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Pure loss of stability calculation of naval ships in regular waves

ZHU Jun[1], *LIU Ruijie*[2], *GE Yijun*[1], *WANG Zhiyu*[1], *HUANG Kunlun*[1]

1 Department of Naval Architecture Engineering, Naval University of Engineering, Wuhan 430033, China

2 Naval Academy of Armament, Beijing 100073, China

Abstract: The pure loss of stability of a ship is one of the failure modes of the second-generation intact stability criteria. Based on the static surface coordinate system, the generalized pitch angle and draught variable are defined, and a wave equation with clear physical meaning is deduced. Based on the Froude-Krylov hypothesis, combined with AutoCAD 2D surface area computing technology and the VBA programming method, a calculation method of the loss of pure stability of ships in regular waves is proposed. For a naval ship, the righting arm is calculated in regular waves, and the large heel ship state is shown to have an identical convergence. The results of the calculations show that a significant reduction in the meta centric height of the maximum righting arm occurs not just in a wave crest but also in a trough. By analyzing the wave profile under the hull, it can clearly be seen that wave amplitude above the deck or below the bottom of the hull causes the pure loss of stability, and in oblique waves or beam seas, the pure loss of stability is caused the asymmetry of the wave profile on the hull. The coinciding convergence of the calculations shows that the process of the definition of generalized pitch can be employed to assess the pure loss of stability of naval ships in regular waves.

Key words: naval ship; pure loss of stability; regular waves

CLC number: U661.2+2

0 Introduction

In the 1930s, through continuous investigation and analysis, Kempf [1] found that when the midship is located near the crest, the ship stability will decline compared with that in the static water. On the contrary, when the midship is located near the trough, the stability will rise slightly. In 1961, Paulling et al. [2-3] studied the stability of ships in waves, and then performed ship test of large scale ratio in the environment of following seas, quartering seas and beam seas in the San Francisco Bay. Combined with the time-domain simulation analysis method, they discovered the capsizing mechanism of ships in the environment of waves. Grim [4] proposed the viewpoint of effective wave, which transforms random waves in the ocean into regular waves. In the 1980s, Hamamoto et al. [5-6] studied the ship stability calculation method of quartering seas, but divergence appeared in the calculation at a large heel angle, then they set up a new coordinate conversion system to study the manoeuvreability of ships in waves [7]. Fang et al. [8] calculated the righting arm of a ship in oblique waves on the basis of Froude-Krylov hypothesis considering the effects of scattering and diffraction. Kreuzer et al. [9] studied the capsizing of ships on the basis of considering rolling, pitching and heaving of ships.

In order to solve the problem of divergence in the calculation at large heel angle, Kong et al. [10] in China used the perturbation method to calculate the cross-sectional area and center of hull under waves. Xie [11] studied the pure loss of stability for the stability vulnerability. Zhou et al. [12-13] analyzed the Level 1 and Level 2 criteria for the vulnerability of the pure loss of stability. Hu et al. [14] reviewed the research

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Author(s): ZHU Jun, male, born in 1959, Ph.D., professor. Research interest: ship manoeuverability. E-mail: zhjun101@sina.com

LIU Ruijie (Corresponding author), male, born in 1987, Ph.D., engineer. Research interest: ship hydrodynamics. E-mail: jackrygy@126.com

status of parametrically excited roll. Zhu et al. [15] used the surface area technique of AutoCAD to calculate the stability and damage stability of a naval ship in static water.

We found from studies that the cause of the divergence of stability calculation at large heel angle lies in that, the pitch angle defined as around the hull coordinate axis and pitching moment (moment composed of gravity and buoyancy) were in different directions, and the greater the heel angle is, the larger the deviation is. In the extreme case of heel angle of 90°, the pitch angle rotates in the horizontal plane, while the pitching moment is always perpendicular to the horizontal plane. This leads to mismatched balance equations of pitching moment at large heel angle.

