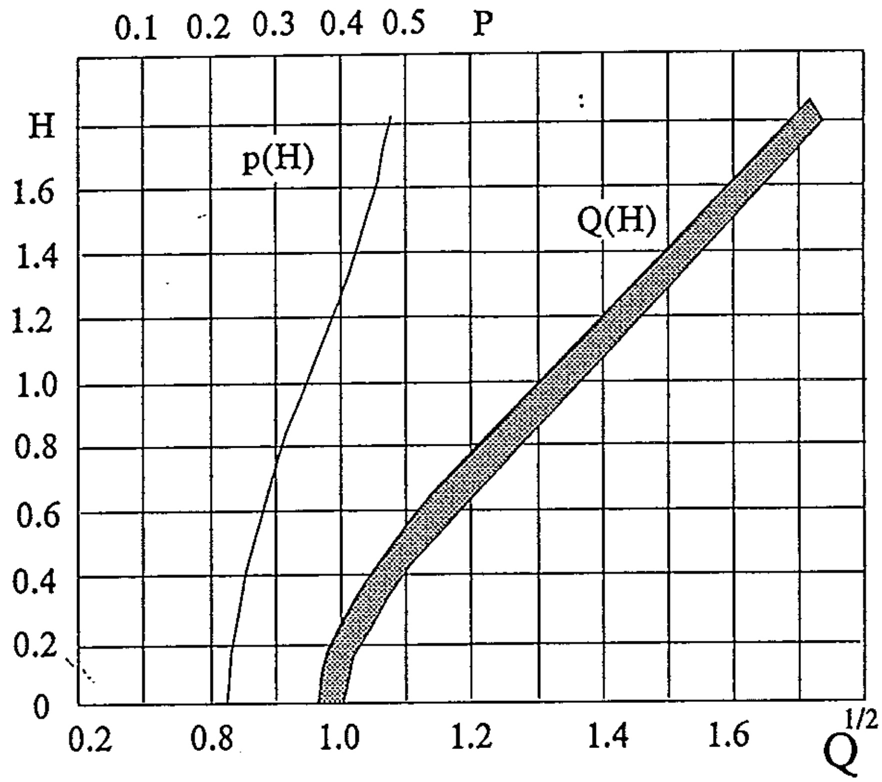

Figure 2.
Universal diagram of stability of the surging

To the left from the curve *Q(H)*, the surging is stable, to the right it is not stable and the ship can move only in the regime of surf-riding. Boundary, which was determined by stability of surging, is named dynamic boundary of surf-riding. For practical use of the diagram the variable u is to be eliminated from formulas (17) and (19). Then the linear dependence $\sqrt{Q}$ from *H* may be found. The graph is traced on the universal diagram to a cross point with boundary *Q(H)*. Then value $|u_a|$ is calculated in the cross point from (17), (19). Then the conditional speeds may be found after taking the value of p from the *p(H)* graph:

$$v^*_{1,2} = c[1 \mp (1+p)|u_a|] \quad (27)$$

If the speed on the still water is between the limits from v^*_1 to v^*_2, then the ship will move inevitably in the surf-riding regime. It is possible ,to draw the dynamic boundary if the steepness of the wave is given. This boundary coincides with the boundary, which was found by calculating of the phase trajectories [2,3,4].

Our dynamic boundary is simpler for calculations and it is confirmed by Yu.Makov's experimental data (fig.3)

In the domain located behind of dynamic boundary the surging is not possible. Other (static) boundary may be determined by the balance of longitudinal forces. Between this limits both regimes of ship movement exist. The surf-riding is not possible out of these domain.

The correlation established above are applicable to a ship moving under and angle ε to the waves.

The values of Q on the boundary of surging stability is about 1. It allows to receive approximate formula (ε=0):

$$v_a \cong c \cdot \left(1 \mp \sqrt{\frac{\alpha_0 \rho A_0}{m}}\right) \quad (28)$$

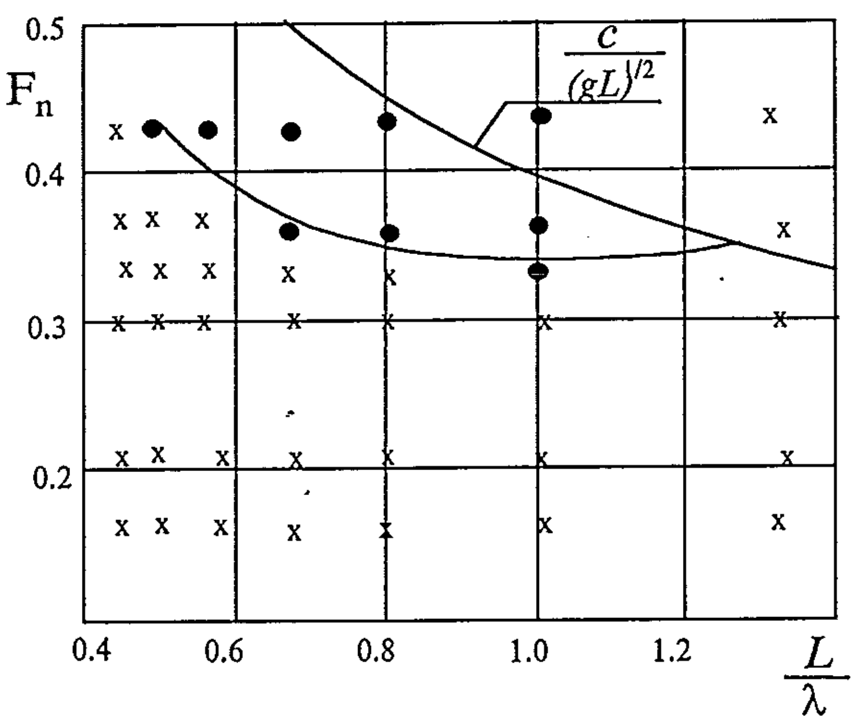

Figure 3. Dynamic boundary of surf-riding for small autopropulsed model (velocity is equal to velocity in still water) . Experiments of Yu Makov: ● surf-riding, x surging, - dynamic boundary according to theory

The statical broaching regime boundary could be found from the equilibrium equation

$$X_{PC} - R_C + X_{W\max} = 0, \tag{29}$$

where R_C is the ships resistance force, and X_{PC} is the traction of the propellers,

when the speed $v=c$,

$$X_{W\max} = \rho g \alpha_0 A_0 \cos\varepsilon \tag{30}$$

The ship's position relatively to the profile of wave in broaching regime is described by the expression

$$q = \arcsin\frac{R_C - X_{PC}}{\rho g \alpha_0 A_0 \cos\varepsilon} \tag{31}$$

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APPENDIX : THE METHOD OF FINDING THE SOLUTION OF THE MOVEMENT EQUATION (15).

The solution is to be found in the form:

$$q_S = \sum_{n=0}^{\infty} q_n Q^n, \qquad p = \sum_{n=0}^{\infty} p_n Q^n \tag{A1}$$

where: $$q_n = \sum_{j=1}^{\infty} (a_{jn} \cos j\tau + b_{jn} \sin j\tau) \tag{A2}$$

Using (A1) and decomposition sin q_S and cos q_S we come to the infinite system of linear differential equation:

$$\begin{aligned} &\frac{d^2 q_1}{d\tau^2} + H\frac{dq_1}{d\tau} + \sin\tau = Hp_1 \\ &\frac{d^2 q_2}{d\tau^2} + H\frac{dq_1}{d\tau} + q_1\cos\tau = Hp_2 \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \end{aligned} \tag{A3}$$

where

$$a_{11} = H/R_1, \quad b_{11} = 1/R_1, \quad a_{22} = 3H/4R_1R_2 \qquad b_{22} = (2-H^2)/4R_1R_2 \tag{A4}$$

$$a_{13} = \frac{-H}{8R^2[(5+H^2)R_1^{-1} - (5-H^2)R_2^{-1}]} \quad b_{13} = \frac{[(2-4H^2)R_2^{-1} + (H^2-3)R_1^{-1}]}{8R_1^2},$$

where $\quad R_m = m^2 + H^2$

$$p = 0,5Q^2R_1^{-1}[1 - 0,25Q^2(9R_2^{-1} + 0,25H^2 + \ldots)] \tag{A5}$$

A STUDY OF STABILITY AND CAPSIZING OF FISHING BOATS IN NORTH CHINA INSHORE WATER

by

D. L. Huang, T. L. Li and Y. Lin*

Abstract

Based on the analyse of fishing boats lost during 1965—1984 in North China inshore water, it is found that the stability of these lost ships were well designed to meet the requirements of Stability Rule excuted currently in China. For this reason, the authors studied environment properties by use of the wind and wave data recorded by coastal stations in this region during 1969—1978. Some main items of Chinese Stability Rule are discusssed in this paper. Nonlinear roll motion of three earlier built fishing boats in this water region are numerically studied in order to certify certain properites of stability of ships in waves. By these studies, some suggestions for improving the stability design of inshore fishing boats, as well as , for revising the relative items of Stability Rule are proposed in present paper.

I. Introduction

Most inshore fishing boats are belong to small vessel, the displacement of which is generally smaller than 250—300t. However, they are required to can operated in vile weather, say, in 6—7 class of sea state. Since the inadequate understanding of the environment features, and some not fully appropriate considerations and handlings in design and application, the loss and capsizing of inshore fishing boats is frequently happened every year. The length and displacement of fishing boats built during 60—80s for North China inshore water (i. e. Yellow sea and Bo-Hei Bay) were in the range of 23. 0—35. 0 m and of 110—250 t, repectively. Because of their smaller displacement and inevitably lower stability, the anti-capsizing ability of these vessels are generally unfavorable.

Since 1965—1984, may be more than 18 fishing boats were capsized in Norht China inshore water caused by stability accidents[1]. With analysing these mishaps, the authors

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recognized that there were about 15 causes that led to these losses, such as too heavy sea state in which the boats operated, over loaded, heavy cargo piled on deck (including the increasing by freezing), operating in quartering waves, unreasonable gravity center height and initial heeling angle, and the wrong operations of crews, et al.

It is hard to collect complete and reliable data of lost ships and environment, so that to research the capsizing of the abovementioned 18 ships will be almost impossible. The pure theoretical methods developed in recent years for advancing the studies of stability of ships in waves are not yet recognized to be appropriate and effective in design practice. For these reasons, the authors would prefer to investigate the stability and capsizing of fishing boats in North China inshore water in following three aspects.

In order to clear the environment feature in North China inshore water, a study of statistical properties of wave in this region is conducted by using the wind and wave data recorded by coastal stations in 1969—1968. The comparison of the obtained results with those given by Pierson—Moskowitz spectra shows that there are some special features which would be important to effect the safety of fishing ships in this region.

Brief discussions of some items of current stability criteria procedure based on Stability Rules and certain revision suggestions are provided in present paper.

In order to investigate the relationships between ship stability and wave parameters, a numerical study of nonlinear roll equation of ships in wave is conducted and accordingly, certain suggestions that relating to advancing stability design are proposed in present paper.

Three fishing boats built earlier and used in North China inshore water are chosen to be used in present research. It is found that thess ships can meet the requirements of "Rules for Stability of Sea Going Ships" issued by Register of Shipping of the People's Republic of China in 1986 (hereafter, named for short ZC Stability Rule 1986). But the numerical studies show that the roll motion of these ships on wave are not all stable and can results in capsizing.

Therefore, a practical problem has been put forward to the ship researchers and designers that, for design of smaller fishing boats, beside to satify the requirements of Stability Rule, whether there are more efforts and measures shoule be taken in order to ensure the stability of these ships in wave. It may be the purpose and attemps of the authors to make present study.

Ⅱ. Statistical Properties of Wave in North China inshore Water

It should be stated that, untill now, there is still not yet a generally recognized wave spectra used specially to present the statistical properties of wave in North China inshore water. During 50—70s of this century the wave spectra with the form of

$$S(\omega) = \frac{0.74}{\omega^5} E_{xp}\left(\frac{-363.5}{U^2\omega^2}\right)$$

$$V = 12.2\sqrt{H_1/3} \tag{1}$$

was ever used for this purpose, where U (kn) is wind speed, $H_{1/3}$ is significant wave height and ω is wave frequency. For the reason that the peak of spectra (1) is too exaggerating and the peak location is always moving to left (side of lower frequency), this spectra had been announced to stop to be used in early 80s.

ZC Stability Rule 1986 didn't give any information describing the statistical properties of wave in North China inshore water. However, some data, coefficients and Charts are provided in ZC stability Rule for calculating the wind pressure and maximum roll angle of ships in various sea regions. It is found that these data corresponding to coastal region (definited as Ⅱ and Ⅲ navigation area) are always smaller than thoes corresponding to unlimited sea region (definited as I navigation region). It will give us a hint that the wave energy in chinese coastal sea is always weaker than that in unlimited sea region. By the way, ZC Rule doesn't give any explanation of the background of these data and charts.

The Department of Naval Architecture of Dallian University of Technology analysed the wind and wave data recorded by coastal stations during 1969—1978 and proposed a wave spectra that represents the statistical property of wave in North China inshore water(2)

$$S(\omega) = 0.2771\, K_s^2$$

$$\frac{H_{1/3}^{0.591}}{\omega^5} E_{xp}\left(-\frac{1.3588}{H_{1/3}^{1.5272}\omega^4}\right) \tag{2}$$

where, K_s is a correction factor

$$K_s = 0.3227 + 0.0177\, U$$

and the relation between significant wave height $H_{1/3}$ and wind speed U has the form as

$$H_{1/3} = 0.053\, U^2$$

Fig. 1 shows the wave spectra (2) corresponding to U=26 and 40 kn. The curves of Pierson-Moslowitz wave spectra corresponding to same wind speed are also plotted in fig. 1.

Some enlightenments can be found from comparison of eq. (2) with P-M spectra. For high sea states, say when wind speed exceeding 36.5 kn, the spectra values in peak region obtained with eq. (2) are stronger than those of P-M spectra, and the peak is moved toward right, i. e. to high frequency region. For the case of lower sea state, for example, the wind speed is less than 30 kn, the spectra values given by eq. (2) are weaker than those given by P-M spectra, and the peak is moved toward left. Some famous inshore wave spectra, such as JONSWAP spectra, show also similar phenomenon.

According to the calssification of sea state suggested by the National Ocean Bureau of China, the wind speed corresponding to sea state of class 7 is larger than 35 kn. In this case, the statistical wave characteristics obtained with eq. (2) will equal to or larger than those obtained with P-M spetra and therefore, certain dangerous threaten will be sufferred by fishing boats which are designed to satisfy the requirements to operate in Ⅱ or Ⅲ Navigation area as definited by ZC Stability Rule 1986. For the case of light sea state, the peak of wave spectra will moved toward left as compared with P-M spectra, it means that the energy of most harmonic waves is located in low frequency region. In this case, for the fishing boats which are designed to possess longer natural roll period in order to keep away the peak frequency region of P-M spectra, it will result in some unfavorable effects to ship stability in wave.

Ⅲ. Current stability criteria Method in Design. [3]

Since 1980, The ZC Stability Rule has been revised three times. But the suggested procedure and requirements for stability criteria are similar to those provided by the stability rules issed by other countries. Fig. 2 shows the principle procdure of stability criteria provided by ZC Stability Rule. Where abscissa θ is heeling angle, ordinate M_s(or l_s) is right moment (or level), θ_1 is maximum roll angle and s KH represents the inclining moment (or level) caused by wind or other forces. If area KHN=PNL, then the ship is considered to be stable and M_q(or l_p) is the minimum capsizing moment (or level) that the ship can bear. The heeling moment must be smaller than M_q. The wind induced heeling moment M_f is computed by the formula as

$$M_f = 0.001\, PA_fZ \quad (kN \cdot m) \tag{3}$$

where A_f and Z is the lateral area above water line and the height of it's center, P is wind pressure as listed in Table 1. The maximum roll angle can be obtained by the formula

Table 1 Values of Wind Pressure

Navigation area		Center height of lateral area above WL												
		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	≥7.0
Unlimited	Ⅰ	829	905	976	1040	1090	1145	1185	1219	1249	1276	1302	1324	1347
Coastal	Ⅱ	448	493	536	574	603	628	647	667	683	698	711	724	736
Close to shore	Ⅲ	228	248	268	284	301	314	326	336	343	350	357	363	368

$$\theta_1 = 87.5C_1C_2C_3\sqrt{0.216 + Z_g/d} \qquad (4)$$

where, coefficient C_1 depends on both the natural period of roll and navigation area, C_2 and C_3 depend on bilge keel area and breadth — draft ratio, respectively. Fig. 3 plots coefficient C_1.