In this paper, the generalized pitch angle around the axis of the static surface and the generalized draught perpendicular to the static surface were defined to ensure the matching of the pitching moment balance equations.

1 Wave equation in the hull coordinate system

1.1 Coordinate system definition

The fixed coordinate system $O-xyz$ of the static surface is shown in Fig. 1. The plane Oxy coincides with the static surface, and the Oz axis is vertically upward. The wave equation is

$$\varsigma_z = \frac{H_w}{2} \times \cos\{\frac{2\pi}{\lambda}[\xi_0 - x\cos\chi - y\sin\chi]\} \quad (1)$$

where λ is wavelength; H_w is wave height; χ is wave angle; ξ_0 is the crest position. When $\xi_0 = 0$, the crest line passes through the origin of coordinates; when $\xi_0 = \lambda/2$, the trough line passes through the origin of coordinates.

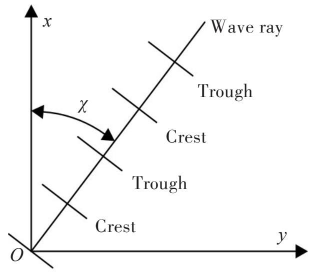


Fig.1 Fixed coordinate system of static surface

The fixed coordinate system $B-x_B y_B z_B$ of hull is shown in Fig. 2. Intersection B of 3 planes, i.e., the left and the right symmetrical planes, keel base plane and midship plane, was used as origin of the coordinate system. Axis Bx_B points to the bow, axis By_B points to the starboard, and axis Bz_B is vertically upward. T is draught at midship in the static water, and the conversion relationship between the fixed coordinate system of static surface and coordinate system of hull was obtained as

$$\begin{cases} x = x_B \\ y = y_B \\ z = z_B - T \end{cases} \quad (2)$$

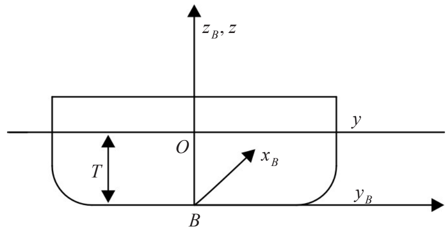
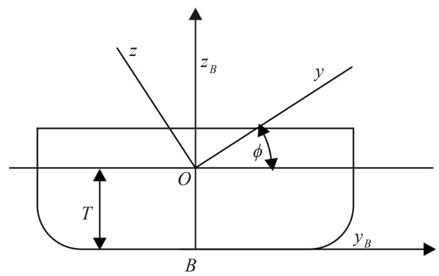


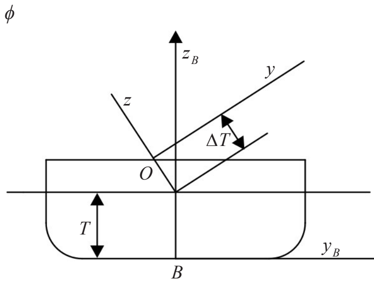
Fig.2 Coordinate system on hull

The coordinate system of static surface rotated around point O by ϕ (Fig. 3(a)), then the coordinate system of static surface was given a shift of ΔT (Fig. 3(b), equivalent to the sinking of the hull) along the static surface. Finally, the coordinate system of static surface rotated around axis Oy by θ (equivalent to the hull rotating around the axis of static surface). The conversion relationship of the two coordinate system after the rotations is

$$\begin{cases} x = -(T\cos\phi + \Delta T)\sin\theta + x_B\cos\theta - y_B\sin\phi\sin\theta + \\ \quad z_B\cos\phi\sin\theta \\ y = -T\sin\phi + y_B\cos\phi + z_B\sin\phi \\ z = -(T\cos\phi + \Delta T)\cos\theta - x_B\sin\theta - y_B\sin\phi\cos\theta + \\ \quad z_B\cos\phi\cos\theta \end{cases} \quad (3)$$



(a) Coordinate system of static surface rotates around the point O by ϕ



(b) Coordinate system of static surface shifts along the static surface by ΔT

Fig.3 Coordinate systems transformed by rotation and shift

1.2 Wave equation in hull coordinate system

The third term z was set to 0 in Formula (3), and the static surface equation in the hull coordinate system is

$$z_B = T + \frac{\Delta T}{\cos\phi} + \frac{1}{\cos\phi}\mathrm{tg}\,\theta \cdot x_B + \mathrm{tg}\,\phi \cdot y_B \qquad (4)$$

Substituting Formula (1) into the third term of Formula (3), we can obtain the wave equation in hull coordinate system:

$$\varsigma_B = T + \frac{\Delta T}{\cos\phi} + \mathrm{tg}\,\phi \cdot y_B + \frac{1}{\cos\phi}\mathrm{tg}\,\theta \cdot x_B + \frac{1}{\cos\phi\cos\theta} \times \frac{H_\mathrm{w}}{2} \times \cos\{\frac{2\pi}{\lambda} \times [\xi_0 - x\cos\chi - y\sin\chi]\} \qquad (5)$$

In the formula, x and y are determined by the first and second terms of Formula (3), and this formula is an implicit equation.

Formula (5) is the expression of the waves in the hull coordinate system. When the draught T, draught increment ΔT, heel angle ϕ and pitch angle θ were of certain values, the wave equation was determined solely. It is worth noting that T and ϕ are consistent with the general definitions. However, the draught increment ΔT is variation of vertical static surface, namely, generalized draught, and θ is the rotation angle around the intersection line of midship section and static surface, namely, generalized pitch angle.

2 Formula of righting arm

2.1 Balance condition of naval ships

The balance condition is that the naval ship weight is equal to the buoyancy under instantaneous wave, and they act in the same plumb line (vertical static surface). The balance equation is

$$\begin{cases} W = \rho g \nabla \\ \mathrm{tg}\,\phi = \dfrac{-(y_{B\mathrm{b}} - y_{B\mathrm{g}})}{z_{B\mathrm{b}} - z_{B\mathrm{g}}} \\ \mathrm{tg}\,\theta = \dfrac{-(x_{B\mathrm{b}} - x_{B\mathrm{g}})}{z_{B\mathrm{b}} - z_{B\mathrm{g}}} \end{cases} \qquad (6)$$

In the formula: ρ is the density of water; g is the acceleration of gravity; ∇ is displacement volume of the hull under instantaneous wave; $(x_{B\mathrm{b}}, y_{B\mathrm{b}}, z_{B\mathrm{b}})$ is the center for displacement volume of the hull; W and $(x_{B\mathrm{g}}, y_{B\mathrm{g}}, z_{B\mathrm{g}})$ are gravity and barycenter of the hull. The displacement volume and the coordinates of the buoyant center were calculated by the two-dimensional slice method:

$$\begin{cases} \nabla = \int A(x_B)\mathrm{d}x_B \\ x_{B\mathrm{b}} = \dfrac{\int x_B A(x_B)\mathrm{d}x_B}{\nabla} \\ y_{B\mathrm{b}} = \dfrac{\int y_{B\mathrm{c}} A(x_B)\mathrm{d}x_B}{\nabla} \\ z_{B\mathrm{b}} = \dfrac{\int z_{B\mathrm{c}} A(x_B)\mathrm{d}x_B}{\nabla} \end{cases} \qquad (7)$$

In the formula: $A(x_B)$ is the area of the hull section under instantaneous wave line; $y_{B\mathrm{c}}$ and $z_{B\mathrm{c}}$ are the corresponding centers of area.