It should be pointed out that there still are certain essential problems to be studied and discussed in furture when the current stability criteria method is used.

The stability of ship in wave should be considered to belong to the problem of motion stability of ship roll in wave and should be solved by investigating the stability of the solution of differential equation of roll motion of ships. For this reason, the current ship stability critria method is simply based on the statical equilibrium between heeling- and righting-moment, and should not be considered to be conviced. Certain essentially important factors relating to hydrodynamics are not taken into account.

The determination of the maximum roll angle is a important step in current ship stability criteria procedure. However, it should be pointed out that eq. (4) is reduced by the linearization of nonlinear damping term and restoring terms in differnetial equatioin of roll motion of ships. By the way, coefficient C_1 in eq. (4), which takes the effect of wave height on the maximum roll angle , is simply reduced as the navigation area is translated from I to II and III , as shown in fig. 3. The property of wave in North China inshore water as discussed in section II is not taken into account For these reasons, the maximum roll angle obtained by eq. (4) will be lower and results in unsafety.

IV. Studies of Nonlinear Differential Equation of Roll Motion

It is well known that the ship motion in waves is a complicate nonlinear random oscillation. In order to simplify present study for engineering purpose, a single degree of freedom nonlinear equation of roll motion of ships in regular wave is used to investigate the stability problems of ship in wave.

a.) Form of roll motion equation and the numerical method

The nonlinear differential equation of roll motion of ship used here has the form as

$$\begin{aligned}\ddot{\theta} + k_1\dot{\theta} + k_2|\dot{\theta}|\dot{\theta} + c_1\theta + c_2|\theta|\theta + C_3\theta^3 + C_4|\theta|\theta^3 + C_5\theta^5 \\ = M_W + \lambda\alpha n_0^2 cos(\omega t + \delta) \qquad (5)\end{aligned}$$

where, θ, $\dot{\theta}$ and $\ddot{\theta}$ is the roll angle, and its first and second derivatives with time, repectively,

k_1 and k_2 are damping coefficients,

c_i, $i = 1 - 5$ are fitting coefficients of statical stability curve, M_W is wind induced inclining moment, λ , α and ω are lenght , slope and frequency of wave, respectively. n_0 is the natural frequency of ship roll.

A numerical procedure for solving nonlinear equation provided by Lambert[4] is applied in our studies.

b.) Bifurcation diagram

In the study of bifurcation phenomenon of nonlinear roll motion, the roll motion is assumed to have been in a stationary state and the wind attack is currently not taken into account. In most cases, the jump of roll will happen. If the roll angle after jump exceeds the vinishing angle of statical stability curve, the roll motion is then considered to be unstable. Bifurcation diagram shows the safe and unsafe region on ω-h plane for ship roll.

c.) Computation of stationary roll amplitude

The amplitude of stationary roll motion of ship in wave is important either for current stability criteria procedure, or for numerical analyse by using eq. (5). The regular waves corresponds to sea state of class 6, i. e. the wind speed is 28—31 kn, the frequency and height of waves are 0. 81—0. 75 and 4. 25—5. 62 m, repectively, are used in this computations.

d.) Check of the stability of roll motion

By using the abovementioned results of computation for stationary roll amplitude as the initial condition of eq. (5), and the wind inclining moment obtained with the wind pressure given by ZC Stability Rule 1986, the history of roll can be obtained numerically. If the roll motion is divergent, the ship is then considered to be not stable.

V. Numerical Results

a.) Ship form for numerical studies

Three fishing boats built earlier before 1980 are chosen for numerical studies. Their main data are listed in Tab. 2. The static stability curves of them shown in fig, 4.

b.) Computation of maximum roll angle

The maximum roll angle are computed by both the ZC Stability Rule 1986 and the numerical solution of eq. (5). The wave height $H_{1/10}$ and mean zero-crossing frequency corresponding to wind speed 28 — 31 kn obtained by spectra (2) is used in these computations. All results obtained are plotted in fig. 5. It is found that the maximum roll angle obtained by Stability Rule are lower than those obtained by numerical solution of eq, (5). Obviously, it seems to be unfavorable to ensure safety of ship if only the current stability criteria procedure is used.

c.) Stability creiteria by ZC Stability Rule 1986

The computation of stability criteria by current Mehtod for the three ships are carried out . The authors found that the stability design of these boats all meet the requirements of ZC Stability Rule 1986 in navigation area Ⅱ and Ⅲ .

d.) Bifurcation diagram

The bifurcation diagram of nonlinear roll motion of the three fishing boats in regular waves with heights 0. 8 — 5. 0 and frequencies 0. 7 — 1. 5 sec^{-1} are computed and the results are plotted in fig, 6.

Table 2. Principle data of Boats A, C and D.

Ship			A	C	D
Length of Water line	L_{WL},	m	27. 80	23. 45	28. 87
Breadth	B,	m	6. 67	4. 95	6. 00
Depth	D,	m	3. 65	2. 65	2. 70
Draught	d,	m	2. 95	2. 25	2. 10
Displacement	Δ,	t	260	160	182
Block coefficient	C_B		0. 480	0. 652	0. 522
Waterplane coeddicient	C_W		0. 753	0. 875	0. 774
Lateral are above WL	A,	m^2	79. 06	55. 00	75. 60
Ceter of A above WL	l_A,	m	1. 30	1. 26	1. 58
Metarceter height	$\frac{A}{GM}$,	m	0. 701	0. 744	0. 717
Height of gravity center	$\overline{KG}$,	m	2. 713	2. 061	2. 180
Bilge keel area	S_K,	m^2	4. 40	2. 11	6. 36
Natrual roll period	T_0,	sec	6. 00	4. 33	6. 97
Material of construction			steel	wood	steel

It can be found that the saddle part of unsafety region of ship A is somewhat higher, but it located at lower frequency region. As pointed out above, it will meet the frequency of peak of wave spectra presented by eq. (2) when wind speed is equal to about 30 kn, and will eassily lead to resonance of roll and will be cosidered to be unfavorable to improve ship stability. The frequency that corresponds to the saddle part of unsafety region of ship C is highter. It will be recognized to be heplfull to prevent resonance of roll motion.

e.) Check of stability of roll motion

Numerical solution of roll motion for ship A, C and D in regular waves with the co-attack of wind induced inclining moment are obtained by using eq. (5). The initial condition used is the maximum roll angle obtained in section b.) as shown in fig. 5. The combinations of height and frequency of waves for numerical studies are 3. 33m versus 0. 81 sec^{-1} and 4. 03 versus 0. 77sec^{-1}, that correponds to the wind speed of 28 kn and 30 kn, respectively. Numerical results show that the roll motion of ship A and D is unstable in the wind and waves mentioned above. The roll motion of ship C will be stable if wind speed is smaller than 29 kn, and will be unstable if the speed of wind increasing furthermore. Fig. 7 shows the history curve of roll motion of ship C.

Ⅵ. Conclustions and Suggestions

Based on the foregoing discussions, it is able to draw following conclusions and suggestions.

a.) For design of fishing boats in North China inshore water, the designers should pay attention to the specialities of environment characteristics in this area. Especially for the case of high sea state, the wave energy will be stronger than that in unlimited sea area that should be minded by the designers.

b.) Stability rules are still now the legal criterion for ship stability design. However, it seems to authors that some items included in the rules, such as the criteria principle, environment parameters, computaional methods, et al , should be revised furthermore.

c.) The modern theoretical methods for studying roll motion stability of ships in wind and waves is an effective toll for rational stability criteria of ships. The Bureau of Register of Shipping should anticipate the researches in this field in order to improve the procedure and requirements for stability criteria in excisting rules.

d.) In order to ensure the safety of smaller fishing boats in inshore water, it is needed to state more strict and detailed instructions of stability control for the crews and ship owners.

Ⅶ. References

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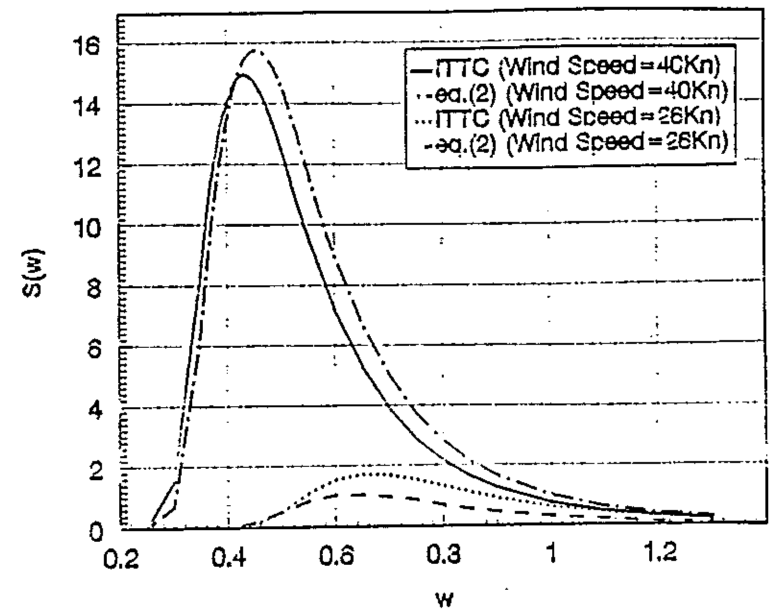

Fig. 1 Comparison of P-M spectra with that given by eq. (2).

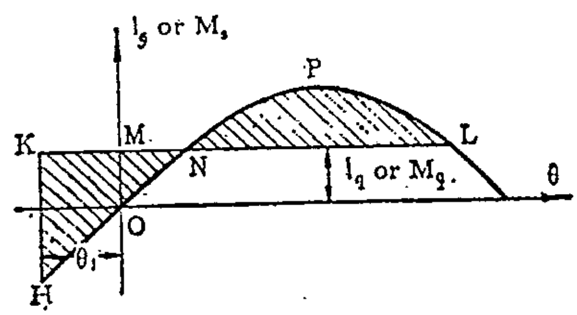

Fig. 2 Principle of stability criteria procedure of ZC Stability Rules.

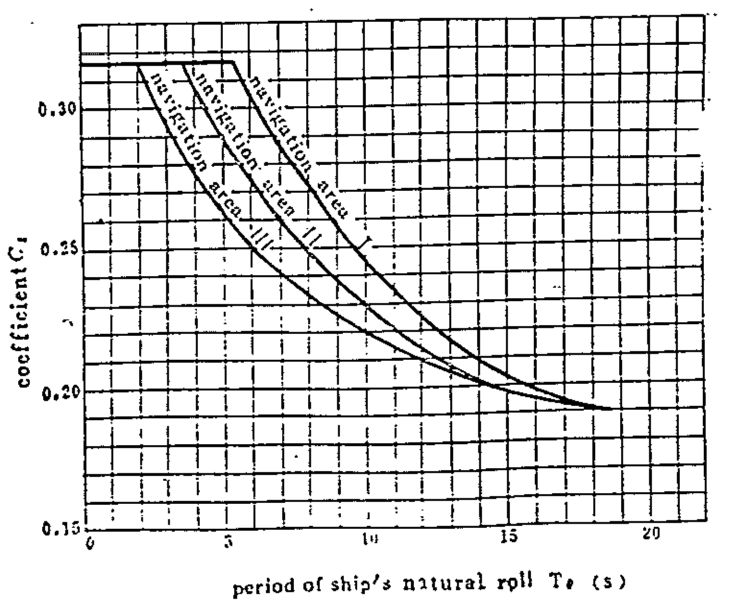

Fig. 3 Coefficient C_1

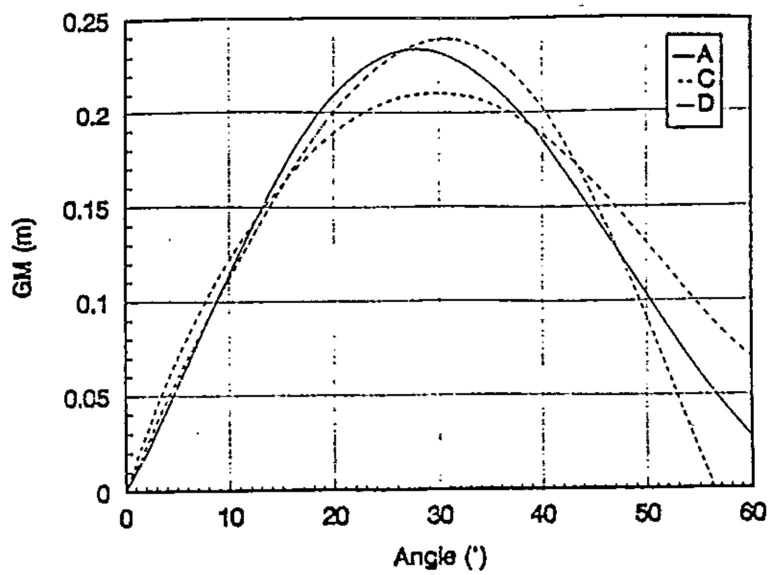

Fig. 4 Static stability curves of ship A, C and D.

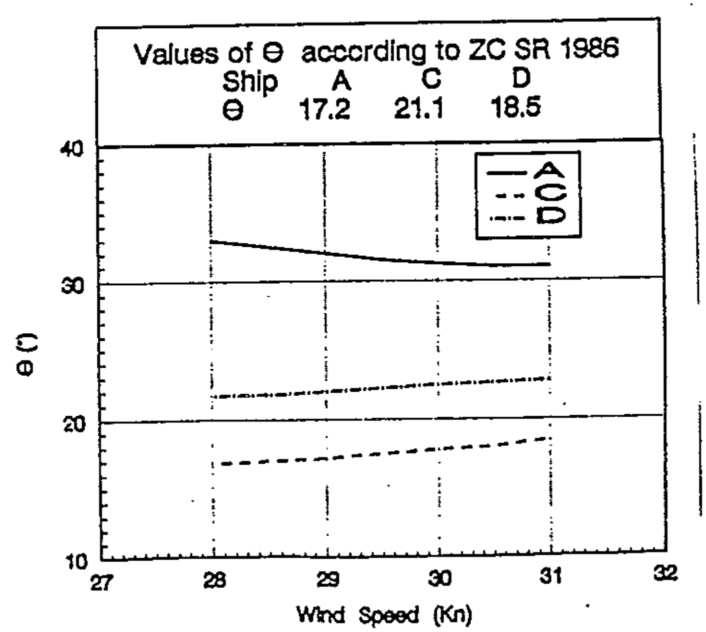

Fig. 5 maximum roll angle θ_1 of ship A, C and D.

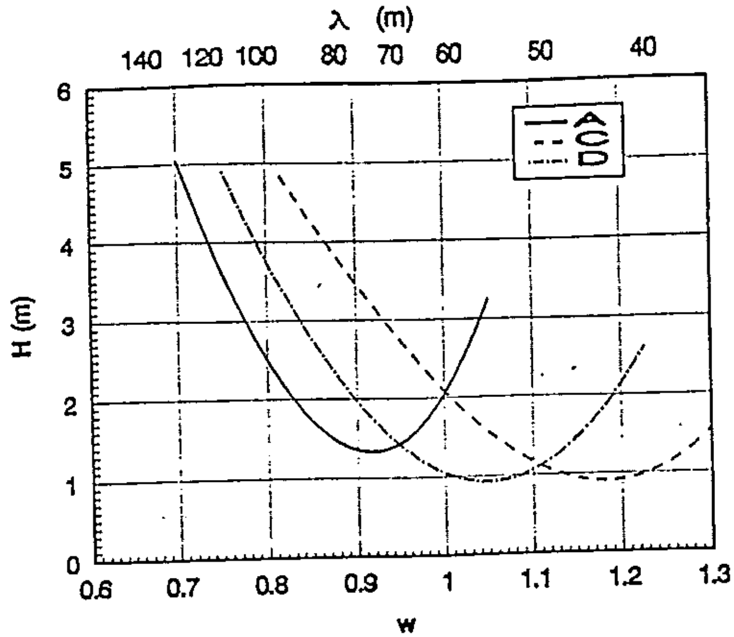

Fig. 6 Bifurcation diagram of roll motion of ship A, C and D.