2.2 Righting arm of hull under instantaneous wave

When the heel angle of the hull is ϕ, under the condition of meeting the first (balance between the gravity and buoyancy) and the third (pitching moment balance) formulas in Formula (7), righting arm GZ of the hull under instantaneous wave is

$$GZ = y_{B\mathrm{b}} \times \cos\phi - (z_{B\mathrm{g}} - z_{B\mathrm{b}}) \times \sin\phi \qquad (8)$$

The above balance conditions and the formula of the righting arm were based on the assumption of hydrostatic pressure (Froude-Krylov) under instantaneous wave, neglecting the dynamic pressure correction term (e^{-kz}) of Smith. In order to simplify the calculation, the displacement weight below wave was taken as the instantaneous buoyancy, and the fluid pressure was approximated as $p = \rho g[z + \varsigma_z \cos(kx)]$. The approximation overestimated the pressure in the crest area and underestimated the pressure in the trough area, i.e., the effective wave steepness should be slightly smaller than the geometric wave steepness. Commonly, the approximate method is to correct the geometric wave steepness, that is, the part of dynamic pressure is taken as $\varsigma_z \mathrm{e}^{-kd/2}\cos(kx)$, where d is the draught. Therefore, the correction will not affect the change law of motion.

3 Numerical calculation and analysis

3.1 Surface area computing technology

In this paper, applying the computational method of AutoCAD surface area [15], a computational procedure for the stability of naval ship in waves was obtained by secondary development of programming language VBA. The calculation steps are as follows:

1) The cross section of the hull was drawn to form the surface area of the hull section;

2) The wave lines were drawn at the corresponding section according to Formula (5), forming the surface

area of the wave line which contains the hull section;

3) Domain eigenvalues (area and centroid coordinates) of union set of the hull domain and surface area of wave line were extracted;

4) By integrating according to Formula (7), the displacement volume and volume center coordinates were obtained. Under the condition of satisfying the first and the third formulas in Formula (6), the righting arm was calculated by Formula (8).

3.2 Numerical calculation of stability in waves

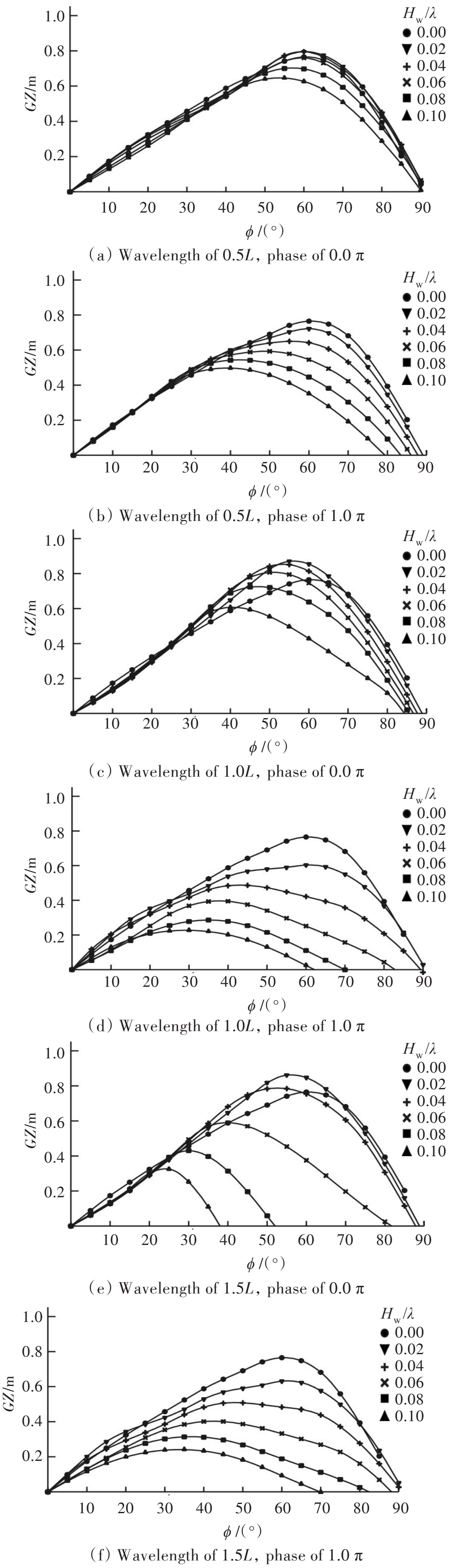
In this paper, the waterline length of the naval ship was calculated to be 125 m. The forecastle was included in the stability part, and there is ladder-shaped deck at the stern. The range of stability calculation in waves was: wave angle χ was 0°, 30°, 60° and 90°, respectively; the ratio of wavelength to ship length λ/L was 0.5, 1.0 and 1.5, respectively; wave steepness H_w/λ was 0.01–0.1, and crest phase $(2\pi/\lambda\times\xi_0)$ was 0– 2π .