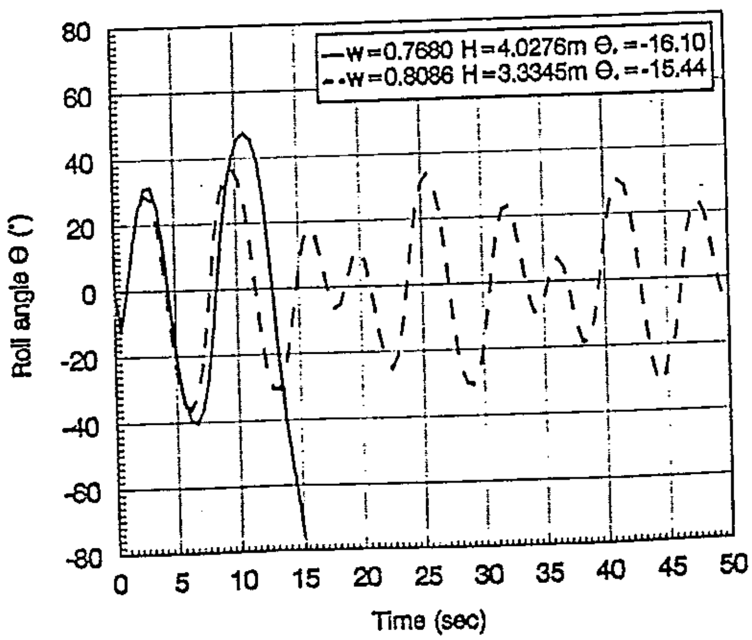

Fig. 7 History curves of roll motion of ship C.

STOCHACTIC STABILITY THEORY OF SHIP MOTION

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The method of investigation of local stability of ship motion stationary random processes and nonlocal stability of initial equilibrium position of ship connected with her noncapsizing under action of wind and waves excitations is presented here. The criteria of local and nonlocal stability are presented also. Their connections with capsizing of ship and generating of her chaotic moving are considered. The example of application of the proposed method on investigation of nonlinear roll motion stability and capsizing of ship is given. With the help of this investigation, some fundamental mechanisms of ship capsizing under action of random wind-wave excitation are discovered.

Introduction

The direct Liapunov method, which operates with the Liapunov functions and the derivatives of Liapunov functions, is the most well-known method of investigation of ship nonlocal stability, connected with the noncapsizing of the ship under wind and waves actions [1, 2, ...].

However, the wide using of this method arouses difficulties, because a general algorithm of Liapunov functions formation is absent, particularly when the ship is situated under action of random wind-waves excitations.

This circumstance is explained by the well-known theorem of general stability theory which says that boundary of stability region of nonlinear dynamic system depends not only on properties of system itself but also on character of acting excitations [3].

Therefore, a general algorithm of the nonlocal stability region determination of a ship must not only include the principal characteristics of acting excitations but contain the description of character their action. Under forming the solution of the ship nonlocal stability problem in class of random functions, such algorithm may be created with the help of the impulse interpretation of random functions and application of the shaping filter method.

1. Description of random processes of wind-waves actions and ship motion

The consideration of gusty wind and irregular waves realizations shows that each of them may be represented by sequence (k = 1, 2, 3,...) of impulse formgenerations (wave trains), a number of generalized parameters of which can contain initial conditions of impulse, speed of amplitude growth α , characteristic frequency β , maximal amplitude A_{max}, etc.

In the simplest case such realizations may be represented by sequences of impulses of the following form

$$\varphi_k(t) = A \exp (\pm \alpha_k t) \cos \beta_k t , \quad k = 1, 2, 3,... \tag{1}$$

It is necessary to note that the base conceptions of the random process theory was formed with the help of analogical presentations [4], i.e. the realization $\zeta^*(t)$ of random function $\zeta (t)$ was written as sequence of nonrandom time functions $\varphi (T)$ represented by the following expression

$$\zeta^*(t) = \sum_k a_k \varphi_k(t - t_k), \tag{2}$$

This is sequece of randomly arising in time impulses of various value and form, t_k is the moment of beginning of k-th impulse.

In formula (2) a_k are random values with known distributions, $\varphi_k(T)$ are determine functions such that $\varphi_k (T) = 0$ for $T < 0$; t_k are random moments of time $t_1 < t_2 < t_3 < ....$

We shall suppose that random values have finite distributions, represented by Pierson's curves (type I) [5]. This will allow us to consider nonlocal stable processes of wind-waves actions and ship motion as subgaussian random processes [6], ordinates of which do not go out over limits of the interval $-4{,}0 < \sigma < 4{,}0$ (where σ is root-mean-square), which is determined by the oceanography observations of wind and waves and observations of the ship motion in rough sea [7].

The law of Pierson's distribution (type I), as it is well-known [5], is completely determined by the first four statistical moments α_1 , $\mu_2 = \sigma^2$, μ_3, μ_4 and is represented in the following form

$$f(X) = N\left(1 - \frac{x}{l_1}\right)^{q_1}\left(1 - \frac{x}{l_2}\right)^{q_2}, \quad (3)$$

Where scope of distribution $l = l_1 + l_2$ is determined by the formula

$$l = 2\sigma\sqrt{(s+1)(1-\chi)}\,.$$

$$S = \frac{6(r_4 - r_3^2 - 1)}{3r_3^2 - 2r_4 + 6};$$

$$\chi = -\frac{r_3^2(s+2)^2}{16(s+1)};$$

$$r_3 = \mu_3/\sigma^3; \quad r_4 = \mu_4/\sigma^4.$$

In special case, this law is transformed into normal distribution, which is completely determined by the first two statistical moments and have ordinates nonlimited . Additional information about statistical moments of third and fourth orders is used by Pierson's law (type I) for determination extremal, finite ordinates of random value [5].

For subgaussian random values and random functions the correlations between statistical moments are written in the forms

$$\alpha_3 = \alpha_1^3 + 3\alpha_1\mu_2;$$

$$\alpha_4 = \alpha_1^4 + 6\alpha_1^2\mu_2 + 3S_1\mu_2^2; \quad (4)$$

$$\dots\dots\dots\dots\dots\dots\dots\dots,$$

where α_i are initial moments of i-th order ; μ_2 is central moment of second order ; $S_1 = (1+\delta)/2$ is parameter of subgaussness ($0 < \delta < 1$).

When $\delta = 1$, the formulas (4) represent the correlationsbetween moments of normal distribution random process. When $\delta = 0$, these terms are the correlations between moments of harmonic function $\zeta(t) = r \cos \omega t$. Thus, parameter δ may be considered as parameter of level of chaoticness of investigated processes, for example, under transition from irregular to regular sea.

If realization of irregular wave process $\zeta^*(t)$ is represented by the sequence impulses (1) of identical form, i.e. such impulses, the parameters α_k and β_k of which are not changed along the realization, then corresponding random process $\zeta (t)$ can be created with the help of excitations $\psi (t)$, close to white noises, and forming filter, the differential equation of which is represented in the following form

$$\ddot{\zeta} + 2 \alpha \dot{\zeta} + b^2 \zeta = \sqrt{2D_\zeta \alpha} \left[\dot{\psi}(t) + b \psi(t) \right] , \qquad (5)$$

where $b^2 = \beta^2 + \alpha^2$; D_ζ is dispersion of $\zeta (t)$ process.

Under taking into account the fluctuations of form of impulse generations and nonlinear dependencies of wave field, it is necessary to use forming filters of more complicated structure

$$\ddot{\zeta} + 2 \delta_1 \left[1 + \varepsilon_1 \psi_1(t) \right] \dot{\zeta} + 2 \delta_3 \dot{\zeta}^3 +$$

$$+ \omega_1^2 \left[1 + \varepsilon_2 \psi_2(t) \right] + \omega_2^2 \zeta^3 = 0 , \qquad (6)$$

where parameters δ_1, δ_3, ε_1, ε_2, ω_1^2, ω_2^2 are determined from conditions of equality of the distribution laws of amplitudes and phases of processes $\zeta (t)$ to real distribution laws of analogical characteristics of waves and from conditions of equality the dispersions of amplitude speeds and dispersions of frequency fluctuations of process $\zeta (t)$, which have expressed through spectral moments of Pierson-Moskovitz's spectral density , to corresponding dispersions of waves [8].

In equation (6) $\delta_1 < 0$ and $\delta_3 > 0$. This conditions the self-excitement of oscillations in filter (6) and the limitation of their amplitudes. Under transition to regular waves of small amplitude, the equations (5) and (6) are resulted into the term

$$\ddot{\zeta} + \omega^2\zeta = 0 ,$$

solution of which is known harmonical function

$$\zeta(t) = r \cos \omega t.$$

2. A method of determination of nonlinear ship motion probability characteristics

It is assumed that the motion of ship, stabled in equilibrium position in a calm sea, is begun under action of random wind-waves excitations $\vec{X}(t)$, intensities of which gradually increase. These excitations and stable process of ship motion $\vec{Y}(t)$ are considered as the finite subgaussian random processes.

Nonlinear differential equations of ship motion are written in the form

$$\frac{d\vec{Y}}{dt} = \vec{F}_1(\vec{Y},\vec{X},t). \tag{7}$$

Acting wind-waves excitations $\vec{X}(t)$ are represented as results of transformation of processes $\vec{\Phi}(t)$, close to white noises, by additional dynamic systems named as forming filters. The equations of forming filters are given by the following expressions

$$\frac{d\vec{X}}{dt} = \vec{F}_2(\vec{X},\vec{\Phi},t), \tag{8}$$

which are added to the system of ship motion equations (7).

With the help of structure and parameter variations of forming filters, there are not only taken into account peculiarities of random excitations, acting on the ship, but also are realized transition to regular sea, to waves of train structure, to single impulse formgeneration,etc.

Investigation of nonlinear ship motion is realized with the help of probability characteristics of processes $\vec{Z}(t)$ represented by the set of statistical moments of the processes $\vec{X}(t)$, $\vec{Y}(t)$ and $\vec{\Phi}(t)$.

An infinite system of equations for statistical moments is composed with the help of equation for characteristic function of processes $\vec{Z}(t)$ [9].

A closing of infinite system of equations for statistical moments is fulfilled on the equations of second order. Therefore, the statistical moments of higher order, coming in equations of first and second order and conditioned by the nonlinearness of motion equations, are expressed through moments of first two orders by the correlations (4), which have place for subgaussian random functions [10].

After the closing, the system of equations for probability characteristics of ship motion and wind-waves actions is reduced to the following form

$$\frac{d\vec{\alpha}_1}{dt} = \vec{Q}_1(\vec{\alpha}_1, \vec{\mu}_2, \vec{G}_1, \vec{G}_2, t);$$
$$\frac{d\vec{\mu}_2}{dt} = \vec{Q}_2(\vec{\alpha}_1, \vec{\mu}_2, \vec{G}_1, \vec{G}_2, t), \tag{9}$$

where $\vec{\alpha}_1(t)$ and $\vec{\mu}_2(t)$ are statistical moments of first and second order of processes $\vec{X}(t)$ and $\vec{Y}(t)$; $\vec{G}_1(t)$ and $\vec{G}_2(t)$ are intensity coefficients of excitations $\vec{\Phi}(t)$ which characterize their mean values and mean powers respectively.

The changing of the sea state are usually took place relatively slowly. Therefore, on the every stage of slow changes of storm the processes of wind-waves actions $\vec{X}(t)$ and ship motion $\vec{Y}(t)$ can be considered as stationary random processes, probability characteristics of which are determined by the following system algebraic equations

$$\vec{Q}_1(\vec{\alpha}_1, \vec{\mu}_2, \vec{G}_1, \vec{G}_2) = 0;$$
$$\vec{Q}_2(\vec{\alpha}_1, \vec{\mu}_2, \vec{G}_1, \vec{G}_2) = 0. \tag{10}$$

Solution of this system is realized numerically by the nonlinear programming methods [13]. Then maximal deviations of ship from equilibrium position on calm water are determined by the formula

$$Y_{i\,max} = \alpha_{1_i} + l_2(\mu_{2_i}) \tag{11}$$

where function $l_2(\mu_{2_i})$ is the larger part of the scope of the Pierson's distribution (3). It is calculated with the help of expressions, given in work [5], in dependence on correlations between moments of first four orders.

For example, if $\alpha_1 = 0$ and $\mu_2 = 0$ and scope l of simmetric distribution, determined by the date of nature observations, takes equal $8{,}0\sqrt{\mu_2}$, then this means that parameter s_1 in formula (4) have value 0,89 and parameter of chaoticness δ accordingly 0,78 and that supposition about maintenance in such form of the correlations between statistical moments of ship motion processes introduces also and uses during formation of equations (9).

3.A method of stability investigation of ship motion processes

The equations of second order statistical moments, coming in the system equations (9) and (10), are equations of mean powers and energies transformations of the wind-waves actions into the ship motion processes. The correlations between statistical moments of first two and higher orders, being used in these equations, determine the maximal ordinates of such processes. Consequently, if stationary states of ship motion exist and they stable then kinetic energy of ship oscillations does not exceed potential energy and ship motion processes are remained by the limited random processes.

A domain of existence of having physical sense solutions of the equations for probability characteristics of ship motion (10) is coinsided with region of real roots (real solutions) of these equations. The boundary of this domain is determined by transition of the real values of these solutions to complex values [9 - 12]. Really, the kinetic energy of ship, under her stable oscillations relatively initial equilibrium position, can not be able to exceed the potential resources. Therefore, the transition of roots in complex region, realizing together with cessation of existence of ship motion stationary state , means an appearance of disbalance between kinetic and potential energies of oscillations. This disbalance may be completed by the transition to new stable stationary state of motion in neighborhood of initial equilibrium position or to capsizing of the ship, i.e. to her oscillations relatively equilibrium position overkeel.

A fixation such transition, under gradual increase of intensities of constantly-acting random wind-waves excitations, can be realized with the help of parallel investigation of local stability of sequence of ship motion stationary states, which are considered during this increase of external action intensities.

For these aims, the small perturbations $\Delta\vec{\alpha}_1$ and $\Delta\vec{\mu}_2$ are added to stationary states of ship motion $\vec{\alpha}_1^{(0)}$ and $\vec{\mu}_2^{(0)}$, which are determined real solutions of the equations (10). Equations for additional perturbations are written in the form

$$\begin{aligned} \frac{d\vec{\alpha}_1}{dt} &= \left.\frac{\partial Q_1}{\partial \alpha_1}\right|_0 \Delta\vec{\alpha}_1 + \left.\frac{\partial Q_1}{\partial \mu_2}\right|_0 \Delta\vec{\mu}_2 ; \\ \frac{d\vec{\mu}_2}{dt} &= \left.\frac{\partial Q_2}{\partial \alpha_1}\right|_0 \Delta\vec{\alpha}_1 + \left.\frac{\partial Q_2}{\partial \mu_2}\right|_0 \Delta\vec{\mu}_2 , \end{aligned} \tag{12}$$

and investigation of local stability stationary states of ship motion is realized by the first Liapunov method [1].