3.3 Stability analysis of naval ship in waves

1) Computational analysis of pure loss of stability in longitudinal waves.

Fig. 4 is computational curves of the righting arm in the longitudinal waves (wave angle χ = 0). The crest phase $(2\pi/\lambda\times\xi_0) = 0$ represents that the crest was located in the midship, and $(2\pi/\lambda\times\xi_0) = \pi$ represents that the trough was located in the midship. The calculation results show that the significant wave height leads to loss of stability, and the maximum value and the range of stability of the righting arm were significantly reduced; another feature is that significant loss of stability also appeared in sagging condition (the trough was located in the midship).

When λ/L = 1.0 and H_w/λ = 0.06, the interface between the hull and waves is shown in Fig. 5. It indicates that when the crest was located in the midship, the effective waterplane (providing stability) was located in the middle of the hull, and the bottom of bow and stern was higher than the waves, leading to the loss of effective waterplane; when the trough was in the midship, and only the 2 areas in front of midship and in the back of midship were effective waterplane, the midship had the loss of effective waterplane because trough was below the hull, and the deck on bow and stern also had the loss of effective waterplane because of submergence of the waves.



(a) Wavelength of 0.5L, phase of 0.0 π

(b) Wavelength of 0.5L, phase of 1.0 π

(c) Wavelength of 1.0L, phase of 0.0 π

(d) Wavelength of 1.0L, phase of 1.0 π

(e) Wavelength of 1.5L, phase of 0.0 π

(f) Wavelength of 1.5L, phase of 1.0 π

Fig.4 Calculating curves of righting arm in longitudinal waves(χ =0°)

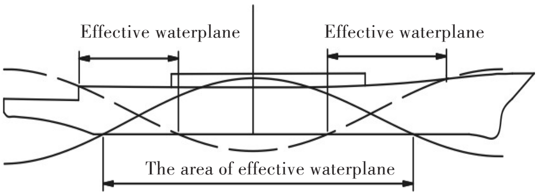


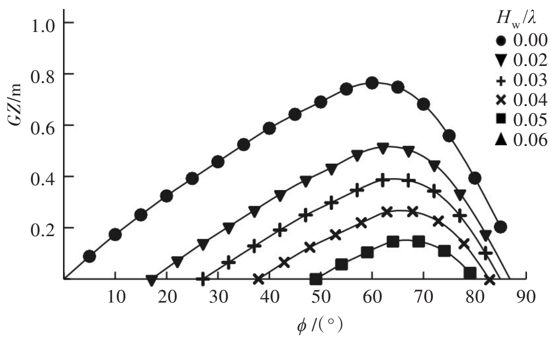
Fig.5 The interface between hull and waves on crest and trough (λ/L =1.0, H_w/λ =0.06)

2) Computational analysis of pure loss of stability in beam seas.