The coefficients of the equations (11) for additional perturbations are first partial derivatives of right parts of the equation (9) with respect to statistical moment $\vec{\alpha}_1$ and $\vec{\mu}_2$ in neighborhood of stationary state determined by $\vec{\alpha}_1^{(0)}$ and $\vec{\mu}_2^{(0)}$. A characteristic equation corresponding the equations (11) is built with the help of a matrix of these first partial derivatives and is represented in the usually form

$$a_n \lambda^n + a_{n-1} \lambda^{n-1} + \ldots + a_1 \lambda + a_0 = 0 . \qquad (13)$$

Under gradual increase of intensities of wind-waves excitations, the states of ship motion will be stable if roots λ_i ($i = 1,2,3,..,n$) of characteristic equation, corresponding to the equations (12), have negative real parts.

The roots of characteristic equation will be really have negative real parts if the following inequalities be satisfied

$$a_n > 0 ; \quad \Delta_1 > 0 ; \quad \Delta_2 > 0 ; \ldots ; \Delta_n > 0 ,$$

where Δ_i ($i = 1,2, \ldots, n$) are the Hurwitz's determinants [14]. From the structure of the building Δ_n follows that

$$\Delta_n = a_0 \Delta_{n-1} .$$

The equaling of Δ_n to zero give us two equations of stability boundaries

$$a_0 = 0 ; \qquad (14)$$

$$\Delta_{n-1} = 0 . \qquad (15)$$

The first boundary corresponds to the presence in the characteristic equation (13) the root equal to zero.

The second boundary corresponds the presence in the characteristic equation (13) the roots having imaginary parts not equal to zero.

In this tie, an introduction in the considering a determinant of the matrix of first partial derivatives of the equation (9), writing in a form of the following inequality

$$a_o = \begin{vmatrix} \dfrac{\partial Q_1}{\partial \alpha_1} & \dfrac{\partial Q_1}{\partial \mu_2} \\ \dfrac{\partial Q_1}{\partial \alpha_1} & \dfrac{\partial Q_2}{\partial \mu_2} \end{vmatrix} \equiv (-1)^n \lambda_1 \lambda_2 \lambda_3 \ldots \lambda_n < 0, \qquad (16)$$

creates the first criterion of local stability of considering stationary random processes of ship motion.

As a rule, this criterion coincides with the criterion of existence of stationary solutions of the equations (10).

Under gradual increase of intensities of wind-waves excitations, this criterion continues to stay by criterion of nonlocal stability of initial equilibrium position of a ship if another stable stationary state of ship motion is found in neighborhood of initial equilibrium position and the inequality (16) after transition of a ship to this state is satisfied.

This criterion is necessary also to consider as criterion of nonlocal stability if there are not remained another attracting centers after $a_o > 0$ in domain of dynamic states of ship , except the equilibrium position overkeel, and ship, after destroying of the criterion (16), transits to oscillations in neighborhood of this position, i.e. capsizing.

The second criterion of local stability of considering sequence of ship motion stationary random processes is determined by the inequality

$$- \Delta_{n-1} < 0 . \qquad (17)$$

This criterion is formed with the help of matrix of first partial derivatives also. As a rule, it determines the loss stability of joint statistical moments (covariances), what means the loss of the phase synchronism of considering processes and the transition of ship to the chaotic moving, what leads to the capsizing of a ship if the other attracting centers are absent in neighborhood of her initial equilibrium position .

Therefore, the system of the equations (9) fulfills role of the stochastic analog of the Liapunov function and the determinant of first partial derivatives matrix of this system - role of derivative of the Liapunov function.

Thus, proposed method of stability investigation of ship motion processes, under above conditions, can be determined as the method of local and nonlocal stability investigation of a ship under action of random wind-waves excitations.

During transition to regular waves, the proposed algorithms lead to results, close to results of determination of amplitude and phase characteristics of ship oscillations and investigation of their stability by the method N.M.Krylov and N.N.Bogolubov [10,11,15].

4. The simplest example of stability investigation

4.1. The system of motion equations.

In simplest case, the system of equations of ship motion andacting wave excitations is represented in the following form

$$(I_x + \mu_{44})\ddot{\vartheta} + \lambda_{44}^{(1)}\dot{\vartheta} + \lambda_{44}^{(2)}\dot{\vartheta}|\dot{\vartheta}| +$$

$$+ D(h_0\vartheta + h_1\vartheta|\vartheta| + h_2\vartheta^3) = \bar{M}_0 + \tilde{M}_B(t) - \frac{b^2}{g} I_x \ae_\theta \ddot{\eta}_B(t); \quad (18)$$

$$\ddot{\eta}_B + 2\alpha\dot{\eta}_B + b^2\eta_B = \sqrt{2 D_\zeta \alpha}\left[\dot{\psi}(t) + b\,\psi(t)\right],$$

where $\vartheta(t)$ is relative angle of roll motion, $\eta_B(t)$ is horizontal displacement of wave surface, $\tilde{M}_B(t)$ is pulse component of wind heeling moment, $\psi(t)$ is random process, close to white noise, with mean value equal to zero and spectral density, close to $1/2\pi$, D_ζ is dispersion of wave process, α and b are width and mean frequency of wave spectrum.

With the help of introducing of new variables by formulas

$$Y_1 = \vartheta; \quad Y_2 = \dot{\vartheta}; \quad Y_3 = \eta_B; \quad Y_4 = \dot{\eta}_B - \sqrt{2 D_\zeta \alpha}\ \psi,$$

we can write the following system of first order equations

$$\frac{d\,Y_1}{d\,t} = a_{1,1_2} Y_2;$$

$$\frac{d\,Y_2}{d\,t} = a_{2,1_1} Y_1 + a_{2,2} Y_1 |Y_1| + a_{2,3_1} Y_1^3 + a_{2,1_2} Y_2 +$$

$$+ a_{2,2_2} Y_2 |Y_2| + \bar{a}_{2,0_2} \bar{X}_2 + \tilde{a}_{2,0_2} \tilde{X}_2(t) + a_{2,1_3} Y_3 +$$

$$+ a_{2,1_4} Y_4 + \tilde{a}_{2,0_3} \tilde{X}_4(t) + \tilde{a}_{2,0_4} \tilde{X}_4(t) ;$$

$$\frac{d\,Y_3}{d\,t} = a_{3,1_4} Y_4 + \tilde{a}_{3,0_3} \tilde{X}_3(t) ;$$

$$\frac{d\,Y_4}{d\,t} = a_{4,1_3} Y_3 + a_{4,1_4} Y_4 + \tilde{a}_{4,0_4} \tilde{X}_4(t) ; \tag{19}$$

where $$a_{1,1_2} = a_{3,1_4} = 1 ;$$

$$\bar{a}_{2,0_2} = \frac{\bar{M}_0}{I_x + \mu_{44}} ; \qquad \tilde{a}_{2,0_2} = \frac{2\,\bar{M}_B}{(I_x + \mu_{44})\, V(\bar{Z}_n)} ;$$

$$a_{2,1_1} = -\frac{D\,h_0}{I_x + \mu_{44}} ; \qquad a_{2,2_1} = -\frac{D\,h_1}{I_x + \mu_{44}} ;$$

$$a_{2,3_1} = -\frac{D\,h_2}{I_x + \mu_{44}} ; \qquad a_{2,1_2} = -\frac{\lambda_{44}^{(1)}}{I_x + \mu_{44}} ;$$

$$a_{2,2_2} = -\frac{\lambda_{44}^{(2)}}{I_x + \mu_{44}} ; \qquad a_{2,1_3} = b^2 æ ;$$

$$a_{2,1_4} = 2\alpha\, æ ; \qquad \tilde{a}_{2,0_3} = -\sqrt{2\, D_\zeta \alpha}\; æ ;$$

$$\tilde{a}_{2,0_4} = -\sqrt{2\, D_\zeta \alpha}\,(b - 2\alpha)\, æ ; \qquad \tilde{a}_{3,0_3} = \sqrt{2\, D_\zeta \alpha} ;$$

$$a_{4,1_4} = -2\alpha ; \qquad a_{4,1_3} = -b^2 ;$$

$$\tilde{a}_{4,i_4} = \sqrt{2\, D_\zeta \alpha}\ (b - 2\alpha)\ ; \qquad \text{æ} = \frac{\text{æ}_\theta(\omega_\theta) b^2\ I_x}{g(I_x + \mu_{44})} .$$

4.2 The system of probability characteristics of motion.

On the base of the equations (19) , the system of statistical moments equations is built. Following to the recommendations of work [9], we get

$$\frac{d\,\alpha_{i_1}}{d\,t} = a_{1,i_2}\alpha_{i_2}\ ; \tag{20}$$

$$\frac{d\,\alpha_{i_2}}{d\,t} = a^*_{2,i_2}\alpha_{i_2} + a^*_{2,i_1}\alpha_{i_1} + a_{2,3_1}(3\,\alpha_{2_1} - 2\alpha^2_{i_1})\alpha_{i_1} +$$

$$+ \bar{G}^*_{i_2} + a_{2,i_3}\alpha_{i_3} + a_{2,i_4}\alpha_{i_4}\ ; \tag{21}$$

$$\frac{d\,\alpha_{i_3}}{d\,t} = a_{3,i_4}\alpha_{i_4}\ ; \tag{22}$$

$$\frac{d\,\alpha_{i_4}}{d\,t} = a_{4,i_3}\alpha_{i_3} + a_{4,i_4}\alpha_{i_4}\ ; \tag{23}$$

$$\frac{1}{2}\ \frac{d\,\alpha_{2_1}}{d\,t} = a_{1,i_2}\alpha_{i_1 i_2}\ ; \tag{24}$$

$$\frac{d\,\alpha_{i_1 i_2}}{d\,t} = a_{1,2_2}\alpha_{2_2} + a^*_{2,i_1}\alpha_{2_1} + a_{2,3_1}(3\alpha^2_{2_1} - 2\alpha^4_{i_1}) +$$

$$+ \bar{G}^*_{i_2}\alpha_{i_1} + a_{2,i_3}\alpha_{i_1 i_3} + a_{2,i_4}\alpha_{i_1 i_4}\ ; \tag{25}$$

$$\frac{d\,\alpha_{i_1 i_3}}{d\,t} = a_{1,i_2}\alpha_{i_2 i_3} + a_{3,i_4}\alpha_{i_1 i_4}\ ; \tag{26}$$

$$\frac{d\,\alpha_{i_1 i_4}}{d\,t} = a_{1,i_2}\alpha_{i_2 i_4} + a_{4,i_3}\alpha_{i_1 i_3} + a_{4,i_4}\alpha_{i_1 i_4}; \tag{27}$$

$$\frac{1}{2}\,\frac{d\,\alpha_{2_2}}{d\,t} = a^*_{2,i_1}\alpha_{i_1 i_2} + a_{2,3_1}3\alpha_{2_1}\alpha_{i_1 i_2} + a^*_{2,i_2}\alpha_{2_2} + \bar{G}^*_{i_2}\alpha_{i_2} + a_{2,i_3}\alpha_{i_2 i_3} + a_{2,i_4}\alpha_{i_2 i_4} + \frac{1}{2}\tilde{a}^2_{2,o_3}\tilde{G}_{2_4} + \frac{1}{2}\tilde{a}^2_{2,o_2}\tilde{G}_{2_2} + \frac{1}{2}\tilde{a}^2_{2,o_4}\tilde{G}_{2_4}; \tag{28}$$

$$\frac{d\,\alpha_{i_2 i_3}}{d\,t} = a^*_{2,i_1}\alpha_{i_1 i_3} + a_{2,3_1}3\alpha_{i_1 i_3}\alpha_{2_1} + a^*_{2,i_2}\alpha_{i_2 i_3} + a_{2,i_3}\alpha_{2_3} + a_{2,i_4}\alpha_{i_3 i_4} + a_{3,i_4}\alpha_{i_2 i_4}; \tag{29}$$

$$\frac{d\,\alpha_{i_2 i_4}}{d\,t} = a^*_{2,i_1}\alpha_{i_1 i_4} + a_{2,3_1}3\alpha_{i_1 i_4}\alpha_{2_1} + a^*_{2,i_2}\alpha_{i_2 i_4} + a_{2,i_3}\alpha_{i_3 i_4} + a_{2,i_4}\alpha_{2_4} + a_{4,i_3}\alpha_{i_2 i_3} + a_{4,i_4}\alpha_{i_2 i_4}; \tag{30}$$

$$\frac{1}{2}\,\frac{d\,\alpha_{2_3}}{d\,t} = a_{3,i_4}\alpha_{i_3 i_4} + \frac{1}{2}\tilde{a}^2_{3,o_3}\tilde{G}_{2_3}; \tag{31}$$

$$\frac{d\,\alpha_{i_3 i_4}}{d\,t} = a_{3,i_4}\alpha_{2_4} + a_{4,i_3}\alpha_{2_3} + a_{4,i_4}\alpha_{i_3 i_4} + \tilde{a}_{3,o_3}\tilde{a}_{4,o_4}\tilde{G}_{i_3 i_4}; \tag{32}$$

$$\frac{1}{2}\,\frac{d\,\alpha_{2_4}}{d\,t} = a_{4,i_3}\alpha_{i_3 i_4} + a_{4,i_4}\alpha_{2_4} + \frac{1}{2}\tilde{a}^2_{4,o_4}\tilde{G}_{2_4}. \tag{33}$$

In equation (20) — (33)

$$G_{1_2} = \bar{a}_{2,0_2} \bar{X}_2 \; ; \; \dot{\tilde{G}}_{2_4} = b^2;$$

$$G_{2_2} = G_{2_3} = G_{2_4} = G_{1_3 1_4} = 1 \; ;$$

Besides, the additions, conditioning by the statistical linearization of nonlinearities $Y_i|Y_i|$ (i = 1, 2), are marked by sign * and represented in the following form

$$a^*_{2,1_1} = a_{2,1_1} + a_{2,2_1} \frac{4}{\sqrt{2\pi}} \left(s_0 \, \mu_{2_1} + \frac{1}{2} \alpha^2_{1_1} \right) \frac{1}{\sqrt{\mu_2}} +$$

$$+ 3a_{2,3_1} (s_1 \mu_{2_1} + \alpha_{1_1}^{\;2});$$

$$a^*_{2,1_2} = a_{2,1_2} + a_{2,2_2} \sqrt{\frac{8}{\pi} s_0 \mu_{2_2}} \, .$$

In these equations are also used the following notations

$$\alpha_{1_1} = M[\; Y_1] = M[\; \vartheta \;] \; ; \qquad \alpha_{1_2} = M[\; Y_1] = M[\; \dot{\vartheta} \;];$$

$$\alpha_{1_3} = M[\; Y_3] = M[\; \eta_B] \; ; \qquad \alpha_{1_4} = M[\; Y_4];$$

$$\alpha_{2_1} = M[\; Y_1^2] = M[\; \vartheta^2] \; ; \qquad \alpha_{2_2} = M[\; Y_2^2] = M[\; \dot{\vartheta}^{\,2}];$$

$$\alpha_{1_1 1_3} = M[\; Y_1 Y_3] = M[\; \vartheta \, \eta_B] \; ; \quad \alpha_{1_1 1_4} = M[\; Y_1 Y_4] \; ;$$

$$\alpha_{1_2 1_3} = M[\; Y_2 Y_3] = M[\; \dot{\vartheta} \, \eta_B] \; ; \quad \alpha_{1_2 1_4} = M[\; Y_2 Y_4] \; ;$$

$$\alpha_{2_3} = M[\; Y_3^2] = M[\; \eta_B^2] \, .$$

Here M[...] is operation of statistical averaging.

The statistical moments used characterize mean values, mean powers and joint correlating connections, established between the processes of wave and ship motion.

As it is shown in work [11], the covariance moments determine the phase synchronism of these processes. A destruction of the phase synchronism leads to chaotization of ship motion.

It is not diffioult to note that the equation (25) determines the balanoe of mean kinetio and mean potential energys of ship osoillations, the equation (28) - balanoe of mean powers of external exoitations and dissipations of energy, eto.

4.3 The system of equations of stationary prooesses.

This system is oreated with the help of the equations (20) - (33) by the equaling of their left parts to zero. The solution of this system is realized by the method of nonlinear programming. In result of suoh solution, so named statistical-moment-frequenoy characteristios of ship motion in irregular waves oan be built .

The example of moment-frequenoy oharaoteristio of ship motion $\mu_{2_1}(\bar{\tau})$ [$\bar{\tau} = 2\pi/b$, $\bar{D}_\zeta$ = const, α = const, T_θ is natural period of rolling] is shown on figure 1. It is probability oharaoteristio of motion of ship model of 2 meter length , with vanish angie of GZ ourve equal to 21.5 degrees, tested beam to irregular waves in towing tank of Kaliningrad Teonioal Institute in 1982.

4.4 Stability investigation of ship motion and initial equilibrium position of ship.

For these aims, the matrix of first partial derivatives of right parts of the equations (20) - (33) is built. On its base the ooeffioients of oharaoteristio equation (13) are determined or the proper numbers of matrix (roots of oharaoteristio equation λ_i (i = 1, 2, ...,n)) are oaloulated direotly.

Then we oan observe as the values of roots are ohanged under inoreasing of intenеities of aoting wave exoitations and as the oriteria of stability (16) - (17) are satisfied.

For first criterion, when $\alpha_{1_1} = 0$, we plaoe the following expression

$$a_0 = - 4(a^*_{2,1_1} \mu_{2_1})' (a^*_{2,1_2} \mu_{2_2})'' \ x$$

$$\times \Big[\big(a^*_{2,1_1} - a_{4,1_3}\big)^2 - a_{4,1_4}\big(a^*_{2,1_2} + a_{4,1_4}\big)\big(a^*_{2,1_1} - a_{4,1_3}\big) -$$

$$- a_{4,1_3}\big(a^*_{2,1_2} + a_{4,1_4}\big)^2\Big] +$$

$$+ 4 \Big[(a^*_{2,1_1})'\mu_{1_1 1_4} - (a^*_{2,1_2})''\mu_{1_2 1_4}(a^*_{2,1_1}\mu_{2_1})'\Big] \times$$

$$\times \Big[(a_{2,1_3} + a_{2,1_4}a_{4,1_4})(a^*_{2,1_1} - a_{4,1_3}) +$$

$$+ a_{2,1_4}a_{4,1_3}(a^*_{2,1_2} + a_{4,1_4}) \Big] +$$

$$+ 4 \Big[(a^*_{2,1_4})'\mu_{1_1 1_3} - (a^*_{2,1_2})''\mu_{1_2 1_3}(a^{**}_{2,1_1}\mu_{2_1})'\Big] \times$$

$$\times a_{4,1_3}\Big[a_{2,1_3}(a^*_{2,1_2} + a_{4,1_4}) + a_{2,1_4}(a^*_{2,1_1} - a_{4,1_3})\Big] +$$

$$+ 4 \Big[(a^*_{2,1_2}\mu_{2_2})''(a^*_{2,1_1})'\mu_{1_1 1_4} \times$$

$$\times \Big[a_{2,1_4}(a^*_{2,1_1} - a_{4,1_3}) + a_{2,1_3}(a_{2,1_2} + a_{4,1_4})\Big] -$$

$$- 4(a^*_{2,1_2}\mu_{2_2})''(a^*_{2,1_1})'\mu_{1_1 1_3} \times$$

$$\times \Big[- a_{2,1_4}a_{4,1_3}(a^*_{2,1_2} + a_{4,1_4}) + a_{2,1_3}\Big[(a_{4,1_3} - a^*_{2,1_1}) +$$

$$+ a_{4,1_4}(a^*_{2,1_2} + a_{4,1_4})\Big]\Big] +$$

$$+ 4 \Big[(a^*_{2,1_2})''\mu_{1_2 1_4}(a^*_{2,1_1})'\mu_{1_2 1_3}(a^*_{2,1_1})'\mu_{1_1 1_4}\Big] \times$$

$$\times \Big[-a^2_{2,1_4} a_{4,1_3} + a_{2,1_3}(a_{2,1_3} + a_{2,1_4}a_{4,1_4})\Big] =$$

$$= (-1)^{14} \lambda_1\lambda_2\lambda_3 \ldots \lambda_{14} < 0 , \qquad (34)$$

where derivatives $d/d\,\mu_{2_1}$ and $d/d\,\mu_{2_2}$ are denoted by symbol ' and '' accordingly.

The second criterion is so large that we have not the place for it.

Results of calculations of stability criteria under α = 0.2 are showed in figure 2. Curves 1a, 1b, and 1c of this figure correspond to condition (14) ($a_0 = 0$), determining the first type of boundary of stability region. Curve 2 is determined under condition $\Delta_{n-1} = 0$ and characterize the second type of stability region boundary.

On the boundary of first type the stationary solution of equations for statistical moments ceases its existence. Therefore, the ship goes over to oscillations relatively new attracting center. Cases 1a and 1b are explained by the transitions of solutions on the other branches of the moment-frequency characteristic as it is shown in figure 1. Case 1c is connected with capsizing of ship directly. The dispersion of ship motion μ_{2_1} losses stability on the lines 1a, 1b and 1c where balance of kinetic and potential energies established by the equation (25) is violated.

When intensities of wave excitations reach level of curve 2 the covariance $\mu_{1_2 1_4}$ begins to loss stability. Since in this case in the neighborhood of the initial equilibrium position of a ship other attracting centers are absent the ship goes over to oscillations relativly equilibrium position overkeel.

Such types of ship behavior were checked by the direct calculations of equations of ship motion in irregular waves (18) with the help of the Runge-Kutta method.

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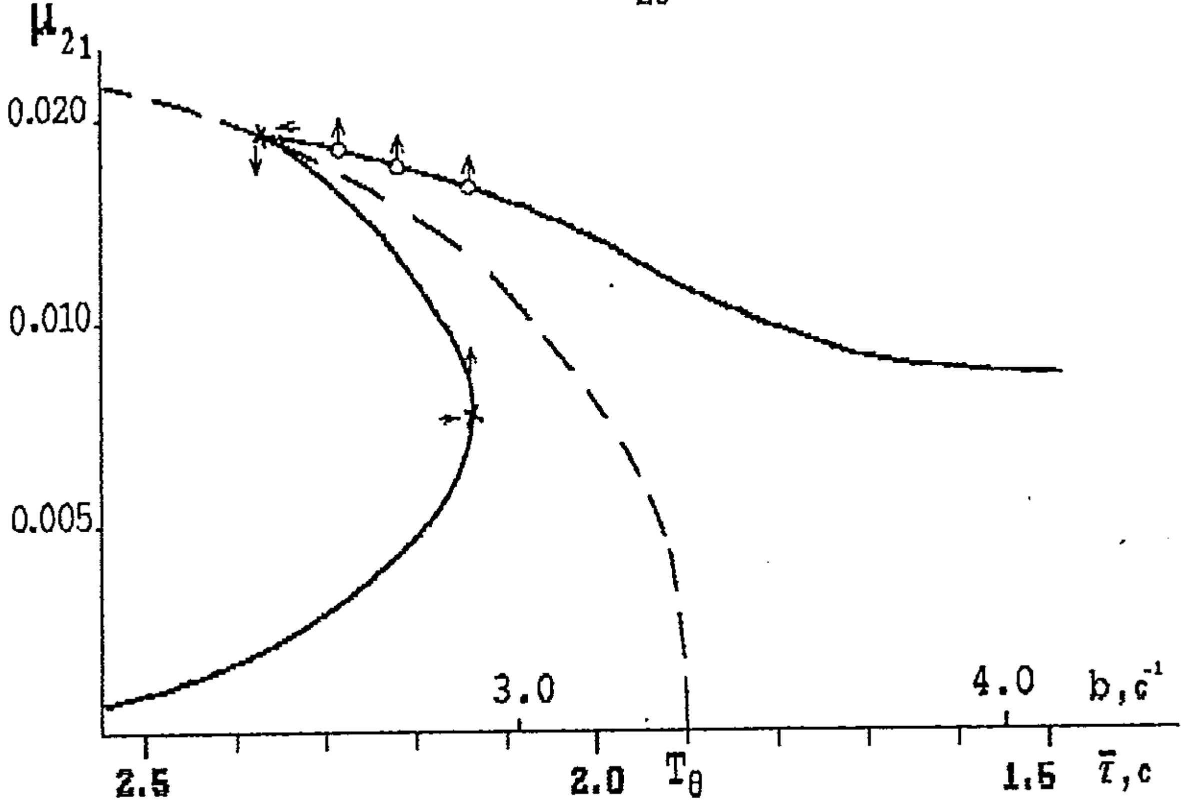

Fig.1 Moment-frequency characteristic of ship model motion.

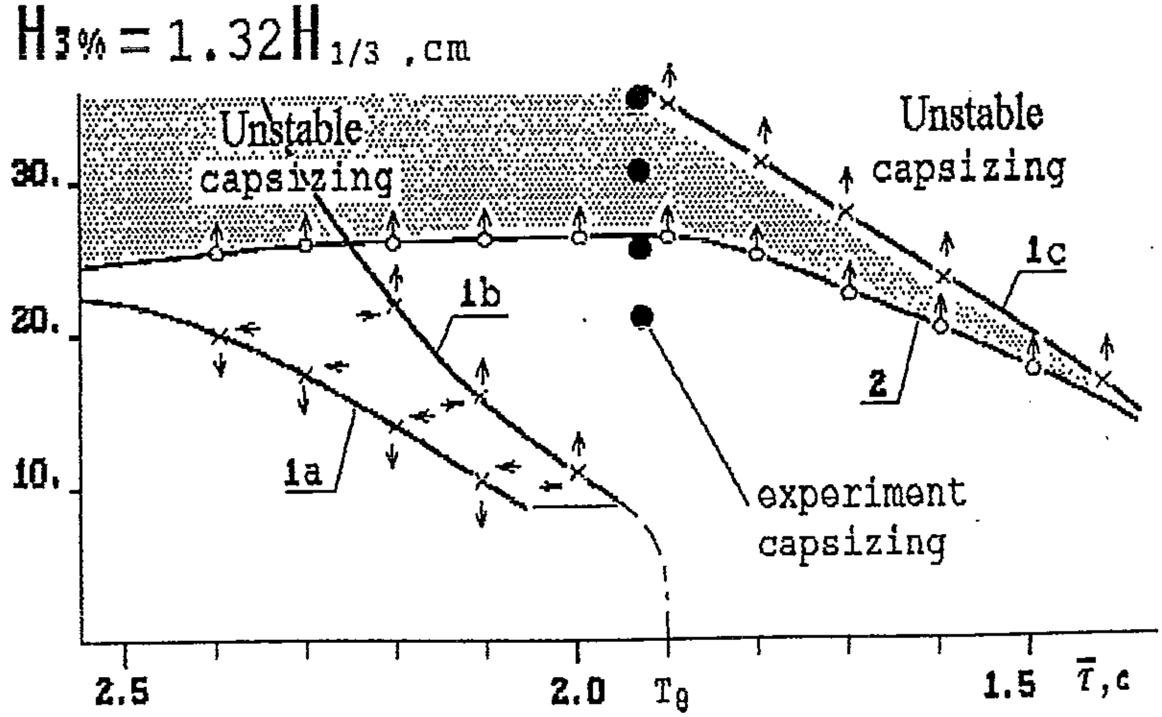

Fig.2 The domain of wave action intensities which are withstood by model of ship.

THE PROBLEM OF PROBABILITY ANALYSIS OF THE VESSEL'S STABILITY ON A SEAWAY

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Summary

Give characteristic of the approach connect with analysis a nonlinear stochastic modell describe a dynamic interaction the vessel with a external environment (wind, waves) in the storm conditions. Consideration the practiculary of the analysis of the vessel's stability based on the method's of statistic tests (Monte-Carlo), the eguations of Fokker-Plank-Colmogorov, the method of moments and the method of functional action.

1. INTRODUCTION

The using of the new mathematical methods and a means of the calculation experiment discover a perspective for the research of the difficulty tesk of the dynamic vessel on a seaway and prepare of the engineering methods calculate in the practic of the designing and vessels expluatation.

For the practice supplement necessary to generalize from the exsistent of the methods describen and research of the stochastic nonlinear system and prepared of the stability in the exploatation's conditions. The results of the decision a nonlinear tesk of the statistical dynamics make it possible to organize the functional connection between a fix significance of the starting chance guantity and the characteristic parameters determine of the vessel's state consideration situation.

2.PROPOUNDING

The mathematical formulate of the tesk consider in following.

Suppose have a nonlinear differential operator with of the chance parameters. On the entry which give the chance function. It is necessary determined the statistical characteristics of the come out process.

The realization this of the general approach may be different. Considerate in the quality of the starting information the data of the hardness distribution a co-ordinates, speed and acceleration, characterizing vessel's moving in the nonlinear waves it can be represented describen of the vessel's motion in the multi-measured of the phase area

$$\Phi_t(\theta,\ \eta,\ \ldots\ ,\zeta,\ \dot{\theta},\ \dot{\eta},\ \ldots\ ,\ \dot{\zeta},\ \ddot{\theta},\ \ddot{\eta},\ \ldots\ ,\ \ddot{\zeta})$$

for all consideration of the static motion (in the strictly propounding - for a six class of the free).

Know of the function Φ_t and calculate the multi-measured surface separatris

$$S(\theta\ ,\ \eta,\ \ldots\ ,\ \zeta,\ \dot{\theta},\ \dot{\eta},\ \ldots\ ,\ \dot{\zeta},\ \ddot{\theta},\ \ddot{\eta},\ \ldots\ ,\ddot{\zeta})$$

derive the area of the stability and nonstability motion in the phase area it can be to determine of the capsizing stability.

The decision consist in determine of the times solidity capsizing probability and reduce for analysis a tesk from throw the multi-measured of the chance process through the surface separatris in the external a phase area. However, this way connection with serious difficult from be lacking the reliable guantity data from function Φ_t and surface separatris.

The difficults of tesk in this propounding curry out necessary of the consideration a stochastic nonlinear differential eguation vessel's rolling on the seaway with used of the series simplity supposition. The one from a ways of the analysis consist in the using on the middle's principle.

The formulate of the task to give I.K.Borodai [1,2] and receive decission in the papers M.Haddara [11,12] and J.Roberts [13, 14]. The other way consists in the using method of the statistical linearization fir receive a moment of the phase coordinate prepare V.A.Necrasovs [3,4].

Below give a characteristics of the several approach for the analys of the stability on the nonlinear waves expounding in the papers [5 - 8] on the base method statistic of the tests, the equation Fokker-Plank-Colmogorov, the method of the monents and of the functional action.

3.METHOD'S OF THE ANALYSIS

Mathematical modell. In the base of the mathematical modell of vessel's dynamic used a nonlinear stochastic differential equation

$$(I_x + \mu_{\theta\theta})\ddot{\theta} + M_R(\dot{\theta}) + M(\theta,t) = M_x(t), \tag{1}$$

where $I_x+\mu_{\theta\theta}$ - the moment of inertia of the vessel's mass tugether with the applied mass of the water relatively a central longitudinal axis; $M_R(\dot{\theta})$, $M(\theta,t)$, $M_x(t)$ - the moments of a dampfer force, the rehabilitate and the indignation; θ, $\dot{\theta}$, $\ddot{\theta}$ - the angle transverse, velocity and acceleration.

The dampfer moment perhabs to represent in a linear or quadratic function of the speed's angle

$$M_R(\dot{\theta}) = \lambda_{\theta\theta}\,\dot{\theta} \ , \ M_R(\dot{\theta}) = W(\dot{\theta})^2 \operatorname{sign} \dot{\theta} \ .$$

The inertion-danpfers components $\mu_{\theta\theta}$, $\lambda_{\theta\theta}$ or W determined of the methods identification in the based results of the full-scale experiment or from the regression modells [6].

The construction of the function $M(\theta,t)$ determine in the dependence from of the angle waves course φ .

The forms of presentation the function $M(\theta,t)$ may be different and a determine of the research methods.

The structure of the intignation moment from a wind action may be different (suddenly or stepped *the* application the case *of* the pulsation close yo middle size) in the dependence from propounding.

Below give the characteristic of the specified methods analysis.