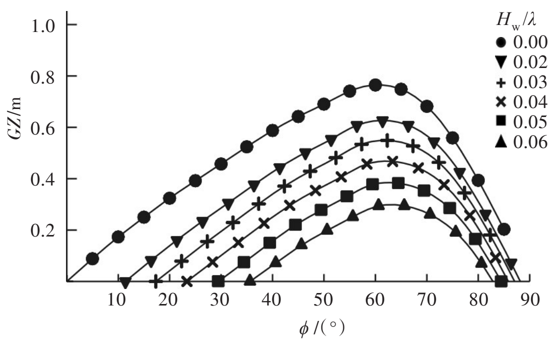
Fig. 6 is the computational curves of the righting arm in beam seas (wave angle χ = 90°), and Fig. 6 shows the 2 cases of serious loss of stability in the crest phase of 0.5 π and 0.75 π, respectively. The results show that wave height is also a main factor that leads to loss of stability, and the loss of stability is shown by the significant decrease of the maximum righting arm as well as the great decrease of stability range with the increase of wave height. Since the waves are oblique relative to the hull section, similar to the existence of initial heel angle for the hull, the righting arm curve shows the left–right asymmetry, resulting in a reduction in the value of the maximum righting arm and the range of stability.

3) Computational analysis of pure loss of stability in oblique waves.

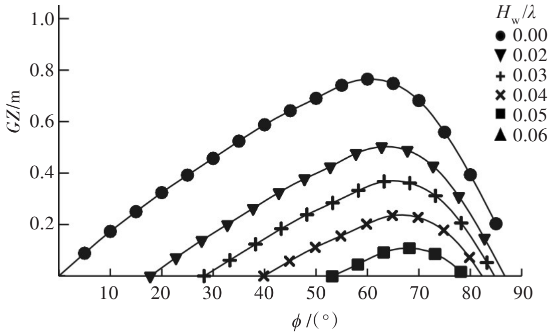
Fig. 7 is the computational curves of the righting arm in the oblique waves (wave angle χ = 30°). The calculation results show that the stability characteristics in the oblique waves were between those in the longitudinal waves and beam seas. The asymmetry of