The Monte-Carlo method. This method open the very much chance of the stability research. He is make it possible to receive a correct estimate of the characteristics stability independent from the forms and difficulty of the mathematics describe.

The idea of the methods considerate in the syntes of the stochastig modell of the research system with give the transmission function. For a chance external influence from a generator of the noises or the data chance number on the going out systems realization the chance process, have numerical chracteristics of the physical process, subject the modelling. Reiteration of the experiment with the mathematical modell it possible to receive necessary a massive of realization of the research a chance size for fillowing the statistical process.

The analysis of modell (1) the Monte-Carlo method comfortably to curry out in the suppose represent of the function rehability moments in the form:

$$m(\theta,t)=M(\theta,t)/(J_x+\mu_{\theta\theta})=D[1+\mu(t)\cos[\sigma_k t-\varepsilon_0(t)]]\ (\omega_\theta^2\ \theta-a_0\theta^3),\quad (3)$$

where σ_k, ω_θ – the appear frequency.

Yhe parameter $\mu(t)$ and phase $\varepsilon_0(t)$ considered as chance, distribution for a normal law and steady hardness law.

$$\mu(t)\in M^*[\mu(t)],\ D^*[\mu(t)],\ \varepsilon_0(t)\in[0,2\pi],$$

where M^*, D^*– the operators of the mathematical waiting and dispers.

Yhe correlation function $R_\mu^*(\tau)$ of the process $\mu(t)$ represent for a calculation's data of the irregular waves and represented express

$$R_\mu^*(\tau)=D^*[\mu(t)]e^{-\alpha(\mu)|t-\tau|}\cos\beta(\mu)(t-\tau),$$

where $\alpha(\mu),\beta(\mu)$ – the parameters installation for a data of the special calculations.

For the modelling of the chance function $\mu(t)$ using the method of the forming filter in the time area. The parameters its simple determination of the size dispersia $D^*[\mu(t)]$ and the correlation function $K_\mu^*(\tau)$.

The filter describe of the systems differential equation

$$d\mu/dt=-\alpha(\mu)\mu(t)+\beta(\mu)\nu(t)+\sqrt{2\alpha(\mu)D_\mu^*}\,W_1(t);$$

$$d\nu/dt=-\beta(\mu)\mu(t)-\alpha(\mu)\nu(t)+\sqrt{2\alpha(\nu)D_\nu^*}\,W_2(t),$$

where

$$M^*[W_1(t)W_1(\tau)]=\delta^*(t-\tau);\ M^*[W_1(t)W_2(\tau)]=0;$$

$$M^*[W_2(t)W_2(\tau)]=\delta^*(t-\tau);\ M^*[\nu(t)]=0;$$

$$M^*[\mu^2(0)]=D_\mu^*;\ M^*[\nu^2(0)]=D_\nu^*;\ D_\mu^*=D_\nu^*;$$

$$M^*[\mu(0)\nu(0)]=0.$$

In this formule $W_1(t)$, $W_2(t)$ – the chance of the processes tupe "white noise"; $\nu(t)$ – ausxilary of the chance process; δ^*– delta-function.

In the process of the practical research of the vessels capsizing on the nonlinear waves important significate have the number tests N, sequre necessary of the calculation. As show a results calculation, the size N expediency to determine by means of the analys become the values for a dispersion with decrease of the number tests. This approach prove to be correctis not only the practical opinion but and the more so, that a usualy value precision of the methods Monte-Carlo prove to be marks that are too high. The analys of the resultate calculation from a practical admissible a value precission of the research modell for comparative little the number tests ($N \approx 200$). In its conditions the relatively errors of calculation the capsizing moments is not exceed 2% from his a maximum significance.

As show the calculation, the Monte-Carlo method have a series advantage in the face of the methods calculate tesk of the statistic dynamic nonlinear system (the method of statistic linearization, the method of moments, the theorie of the Marcov process). The based advantage - the compactness of the calculate sceme and the stability for a computers get confused. The comfortable using this method considered in that is not put a limitation on the structure of research of the differential equation while may be include a nonlinear member with any condition nonlinear [5].

The equation of the Fokker-Plank-Colmogorov. This equation describe a change of hardness probability on the chance process for give indignation. The analys is based on presentation of the function $m(\theta,t)$ in form

$$m(\theta,t) = \omega_\theta^2 f(\theta) + \phi(\theta)m(t), \tag{4}$$

where $\omega_0^2\, f(\theta)$ - the mathematical waiting the chance function $m(\theta,t)$; $\phi(\theta)m(t)$ - the nonstationar fluctuation of the rehabilitate moments; $\phi(\theta)$ - scirting, deformation with changing the fluctuation $m(\theta,t)$ around $\omega_0^2\, f(\theta)$ for change θ; $m(t)$ - the certain normal stationar process with the dispersia σ_m^2 .

For function $f(\theta)$ and a skirting $\phi(\theta)$ in the dependence from of the angle course using a several approximation based on the results of the experimental research.

The hardness of the chance emergency process $\theta(t)$ represent form

$$P(\theta,t) = BP_C, \tag{5}$$

where

$$B = \beta_0 + \beta_1(\theta - \langle\theta\rangle)^2 + \beta_1(\theta - \langle\theta\rangle)^4 + \ldots + \beta_r(\theta - \langle\theta\rangle)^{2r};$$
$$P_0 = (1/\sigma_0(t)\sqrt{2\pi})\exp[-(\theta - \langle\theta\rangle)^2/2\sigma_0(t)];$$

$\beta_0, \ldots, \beta_r, \langle\theta\rangle$ - the unknown size (the angle bracket signity middle for ensemble).

The odd degree in formule for B be lacking owing to intuitive accept of the symmetry emergency distribution.

For receive of nonstationar decision and approximation high order for starting equation (1) with a function $M(\theta,t)$ in the form (4) addition the equation second while through "white noise" to forming narrow-strip a chance process.

The receive system of the differential equation with help of standard substitution $\theta = u_1$, $\dot{\theta} = u_2$, $q = u_3$, $\dot{q} = u_4$ (where $q(t) = M_x(t)/(J_x + \mu_{\theta\theta})$)- the variable quantity of the addition equation) transformation in the system of the differential equation first order, determined of the evolution components multi-measure choice

Marcov's process

$$u_j + f_j(u_1, \dots, u_m, t) = \xi_j(t), \quad j=\overline{1,m}, \tag{6}$$

where $\xi(t)$ - the "white noice".

For a function (6) equation Fokker-Planck-Kolmigorov to have air

$$\frac{dp}{dt} = \sum_{j=1}^{m} \frac{d}{du_j} (f_j, p) + \frac{1}{2} \sum_{j=1}^{m} \sum_{k=1}^{m} S_{jk} \frac{d^2 p}{du_j du_k} , \tag{7}$$

where s - the intensiveness "white noice" having of the correlation finction $K(\tau) = S\delta(\tau)$.

Research of the equation (7) devote enormous technical publications. However, it is known only a single decision describe a fluctuation of the nonlinear system for a chance influence. This a stationar distribution Macsvell - Boltsman widely using for the analysis choice fluctuation of the nonlinear system.

For make an solve equation in the nonstationar propounding with the aproach a high order have be folloving the group unknown: two of the mathematical expectations $< \theta^2 >$ and $< \dot{\theta}^2 >$, five on the mutual dispersia, dependence from the times and coefficients β_0, β_1, β_2.

The decision of the equation type (7) in the dependence from a propounding tesk must be satisty of the starting condition

$$P|_{t=t_0} = P\ (u_1^0, \dots, u_m^0, t_0)$$

and in the special case - the condition stationary $dP/dt = 0$.

The procedure of the analysis equation (7) consider in follows [8].:

1.For a set systems write the equation Fokker-Plank-Colmogorov, a decision while be the multi-measuring the hardness probability considered in the quality unknown the moments of the phase variable and a coefficients of decomposition.

2.Curry out the quest of the nonstationar decision whith order of the approach. For this forming a three groups equations. The first group consideration a way in turn multiply the equation (7) on the every phase variable and following integration for all a phase variable. The second droup consideration relatively of the correlation moments second order. For this equation (7) multiply on the correspondent make of phase variable and integration. The third group determine the approach of the high order, consideration on the base a princip of the maximum entropie condition.

3.To curry out quest of the decision receive the system equation possible to determine an unknown the distribute on the going out on nonlinear system and research deformation of the hardness probability the normal entrance process from pass through a this system. For this to a receive equations addition the condition standardize and the conduction while the dispersie of the phase variable and it is known of the function m(t) characterizing the fluctuation a rehabilitate moment with the dispersia σ_m^2 have be zero

$$\begin{aligned}
&(d/dt)\langle\overline{Bu_k}\rangle + \langle Bf_k\rangle = 0, \quad k = \overline{1,n}\ ;\\
&(d/dt)\langle\overline{Bu_k u_l}\rangle + \langle\overline{Bf_k u_k}\rangle + \langle\overline{Bf_l u_k}\rangle = S_{kl}\ ; \qquad (8)\\
&dH/d\beta_1 = 0,\ dH/d\beta_2 = 0,\ dH/d\beta_3 = 0,\ \dots ,
\end{aligned}$$

where $u_1, \dots, u_n$ - the unknown of the phase variable; $u_{n+1},\dots,u_m$- the known of the phase variable; $f_1=\dot{\theta}$, $f_2= -\ddot{\theta}$, $f_3=-q$, $f_4= \ddot{q}$.

Suplement the equation (8) codition of the standard

$$\int_{-\infty}^{\infty} P(\theta)d\theta = 1,$$

receive a system of equation for determined of the sought unknown.

The analys of receive decision considered in substitution the extent function Φ and $f_j(j=\overline{1,m})$ and fulfil the operation of multiply the polynormial. It is case under a symbol middle receive the summ products of the phase variable. Futher realize a centralize of the process with help transformation $\theta = \langle\bar{\theta}\rangle + \theta_1$, $\dot{\theta} = \langle\bar{\dot{\theta}}\rangle + \dot{\theta}_1$ and middle on the base of the quasigauss hypothesis. According to this a hypotesis the unknown process to have following characteristic: his the old moments equal zero, but a high moments of even order find expression througch the moments second order olso as and for a gauss chance function. In the results a odd product level zero, but even express through a moments a second order.

The research [7] show, what a approach to analys of the vessel's stability on the irregular waves in the base equation Fokker-Plank-Colmogorov it turns out more cumbersome comparad with the methods Monte-Carlo.

One from the possible way simply of the task and go through with he for a practical calculation sceme show approach maturity in the works V.A.Nekrasov in the base of the method of moments [3,4].

The method of moments. The method of moments possible to find of the size probability characteristics the choice process a nonlinear dynamic system. This method consist in equate of determine number the selective moments for corresponding of moments distribution while is function from the unknown parameters. Practical the method moments lead to sufficiently a simple calculation. However, value, receive from this methods, include a separate case (example for a normal distribution) -is not the best from possible with the position their effectiveness, that is to say from selection high the volume a their dispersion is not minimum.

The method of the functional action.The method of the functional action based on used the procedure of the value probability on a reaching trajectory of dynamic systems of the give area phase space. This result employment used for a calculation of a vessel's probability capsizing in the storm conditions.

Essence this approach consist in follow.

Considerate a task of the optimal operation as the variation Lagrangian problem in the in the Pontryagin version. In the process curry out the guest for stationary value of the integral by on action and making it possible to coose amoung all the possible methods of transition from the initial state into the final state such a method for which the action (i.e. integral) aquires the minimal value. The importance of such on approach is emphasized by the difficulty to accurately describe external excitations. The systems diooses automatically the worst initial conditions causing capsizing. Solwing the task is reductedto a simple and convenient form and expressed as a compact procedure on the real time scale.

For set of the mathematical modells (1) function $M(\theta,t)$ in this case for all φ excepting the case (2) comfortable represend in the form

$$M(\theta,t)=D[l(\theta)_{max}+l(\theta)_{min}]/2+\{D[l(\theta)_{max}-l(\theta)_{min}]/2\}\xi_1(t), \quad (9)$$

where $l(\theta)_{max}, l(\theta)_{min}$-the extremal significance of the static arm stability; $\xi_1(t)$ - the stationar Gäüss process.

In the quality starting information for calculation of extremal significance function $M(\theta,t)$ used the regression modells, describute of the experimental data measurement of the rehabilitate moment in the different angle course to towards wave [6].

Take down the equation (1) in the form

$$\begin{aligned} \dot{X}_t^{\varepsilon} &= b(X_t^{\varepsilon}) + \sigma(X_t^{\varepsilon})\xi_t ; \\ \dot{X}_t^{\varepsilon} &= \mathrm{col}(\theta_t,\dot{\theta}_t) \in R^n ; \\ X_0^{\varepsilon} &= X \in D^* \subset R^n \ (n=2), \end{aligned} \tag{10}$$

where b,σ - the parameters connect with components of the modell (1); $\theta_t,\dot{\theta}_t$ - the angle velosity and acceleration; D^*- the field of stability.

The process $\xi_1(t)$ represent oneself going out forming filter

$$\dot{\xi}_t = F\xi_t + \varepsilon G u_t, \quad \xi_0 = \xi \in R^r \ (r=4),$$

where F, G - the matrix of the parameter filters, connect with a characteristics: a dominant of frecuency and significance width of the waves spectrum;

$$u_t = \dot{w}_t \quad , \tag{11}$$

u_t - the formal of derived quantity from of the Viner stochastic process w_t; $\varepsilon > 0$ - the small parameter.

This solution reduce for variation Lagrangian problem in the Pountryagin: for any $T>0$ chose $0 < t_f < T$ and the operation u_t from class $C_{OT}(R^m)$ continuouncy on $[0,T]$ function thus, so as to ensuring to boundary conditions $X_0 = X$, $\xi_0 = \xi$, $X_t^{\varepsilon} \in \partial D^*$ and minimization the functional

$$S_{OT} = \int_0^{t_f} u_t^T u_t dt$$

on the motions system (10), (11).

The probability achieve of the critical multitude dD^* a process (10) characterizing of the capsizing probability

$$\lim \varepsilon^2 \ln P_x\{X_t^\varepsilon \in D\} = -\min S_{0t}(\varphi^*) \quad (12)$$

$$\varphi^* \in C_{0t}(R^{r+n}) , \varphi_0^* = (X, \xi), (\varphi_t^*) \in dD^*.$$

The decision this tesk in the correspondent with (12) give a chiv part of logariphm asimptotical specified probability from $\varepsilon \to 0$.

The receive results permission to do conclusion about effectiveness of the methods functional of action in the quality means express-analys of the vessel's stability. Dignity of the method is mathematical strictness in substantion, practicial unlimitcal a possibility in the difficult used a modell wind-wave indignation and extremly modest of calculate expenditure. This possible to used a describe method in the expert systems value vessel's stability, functioning in the real time scale.

4.CONCLUSION

The theory of stability on a seaway - one of them important direction of the vessel's dynamic. The improvement a theoretical and experimental base of the shipbuilding, provide the physical and mathematical modelling of the vessel's stability. The scientific results to do possible not only approach with describe the general behaviour and dynamic vessels heel in the storm conditions, but and more accurate the formulate myself a concept about the stability. Change of the tradition represent from value this sea-keeping qualities. The prepare of the effective methods analysis of stability in the different situation.

The complex using of the means experimental gydromechanic a new mathematical methods and computers technical lead to a correct and detailed the research behaviour vessel in the diffirent conditions of the expluatation, to prepare of the effective method of the control and secure the stability.

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VESSEL'S EXPERT SYSTEMS-CONCEPTION,PROBLEMS,PERSPECTIVS

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SUMMARY

The papers estimates the experience of the development and full-scale tests of on expert system (ES) for finding solutions in the extreme situation. The ES intend for ensuring seaworthiness and unsincability of marine vessels. Give formulate the concept of the base development of the ES, functioning on the real time scale. Consideration the problem and perspective of the practical using ES in quality intelligent assistant for navigator.

1.INTRODUCTION

ES simbolyse a new stade in the development of artifical intelligence (AI) in many direction of computer technologue. A phenomen of ES may be make the possible used methods "knowledge ingeneering" and the achivement in the area AI for a several class nonformalisation tasks.

Vessel's ES appearance comparatively recently [1]. They task to replace noneffective of information-measuring systems, while not find wide use in the practice vessel's exploatation.

In the report give characteristic of ES monitoring safety navigation: ES "Seaworthiness" realize of operative control and presentation of practical recommendations on the sea-keeeping qualities under different working conditions and ES "Unsincability", used for the maintain of damage vessel's vitality for a fload one or several module.

ES "Seaworthiness" use the navigator to solve different practical problems include value the parameters of following waves, choice optimal angle course and vessel's speed using reduce if rolling, flooding and slemming, but olso to curry out the value and forecasting of stability in a process development of the storm and heavy ising. With use ES "Unsincability" provide the operative control of emergency situation, determination the angle balance heel and diffirent, identification to case flooding and give practical recommendation on rehabilitate stability and planting of the damage vessels.

The concept of the development of ES is based on the following considerations:

1.Formulating the decision by the ES is based on the analysis on real time scale of dynamical measurements data of oscilating motions off the vessel's on a seaway. To ensure reliable estimation of the situation and find well-grounded solutions to take into account:

-the actual structure of the wave field acting on the vessel;

-wave's transformation in the vicinty of the vessel's due to difraction and interference of shipping and oncoming waves;

-peculiarities of dynamics of vessel's interaction while the environment under various conditions of operation.

2.Creation of estimation techniques for seaworthiness in based on the combination of methods of mathemetical modelling with measurements, data as well as the achivements theory of experiment within the field under consideration [2].

During development of ES a principle meaning to have the questions of the methodologue and choice of the instrumental means. The consistency to development have usually and include the stade identification, conseptualization, formalization, execution, experimental and experience expluatation. The language of programming is Turbo PASCAL and Turbo C++.

The hardware ensuring the functioning of the ES include a vessels-board personal computer of the standard form, the module of transforming of the input data and the sensor block for rolling and pitching. The systems together with sensor installation on the wheel house and include in vessel's electrical system 220V 50Hz, 36V 400hz alternating current and 27V direct current.

2.THE STRUCTURE AND MODELLS REPRESENTATIVE OF KNOWLEDGE

The small area of quest for new forms and highly subject fild secure a simple architecture of the ES while ussualy a systems concultative type. The components of ES is data base, knowledge base, machine of logic conclusion, module extract of knowledge and system of explanation (interface). The data knowledge based on the facts (affirmations) and the rulles. The machine of conclusion - on the used several strategy building of the logic conclusion. To deal with computer navigator use limited a natural language but not formal programming one. The dialog's process organization as accompanying interaction of the participant.

The represent of knowledge in the vessel's ES is ussualy for a system used the tecnology of AI.

The formal system of the knowledge ES building on the base analys the systematization and structurization conflicting, incompatible and disorderly a knowledge. For the building of the ES prepare of the modell knowledge with help formulate the practical recommendation, based on the theoretical-experimental research in the area vessel's seaworthiness and individual accumulation the professional knowledge. A calculation systems function on the base of achieve AI capable into consideration this information, the structurization his and building the effective strategy of the decision a practical tesk. The area of the alternativs amoung with realize the quest of decision in the ES, considered a limited subject area and used the guality continuity and predicting.

In the correspondent with particular of the tesk realization of the indefinite a starting information and a rules a logic conclusion on the base theory a fuzzi logic.

The structure of knowledge ES prepare proceed from the supposition with organization systems, functioning on the real time scale. Unlike from different determine of the system on the real time scale (a systems secure the running processing of information; a systems working rapidly of a man; a systems reacting on the received information with a speed received) a board-vessel ES of monitoring safety navigation provide give of the time's reaction on the received information. From this times understand the time necessary of the recognize a external force and the formulate corresponding signal.

The functioning ES in the real time scale characteristic several the particulars.

The work of information. The entrance data form a sensors is not constant and periodic be reborn in dependence from the external conditions. In the ES have the means for a analys of situation in the condition incomplete and indefinite of the information.

The refusal-stability (the vitality). The work of ES sequre from going out information system or the several of elements of the system.

The initial data. In the difference from tradetional ES working from statical of subject area, the board-vessel ES a base value information receive from the sensors of the vessel's dynamic.

The logic structure. In the ES provide a possible the time reasoning and the operation with a events of the past, present and future.

The integration of the software. The conditions of effective function of the ES is integration of tradition the data compression, the signal processing, the select of the charactere indication) and euristic of the software.

The function's differentiation. The recommendation of the ES immediate is not using in the contour a vessel's operation. Therefore necessary the clear delimination of the navigator's function and the ES olso the responsibility for a take down decision.

The data knowledge include the declarative and procedure components. Its fulfil propounding tesk in the consideration area of the expertize. In the quality of the modell knowledge used the production's rules. This rules is formal construction operation of the knowledge and sequre module organization, independence of the rules and possible separate the operation knowledge from the subject.

In process of functioning ES in base information from a sensors realize the orerate quality and nomenclature of information, the prognozing of situation's development, the syntesis of information for the accept decision, the choice of formats for presentation of information and organization of graphic interface. Using for development of the ES the paradigms AI and analysis of alternatives expound in paper [3].

3.THE PRACTICAL RESULTS

For estabilishment of the accuracy production knowledge the stability of formulate recommendation and the logic conclusion, the rapidly and reliable foundation, simplicity and covenience interaction provide control of the effectiveness ES "Seaworthiness". The experiments realize in 1991 year on the small vessels in the Black sea and in 1992 year during regular voyage the containership in Mediterrane sea and Atlantic ocean.

The information about this tests given in paper [4].

In the processes of the tests produce the value particulaly of the functioning ES in the different condition of the expluatation. Considered of reaction of the ES on a condition seas and of the vessel's conduct on a seaway. For give speed and orientation of the vessels relatively of general direction moving wave's system value folloving proof:

-parameters of the sea waves;

-characteristics of the rolling and pithing;

-characteristics of the vessel's stability;

-work of the base knowledge on the base of information from sensors.

Below bring results if the tests receive in Tirrenscoesea 12 november 1992 year for vessel's moving in the course angle on the same direction waves. The prognozing of the parameters waves and vessel's stability realize with interval in the 8 hour.

The results of the test represent follow.

The measure data characteristic	The test results	
Vessel's speed, knot	14,5	14,0
displacement,tonns	14500	14478
draught,meter	7,65	7,64
Angle course,degree	10	10
Wave's characteristics(firce six storm):		
middle wave's lengh,meter	42,4	67,5
high3% provision,meter	3,96	5,00
		(prognoz 4,85)
middle period,second	5,57	8,05
Rolling:		
middle amplitude,degree	2,7	3,1
amplitude 3% provission,degree	5,6	6,5
Pitching:		
middle amplitude,degree	0,6	0,7
amplitude 3% provision,degree	1,3	1,5
Vessel's stability(metacentric heigh):		
actual	0,530	0,525
critical	0,328	0,327

The reaction of ES - correspondend the condition of expluatation.

The tests demonstrate what the ES correctly reaction on the vessel's conduct in the condition waves and possible curry out of operative valye stability, rolling and parameters of waves.

The time reaction of the system after receive information from sensors not exceding 20 second.

4.THE PROBLEMS AND PERSPECTIVE

The prepare of the ES represented long and the labour-intensive process. He is very difficult for the board system function in the real time scale. Weakest point here is attain knowledge. This stade is difficult formalization and the tesk of the identification and conseptualization is not support of instrumental means. The ensuring of the demand repidly operate and realization of times correct reasoning in this conditions determine of the know-how of the prepare.

The base composite of the prepare ES have be over-come difficulties in the results decision problem of organization represented of the knowledge. This achieve for the approach based on the principles compactness and continuty determine of the "area knowledge".

The apparatus realization of the ES realize on the standard board computers little adapt oneself to decision difficult of the tesk AI in the real time scale owing to lask of instrumental means and diffilulties connect with complication following the programm.

Exsistence other the problems of the realization board ES. The training of specialists in the area of the ES practical is not carried. The majority system flood the market computer programms have be statical base knowledge is not operation on the decision of the tesk in the real time scale. The development of the ES curry out the academic and educational institutes while is not go through with to completed and the industrial using.

The there is another and a psychological moment connection with a separate of the function ES and navigator. In the emergency sityation the navigator may be not avail oneself of the recommendation ES. Then the ES play the past of "black books" while characteristics of situation preserve in the memory of the computers.

The perspective of development ES connect with decision much of the problems.Attached to base attention to provid of the specialization envelope, the instrumental means, olso the system creation and support of base knowledge. The prepare hardware for board realization suppose widely used microprocessing technology particulary the processors of fuzzy logic. Attach great importance to prepare of ES real time equipment for a perception and analys of the external environment, increase the investigate and production board computers.

5.COOLUSION

Formulate of the results achieve attached to prepare of the ES. The base merit this system to be practical useful for the value of the sea-keeping and unsincability of vessels in the several conditions of the expluatation. The simplicity, convenience using of the expluatation. The simplicity, convenience using and reliable of the ES possible to formulate the practical recommendation is not be as clever of the spesialist-experts. Using in the ES information to be unique and inaccessible for the navigator from vessel's documentation. The based merit of the ES considere in the possible of the operative control of the parameters towards waves and characteristic seaworthiness damage and non-damage vessels especially of the stability and rolling on the waves.

The computers programm orientatrion on acquirement and modification of the knowledge and possible curry a dyalogue in the form understance of the navigator.

The adaptation of the ES with a concrete conditions of the expluatationcurry out in the process of the finishing touches of the system with into consideration of the vessel's characteristic espectially of the wind-wave regime, the possible rise in the assignment regione of the extremal waves and intensive ising. Un the correspondent with own request the customer the systems may be addition other tesus it possible increase they a functional possibility.

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AN ALGORITHM OF PROBABILISTIC STABILITY ASSESSMENT AND STANDARDS

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ABSTRACT

The paper contains the generalization of the author's works done in 1963 - 1993.

Logically completed algorithm is given for the probabilistic estimation of vessel's stability. Two basic problems are considered in the paper: choice of probabilistic criteria and setting of norms (standards) for them. The main concepts of probabilistic approach are determined (the accidental vectors of assumed situations and conditions of loading, risk function, safety guarantee).

The suggested algorithm of probabilistic estimation is applicable as a basis for estimation or regulation of any ship qualities the loss of which may cause a sudden and full loss of the vessel.

1. INTRODUCTION. GENERAL PLAN OF REGULATION PROBLEM

Setting standards for estimation of any technical structures may be reduced to the common enumeration of four subtasks:

1.1 Declaration of the aims of regulation.

1.2 Choice of criteria.

1.3 Setting of the norm (standard) for each criterion.

1.4 Evaluation of guarantee that the declared aims will be achieved by implementing of new regulations; the forecast of its technical and economic consequences.

Only the second subtask is specific. The other subproblems are beyond the frames of naval architecture, structural strength or another technical science. They belong rather to domain of applied reliability theory and ship design.

2. STATISTICAL AND PHYSICAL APPROACHES TO THE STABILITY REGULATION

2.1 Stability Criteria

There are two sources of deterministic criteria and norms:

- experience in ship design and operation in form of statistics;
- mechanics and hydromechanics of vessels' capsizing.

2.1.1 In this paper the word "criteria" means such characteristics of a ship and her operational conditions which in their totality may be used for judging the stability of a vessel.

According to the statistical approach criteria $K_1, K_2, \ldots, K_n$ may be set by the common sense together with some minimal knowledge of ship's theory.

2.1.3 In physical (mechanical) approach the criteria are to be found from the equations which link together the angles of vessel's heel with the forces affecting the vessel under various conditions of loading and service. The latter forms so called assumed situations.

2.1.4 The number of statistical criteria is not limited. The number of criteria in deterministic physical regulations is equal to the number of assumed situations since each situation requires a special mathematical model and special equation.

2.2 Stability Norms (Standards).

2.2.1 Norm (or standard) N_i corresponding to a given criterion K_i is an extreme value of the criterion permitted by the given regulation. As a rule the correlation between criteria K_i and norms N_i may be presented in the form of criterial inequality system.

$$K_i \geq N_i \tag{2.1}$$

Such a system is the basement of any deterministic regulation. If the vessel does not meet even a single criterial inequalities it can not be considered stable enough.

2.2.2 Jaakko Rahola [22] suggested to determine the norms for a chosen system of statistical criteria on the basis of a balance between statistics of the lost vessels and the statistics of the vessels which had operated many years without stability casualties. Now it has become a conventional principle to compile the statistical stability regulations.

2.2.3 The physical approach gets its norms from the same equations which are used to obtain criteria. A concept of the worst (most dangerous) situation is usually introduced while searching the norms. Such a concept is not quite clear and strict from the probabilistic point of view. It will be shown that in the case of probabilistic approach it is enough to have a single universal stability criterion.

3. BASIC IDEAS AND CONCEPTS OF PROBABILISTIC APPROACH TO THE STABILITY ESTIMATION

3.1 The Concept of Vector of Assumed Situations.

The probabilistic approach considers the whole lifetime of a vessel as a continuous flow of changing accidental situations and conditions of loading. They may cause capsizing of a vessel at some accidental moment t with some probability $P_t\,(X)$.

Let us determine the concept of the assumed situation.

The vector of assumed situation $\vec{S}$ may be described by the set of certain parameters (components), for example:

- mean wind velocity $\bar{u}$;
- root-mean-square pulsation of the wind velocity σ_u;
- height of the significant waves h_s;
- mean period of the visible waves τ;
- speed of the vessel v;
- heading to the wind φ;
- heading to the waves ψ;
- resultant vector of additional external forces $\vec{P}_e$.

Thus
$$\vec{S} = \vec{S}(\bar{u}, \sigma_u, h_s, \tau, \varphi, \psi, \vec{P}_e). \qquad (3.1)$$

In the course of time the components of $\vec{S}$ - vector change. Therefore
$$\vec{S} = \vec{S}(t) \qquad (3.2)$$

3.2 The Concept of Vector of Loading Conditions

Condition of loading may be represented by vector $\vec{L} = \vec{L}(L_1, L_2, \ldots, L_k)$. The minimal number of the components $L_1, L_2, \ldots, L_k$ should provide the possibility to solve the tasks of statics and dynamics of the vessel's heeling. The following forms of components are usually applied [10]:

$$\begin{cases} L_{11} = \Delta \\ L_{12} = KG \\ L_{13} = R_X \end{cases} \qquad (3.3)$$

or, in another but equivalent form

$$\begin{cases} L_{21} = \Delta \\ L_{22} = M_{XOY} \\ L_{23} = n_\theta \end{cases} \qquad (3.4)$$

Here : $L_{11} = \Delta$; is a displacement of the vessel;

$L_{12} = KG$; is a height of the center of gravity above the base plane;

$L_{13} = R_X$; is a vessel's radius of gyration around the central longitudinal axis;

$L_{22} = \Delta \times KG = M_{XOY}$ is a statical moment of the vessel's mass relating to the base plane;

$L_{23} = n_\theta$ is a natural free rolling frequency.

Since all the components of change in the course of time it may be written as

$$\bar{L} = \bar{L}(t) \qquad (3.5)$$

Vectors $\bar{S}(t)$ and $\bar{L}(t)$ should be considered as stochastic multidimensional processes.

3.3 The Risk Function Concept

To solve the equation of heeling and capsizing it is necessary first of all to determine the vectors $\bar{S}$ and $\bar{L}$.

Besides the line drawing and the plans of the general arrangement of the vessel should be available. Then we can introduce some measure of current risk existing at each moment t. Such a measure we'll call below risk function and denote

$$\lambda(t) = \lambda(X, \bar{S}, \bar{L}) \qquad (3.6)$$

There are three symbols in the square brackets above: vector of assumed situation $\bar{S}$, vector of loading condition $\bar{L}$ and a symbol X. The latter means the event of capsizing just at the time when the vectors $\bar{S}$ and $\bar{L}$ exist. If vectors $\bar{S}$ and $\bar{L}$ can be described at some time interval as some stationary processes then function $\lambda(t)$ becomes a constant number during this interval.