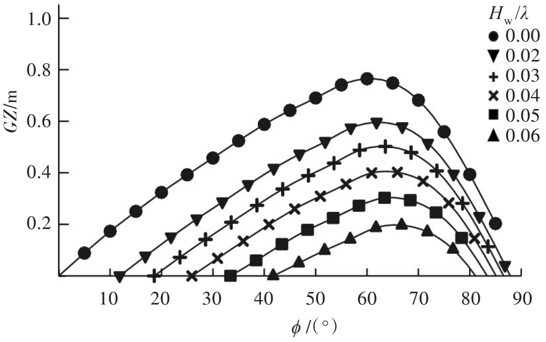
(a) Wavelength of 0.5L, phase of 0.50 π



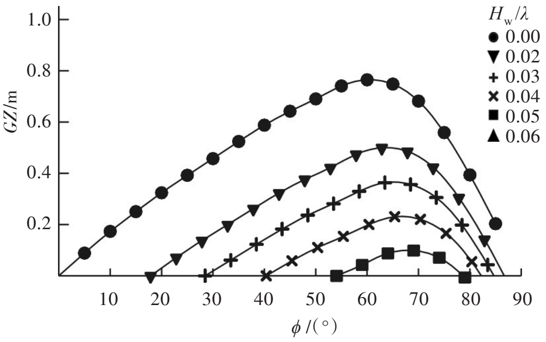
(b) Wavelength of 0.5L, phase of 0.75 π



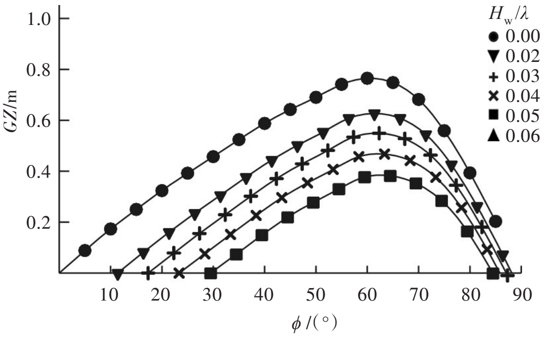
(c) Wavelength of 1.0L, phase of 0.50 π



(d) Wavelength of 1.0L, phase of 0.75 π



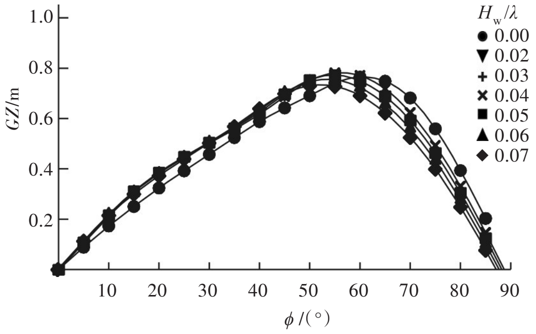
(e) Wavelength of 1.50L, phase of 0.50 π



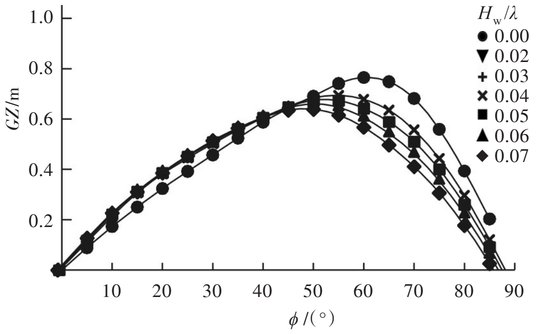
(f) Wavelength of 1.50L, phase of 0.75 π

Fig.6 Calculating curves of righting arm in beam seas(χ =90°)

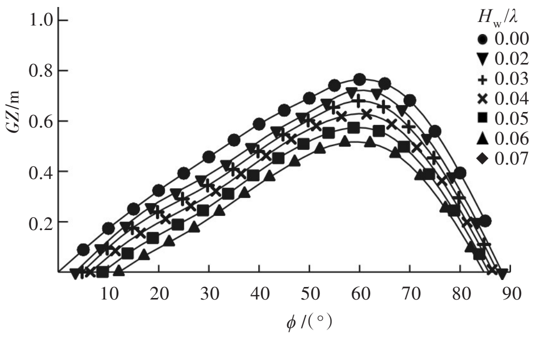
the left and right of the righting arm was not obvious when the wavelength was relatively short, which was because when the wavelength was short, the waves were opposite to the oblique direction of hull section, offsetting the asymmetry of obliqueness. With the increase of the wavelength, the asymmetry of obliqueness became obvious, and the maximum value of righting arm decreased obviously with the increase of wave height.