The risk function is the most important concept in the probabilistic estimating. A stricter definition of $\lambda(t)$ is given below. Here we shall limit ourselves to an example of intuitive use of this function as a risk measure at any moment.

Let function $\lambda(t)$ be known for two different vessels A and B (Fig.1). And let us assume that minimal and maximal values of risk function for these two vessels are equal within a certain time interval T, that is

$$\begin{cases} \lambda_{A\max} = \lambda_{B\max} \\ \lambda_{B\min} = \lambda_{B\min} \end{cases}$$

But on the whole functions $\lambda_A(t)$ and $\lambda_B(t)$ are different. Which of these vessels, A or B, is safer in this case ?

At least three answers may be given to this question depending on what moment or what interval of time this question refers to.

Indeed it is possible to compare the safety of these two vessels:

- at the same moment t_1;
- at different time moments t_2 and t_3 which correspond to condition $\lambda_{A\max} = \lambda_{B\max}$;
- during the given interval of time T taken as a whole.

Let us note that from the viewpoint of existing deterministic stability standards there is no difference between the second and the third answers since both of the variants would be considered equally dangerous (and the most dangerous !) during the interval T.

But type A is much more reliable than type B from the viewpoint of the people who are working or traveling aboard the vessel and from the viewpoint of the shipowner or the insurance company. One can assert it because the critical state $\lambda_A(t_2) = \lambda_B(t_3) = \lambda_{max}$ lasts only during a small part of time interval T for the vessel A while for vessel B it lasts much longer. This fact increases the chance of vessel A to avoid capsizing.

The probabilistic approach to the evaluating stability is in full agreement with the last point of view. One can say that deterministic approach gives a definite answer to the question whether the vessel will capsize or not being affected by the external forces caused by determined vector $\vec{S}$ under determined condition of loading $\vec{L}$. This answer must be unconditional "Yes" or "No" without any stipulations.

The probabilistic answer is also "Yes" or "No" but with two principal stipulations: during the given time interval and with a certain probability.

For better understanding of the differences between the deterministic and the probabilistic approaches it would be useful to think over an example taken from quite a different field. Let us imagine some advanced fortifications which are under the fire of enemy at random moments of time. And we can see a soldier standing at the front line near a high-ranked general who had come from the head-quarters to inspect the regiment. The risk to be killed during the shooting is the same for the soldier and for the general. But an important question arises: which of them has more chances to survive till the end of whole war ? The answer is clear because such a dangerous shooting is a constant or in any case frequent situation for the soldier but it is only a short episode in the general's service.

So the heart of the matter in the development of probabilistic approach to setting stability regulation is the discovery of links between probability of capsizing and certain time interval given in advance.

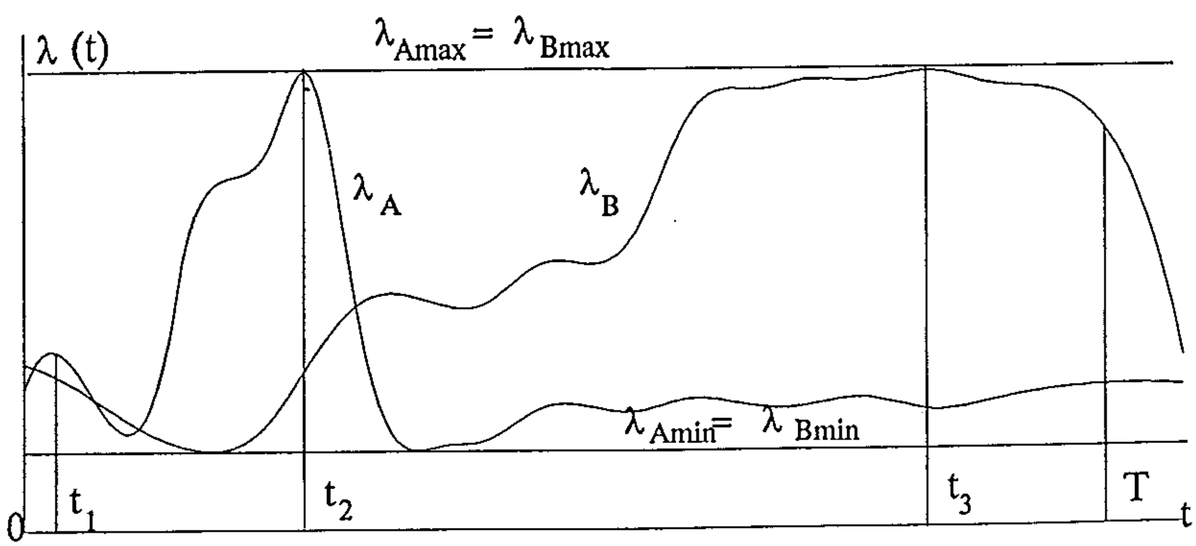

Figure 1

4. PROBABILITY OF SURVIVAL

4.1 Risk Function from the Mathematical Point of View

The risk function was defined in the papers [16,17,19,20,22] as a probability of capsizing during the time unit adjacent to moment *t*. This conditional probability should be determined in the assumption that capsizing has not occurred till the current moment *t*. In every infinitely small interval *dt* only an infinitely small probability of capsizing exists and it is proportional to *dt*:

$$dP_{t,dt}(X) = \lambda(t)dt \qquad (4.1)$$

The probability of non-capsizing during the same interval dt is equal to

$$dP_{t,dt}(\overline{X}) = 1 - \lambda(t)dt$$

4.2 Probability of Survival and Its Formula

In paper [17] published in 1963 it was proved that the probability of non-capsizing during any finite interval *T* may be expressed by formula

$$P_T(\overline{X}) = \exp\left[-\int_0^T \lambda(t)dt\right] \qquad (4.2)$$

Absolutely the same expression is used in contemporary general theory of reliability to calculate the probability of failureless operation of an element or a system during the given time interval T. In English scientific literature this probability has its own impressive name "probability of survival". We shall also use this term everywhere.

Let us note the main properties of the probability of survival.

4.3 Probability of Survival and Its Link with Average Value of Risk Function

The absolute value of the exponent in formula 4.2 is equal to the area between the risk function curve and the t-axis within interval $0<t<T$

$$F = \int_0^T \lambda(t)dt = \lambda_a T \qquad (4.3)$$

Here λ_a is an average value of risk function within the same interval T:

$$\lambda_a = \frac{F}{T} \qquad (4.4)$$

Hence

$$P_T(\overline{X}) = \exp(-\lambda_a T) \qquad (4.5)$$

The value of λ_a at given area F does not depend on the form of the risk function curve within interval T.

4.4 Risk Function λ_a and the Average Stability Casualty Index

The probability of survival for $T = 1$ is equal to

$$P_{T=1}(\overline{X}) = \exp(-\lambda_a \cdot 1) = 1 - \lambda_a + \frac{\lambda_a^2}{2!} - \frac{\lambda_a^3}{3!} + \ldots (-1)^n \cdot \frac{\lambda_a^n}{n!} \qquad (4.6)$$

In accordance with IMO stability casualty statistics average λ_a -value for medium - sized and small fishing vessels of various countries lies within the limits

$$10^{-4} \le \lambda_a \le 3 \cdot 10^{-3}, 1/\mathit{year} \qquad (4.7)$$

Hence with a great accuracy

$$P_{T=1}(\overline{X}) = 1 - \lambda_a$$

It means that average number of capsized vessels N_C during a year is equal to

$$N_C = \lambda_a \cdot N$$

where N is total number of the vessels in operation during the given year.

But in majority of marine countries there is state statistics of different kinds of casualties including stability accidents. The main index for each kind of casualties is usually the annual frequency of accidents

$$n_C = \frac{N_C}{N}, \quad 1/\mathit{year}$$

Consequently

$$\lambda_a = n_{Ca} \qquad (4.8)$$

Here n_{Ca} is an average value of stability casualty index for the given type of vessels.

5. PROBLEMS OF CRITERIA AND NORMS IN PROBABILISTIC ESTIMATION OF STABILITY

5.1 Probability of Survival as a Stability Criterion

It is evident from 4.2 and 4.5 that the probability of survival may be suggested as a universal stability criterion. The acceptance of such a criterion solves at the same time the problem of guarantee.

5.2 Estimation of the Range for the Norm of

However the acceptance of such a criterion will entail some difficulties. First of all they are caused by the properties of function $P_T(\overline{X})$ in the vicinity of its permissible values.

It is clear that it is possible to accept some norm N_P for criterion only in the case when this norm is not less than the values which have been achieved in practice. But assuming T = 20 years these values for fishing vessels at the end of the 60-ties lay within rather narrow limits

$$0.942 \le P_T(\overline{X}) \le 0.998 \qquad (5.1)$$

The acceptance of the lower bound would mean that approximately six vessels of a hundred will, upon the average, capsize during twenty years of operation.

Even the norm N_P=0.99 is not indisputable since the probability of survival of each vessel out of a hundred is equal only to

$$P_{100T}(\overline{X}) = 0.99^{100} \approx 0.37$$

Consequently the sufficiently strict norm for criterion $P_T(\overline{X})$ should be between 0.99 and 1.0 But an absolutely stable vessel with $P_T(\overline{X}) = 1.0$ is nothing but an unattainable theoretical image. Thus we have a very narrow range to choose a sufficient and achievable norm N_P

5.3 Sensitivity of $P_T(\overline{X})$ to the Alterations of Usual Stability Parameters and Risk Function

But just that narrowness gives raise to some doubts: is the criterion $P_T(\overline{X})$ sensitive enough to the usual measures of stability improvement ?

Let us consider the practical question: if probability $P_T(\overline{X}) = 0.99$ is insufficient but value $P_T(\overline{X}) = 1.0$ is unattainable then how much ballast should be laid onto the vessel's bottom to increase the stability criterion from 0.990 up to 0.991 and to ensure the observance of such a stability standard ?

Only rather bulky calculations might give on the exhaustive answer to this simple question. But it is clear without any calculations that, lowering the vessel's center of gravity as much as possible, we can increase the existing probability of survival only by a very small quantity. Fig. 2 clarifies this statement. The abscissa of this graph shows how great the relative decrease of the risk function should be to increase the initial value of probability $P_T(\overline{X})$ by 0.001.

Such a small sensitivity of the analyzed criterion to the large alterations of risk function (and of the traditional stability characteristics) is the main reason for abstaining from accepting this criterion.

The problem of choice of probabilistic criterion may be now reformulated as follows: it is necessary to find some function which would be linked uniquely with probability of survival but at the same time would be more sensitive to alterations of usual stability characteristics.

5.4 Casualty Index as a Basis for Probabilistic Stability Standards

We have found above such a function. It was the risk function averaged over the time interval T. The basis of the norm for such a criterion is evident: it should be equal to the wanted average stability casualty index. In this case the criterial inequality may be written in the following form:

$$\lambda_a = \frac{n_{Ca}}{k} \qquad (5.2)$$

Here: λ_a appears in the role of a universal stability criterion;

k is the factor of stability reserve which meets the social needs to preserve (if k = 1.0) or to increase (if k > 1.0) the achieved safety level.

Such a norm corresponds to the guarantee (for T years)

$$\Gamma = P_{T=20}\left(\overline{X}\right) = \exp\left(-\frac{20 n_{Ca}}{k}\right) \qquad (5.3)$$

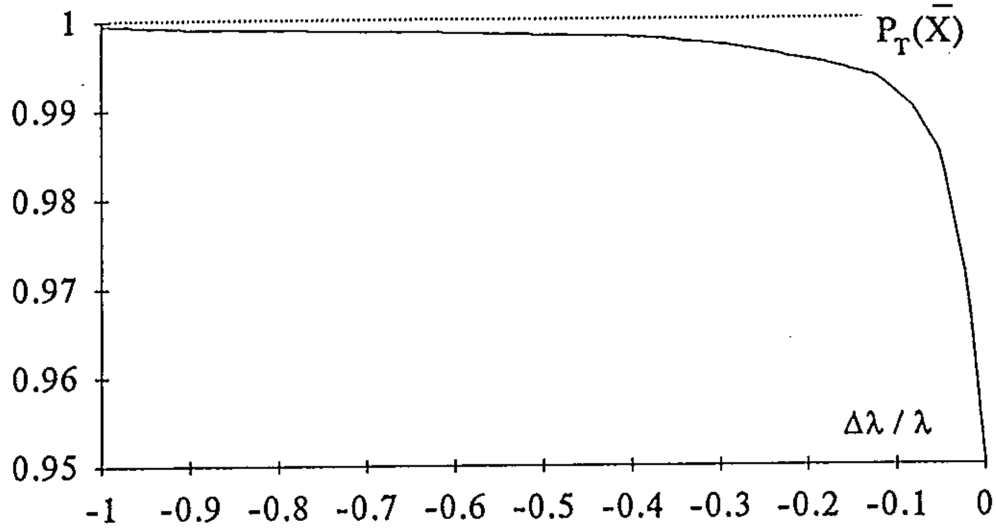

Figure 2

6. ALGORITHM FOR CALCULATION OF RISK FUNCTION AVERAGED OVER THE LARGE TIME INTERVAL

6.1 Risk Function Averaged over All Possible Assumed Situations and All Conditions of Loading.

Such an algorithm was suggested in paper [20]:

$$\lambda_a = \sum_{i=1}^{i=n} P(\vec{S}_i) \sum_{j=1}^{j=m} P(\vec{L}_j | \vec{S}_i) \times \lambda(X | \vec{L}_j, \vec{S}_i) \qquad (6.1)$$

This formula was derived quite strictly with a single assumption. It was assumed that the uncountable infinite set of situations and the similar set of loading conditions may be substituted with acceptable accuracy by the countable and finite sets of discrete situations and conditions of loading. Such an assumption corresponds to the common practice of describing situations in the terms of discrete numbers (scales) for external forces and weather conditions. The analogous discrete scales are applicable for so called "nets" of discrete conditions of loading.

6.2 Conclusions and Outlook

The structure of algorithm 6.1 indicates three problems existing in the domain of gradual transition to the probabilistic evaluation of vessel's stability and of risk at sea in general.

The first and the most complicated problem is determining risk function values in various combinations of a certain assumed situation $\vec{S}_i$ and a certain condition of loading $\vec{L}_j$. In its nature this task is a task of ship's theory and hydromechanics.

It would be very useful to create, to publish and to replenish some kind of international bank of accumulated mathematical models for different situations. At the same time it would be possible to make clear which situations are not yet investigated. But this subject is beyond the frames of a single report. The references are given below to some researches carried out recently in the countries of the former USSR. They embrace only a small part of accumulated data and are mentioned only for example [2, 3, 4, 5, 7, 11, 12, 13, 21, 23, 27, 28].

Special attention should be paid to the problem of adequacy of the suggested mathematical models and their physical realizations in the course of the full scale tests or of laboratory experiments [23]. International cooperation of the experts is absolutely necessary. Corresponding proposals may be discussed during the Conference STAB-94.

Two other directions of research works in the domain of probabilistic estimation of stability are simpler and close to practical implementing.

One of these directions concerns the enumeration of assumed situations and determining of their probabilities. The probabilities of various situations $\vec{S}_i$ may be determined according to the oceanographic data:

$$P(\vec{S}_i) = \frac{T_i}{T} \qquad (6.2)$$

Here : T is a certain time interval as large as possible and in any case commensurable with the lifetime of a vessel;

T_i is an average duration of situation $\vec{S}_i$ in the course of interval T

The last direction is connected with the probabilities of different loading conditions $\vec{L}_j$. These problems were analyzed in the books and reports [1, 6, 8, 9, 10, 14, 16, 18]. General concepts and computing procedures were included into the manuals for students [14].

Thus as soon as the fund of hydromecanical solutions will become wider formula 6.1 may be interpreted as a practical algorithm for probabilistic stability estimation and at the same time for calculation of corresponding safety guarantee of different vessels operating under different conditions.

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