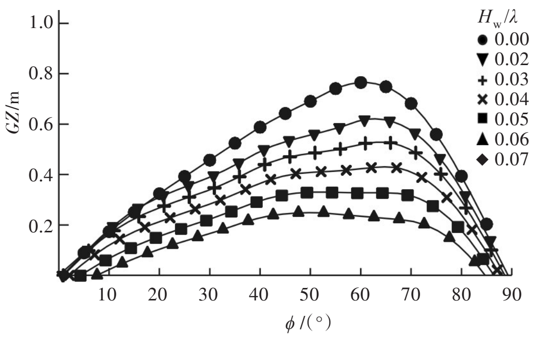
(a) Wavelength of 0.5L, phase of 0.50 π



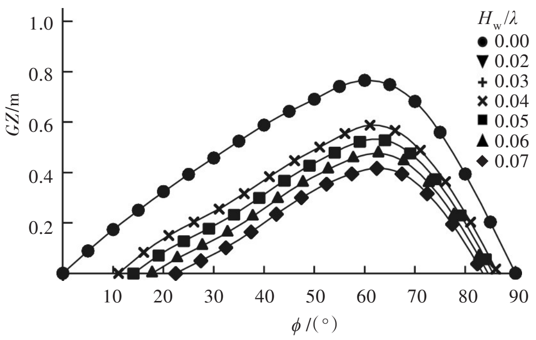
(b) Wavelength of 0.5L, phase of 0.75 π



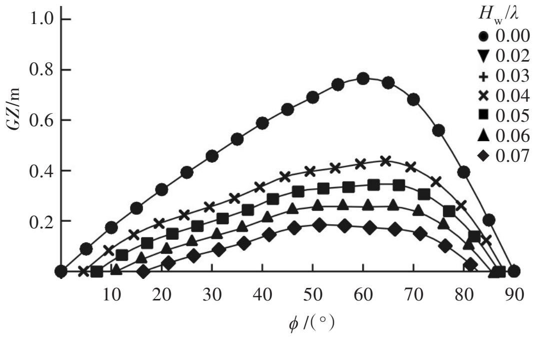
(c) Wavelength of 1.0L, phase of 0.50 π



(d) Wavelength of 1.0L, phase of 0.75 π



(e) Wavelength of 1.5L, phase of 0.50 π



(f) Wavelength of 1.5L, phase of 0.75 π

Fig.7 Calculating curves of righting arm in oblique waves (χ =30°)

4 Conclusion

The generalized pitch angle θ and generalized draught ΔT were defined in this paper, and the wave equation in the hull coordinate system was derived. The derived wave equation in the hull coordinate system was composed of 5 terms with clear physical meaning. The draught increment ΔT, heel angle ϕ and pitch angle θ mainly affected the buoyancy, transverse moment and longitudinal moment respectively, so that the iterative calculation has stable convergence characteristics. Under the assumption of Froude–Krylov, the comparison and analysis of the calculation results of the righting arm of a naval ship with ladder–shaped deck in waves demonstrate the following conclusions:

1) λ/L =1.0 is the main wave environment for the pure loss of stability of naval ships in waves, and wave height is the main factor leading to the loss of stability.

2) In the longitudinal waves, when the trough is located in midship (when some wave heights are large), the stability will be greatly reduced, and the main reason is the disappearance of the effective waterplane due to wave being higher than the deck or lower than the bottom.

3) In the cases of beam seas and oblique waves, because the asymmetry is the main reason for the great loss of stability, which is caused by obliqueness of wave relative to the hull cross section, the case of beam seas is the most serious.

A method of direct calculation for pure loss of stability of naval ship in regular waves was presented in this paper, which features stable convergence characteristics, and can be extended to the calculation method of coupled motion of ship oscillation.

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规则波浪中舰船纯稳性丧失计算研究

朱军[1], 刘瑞杰[2], 葛义军[1], 王智宇[1], 黄昆仑[1]

1 海军工程大学 舰船工程系,湖北 武汉 430033

2 海军装备研究院,北京 100073

摘 要:[**目的**]波浪中纯稳性丧失是第二代舰船完整稳性中稳性薄弱性的衡准之一。针对波浪中大倾斜角稳性计算发散问题,[**方法**]以静水面坐标系为基准,定义了广义纵倾角和广义吃水变量,推导出物理含义清晰的波面方程。在Froude-Krylov假定条件下,结合AutoCAD二维图形面域计算技术和VBA编程方法,提出了规则波浪中舰船纯稳性丧失的计算方法。针对一艘具有阶梯式甲板的舰船,计算了规则波浪中舰船复原力臂曲线,证明大横倾状态具有一致收敛性。[**结果**]计算得到了规则波浪中稳性变化规律:纵向波浪中,波面高于甲板或低于船底导致有效水线面消失是稳性降低的主要原因;斜浪和正横浪中,波面相对船体横剖面倾斜引起的不对称性,是稳性大幅度降低的主要原因。[**结论**]计算收敛一致性表明,基于广义纵倾角定义的计算方法可成为评估舰船波浪中纯稳性丧失的有效手段。

关键词:舰船;纯稳性丧失;规则波浪